Additive Manufacturing

ExaAM: Transforming Additive Manufacturing through Exascale Simulation

Additive Manufacturing (AM) is revolutionizing manufacturing, allowing construction of complex parts not readily fabricated by traditional techniques. Although there has been significant interest and investment in AM, the fraction of this investment devoted to modeling and simulation is relatively small and not focused on the development of high-fidelity predictive models but instead on reduced-order models for industry use. The Exascale Additive Manufacturing project (ExaAM) represents a unique opportunity to use exascale simulation to enable the design of AM components with location-specific properties and acceleration of performance certification.

ExaAM aims to develop the Integrated Platform for Additive Manufacturing Simulation (or IPAMS), a collection of capabilities that directly incorporate microstructure evolution and the effects of microstructure within AM process simulation.
In AM, a geometric description of the part is processed into 2D slices. A feedstock material is melted, and the part is built layer by layer. In metal AM, the feedstock is often in wire or powder form, and the energy source is a laser or electron beam. ExaAM focuses on powder bed processes, where each layer is approximately 50 microns. A part that is 1 cm tall, for example, would require 200 layers, each requiring the spreading of new feedstock powder and one or more passes of the laser or electron beam to sinter and/or melt the powder in appropriate locations.

The physical processes involved in AM are similar to those of welding—a field with decades' worth of experimental, modeling, simulation, and characterization research. Unfortunately, the simulation tools developed for welding and other similar processes, while calibrated and approaching predictive capability, are inadequate for AM processes, as demonstrated by the inability to predict the failure rate for new AM parts, which can be as high as 80%. This is believed to be largely due to the fact that the process–structure–property–performance relationship is traditionally modeled in an uncoupled manner, relying on tabular databases that are unable to adequately capture the implicit, dynamic, nonequilibrium nature of AM processes.

One of the goals of ExaAM is to remove those limitations by coupling high-fidelity mesoscale simulations within continuum process simulations to determine the microstructure and properties using local conditions. Typically, thermomechanical finite element models are employed at the macroscopic part scale; finite volume or finite element models are used at millimeter scales for fluid dynamics and heat transfer to capture the melt pool dynamics and solidification; mesoscale approaches [e.g., discrete elements, cellular automata, kinetic Monte Carlo (MC), or phase field models] are used at the micron scale to simulate melting, solidification, and microstructure formation; and polycrystal plasticity models are used to develop the microscale mechanical property relationships.

ExaAM will develop and deploy a collection of simulation capabilities for performing process-aware performance modeling of additively manufactured parts using locally accurate properties predicted from microstructures that develop based on local processing conditions. ExaAM will demonstrate this capability by simulating the complex bridge structure developed for the 2018 National Institute of Standards and Technology AM-Bench Conference, known as AMB2018-01. The simulation will be performed where measurements were taken (e.g., "cut locations" for transverse and longitudinal scanning electron microscope specimens for microstructure images), and each location will require a four-stage sequence of simulations.

PI: John Turner, Oak Ridge National Laboratory

Collaborators: Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, National Institute of Standards and Technology, University of Tennessee

Progress to date

- Leveraged other ECP projects to create new exascale-ready AM-specific capabilities—MFEM for polycrystal plasticity (ExaConstit), AMReX for both a new version of Truchas (TruchasPBF) and a new cellular automata capability for microstructure evolution (ExaCA).
- Implemented and demonstrated initial coupled physics capabilities—in-memory DTK-based integration of melt pool thermal fluids (TruchasPBF) + thermomechanics (Diablo), file-based coupling of melt pool thermal fluids + microstructure evolution (ExaCA), and microstructure + micromechanical properties (ExaConstit).
- Ported multiple components to Summit (ExaConstit, MEUMAPPS-SS, TruchasPBF, ExaCA), with others in progress (Diablo).

ExaAM is coupling multiple physics applications to enable an exascale-capable, multiscale, multiphysics simulation toolkit that can be used to accelerate certification of AM processes.