OAK RIDGE NATIONAL LABORATORY

Lonnie J. Love received his B.S. and M.S. degree in mechanical engineering from Old Dominion University, and a Ph.D. in mechanical engineering from the Georgia Institute of Technology.

He is currently a distinguished research scientist in the Energy and Transportation Science Division and group leader of the Manufacturing Systems Research Group at the Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL). He has made major contributions at ORNL as a researcher, a leader, and an innovator in advanced robotics and additive manufacturing (AM). His research has most recently focused on largescale and highspeed advanced AM and 3D printing.

What are some of the biggest bottlenecks slowing AM from becoming a mainstream manufacturing technology and what is the DOE's Manufacturing Demonstration Facility (MDF) at ORNL doing to address these challenges?

Reliability, cost and being user friendly.

- Reliability and being user friendly because what you design, can be printed. Design rules are different from machine to machine, technology to technology. We need tools to aid the engineer in designing for different AM processes.
- Cost, especially for metals, is prohibitive for a lot of applications. Material costs can be as high a $50 to $200/lb for some materials. But what's worse is the machines are expensive (~$500K to $2M) with often low production rates (1 to 5 ci/hr., or 1000 lb./yr. to 2000 lb./ yr.). In general, net cost of printing is closer to $500/lb. to $2000/lb. for final parts.

ORNL is focusing on large scale, high deposition rate systems that can use commodity grade feedstocks. Our goal is to get to $20/lb. for final parts.

When the MDF research team printed the first ever composites car using Big Area Additive Manufacturing (BAAM), a ground-breaking 3D printing system developed jointly between ORNL and Cincinnati Incorporated, there was a lot of excitement in the industry on the possibilities for the technology. How is that research maturing?

The Local Motors Strati car showed the scalability and impact of composites on AM. However, it also showed some of the challenges. A big one is surface finish. There has been a lot of activity on low cost, rapid coating technologies. Also, the killer application is tooling, being able to print molds in hours rather than weeks at costs of thousands of dollars rather than $10K's to $100K's. We have fabricated tooling for the aerospace, automotive, appliance, marine (boats), and precast concrete industries…tooling impacts every industry.

Do you anticipate large-scale metal systems as a way of moving away from small build volumes and moving to larger equipment and parts? Will it be combined with hybrid machining methods so large parts can be printed and machined at the same time?

Yes, large scale metal systems will evolve to multi-material (low cost inner core with hard outer surface) with integrated machining. ORNL will be doing a demonstration of a production hot stamping die later this year with conformal cooling.

What role do you see simulation playing in developing the large-scale metal systems method?

Simulation is critical. We need to be able to predict whether a part is 'printable' and the expected properties. First, we will use modeling and simulation to guide us on the design of the parts. Next, we will use it to help guide us on the toolpaths that minimize stresses in the part. The simulation tools need to be directly integrated into the design tools.

Do you see simulation being used to control and optimize the manufacturing process itself someday? If so, what are some of the simulation based analytics you see necessary to drive such controls?

Yes. But simulation is only animation until you validate the models. I believe that there will be different levels of simulation.

- As above, we need tools that may be reduced model to help us design the parts.

Image courtesy of Oak Ridge National Laboratory, U.S. Dept. of Energy

Excavator arm process modeling and validation for additive manufacturing.

- All AM systems are limited by thermodynamics and heat transfer. I believe there is a big need for modeling and simulation to design AM systems
- We need higher fidelity AM modeling to help optimize the process and systems (e.g. what infill patterns are best for different geometries…)

In this work, you've spent a lot of effort in careful experimentation of parts and then validated them with simulation. For mainstream usage, do you expect every manufactured part to have to go through the same rigor, or, do you see good benchmarks as a way to help build confidence in the predictive nature and accuracy of your simulation models?

As above, I believe the mainstream engineer needs something simple and intuitive that gives them the confidence that the part can be printed successfully and will have predictable properties. Fifteen years ago, Finite Element Analysis (FEA) and design were two different pieces of software. Dassault Systèmes started bundling them together to make it more efficient and easier to use. Today, we have the same problem with slicing software. A similar approach needs to be taken for the AM process itself. The way you print the part will impact material properties. Therefore, we need to have slicing software directly integrated into the design package. You design, slice, and THEN analyze before manufacturing.

Outside of large scale metal systems, are there other areas you are exploring? Tell us about any upcoming technologies in the AM space that you think have the capability to bring scale, volume and size to make AM economically viable for volume production.

A couple:

Data analytics and artificial intelligence (AI): AM is very data intensive but few are really using that data to improve the process or designs. I believe there is an enormous potential to collect data and use it to validate and improve the process, as well as qualify additive parts. At the MDF, we have key experts working with other government agencies and industry to develop new strategies, software tools, and qualification frameworks increasing the confidence of additive components.

Microfactories: I believe we are already seeing the start of hybrid systems where additive is a component in an integrated work cell. There is tremendous potential in the area of hybrid machines where you are printing systems rather than parts. AM can be one part of a system that includes subtractive, pick and place, multi-material, etc. Traditional factories are geared towards manufacturing one thing a million times. This leads to centralization (e.g. massive automotive assembly plants). I think the microfactory could enable massive decentralization where a factory can produce a million different things one at a time, enabling local manufacturing. At the core, it's really getting us back to pre-industrial revolution societies where every town had a blacksmith, a carpenter, etc., where you locally made what your town needed with local talent and local resources. I think this is what the fourth industrial revolution could enable.

PROCESS MODELING AND VALIDATION FOR METAL BIG AREA ADDITIVE MANUFACTURING

An extended summary of the publication by Srdjan Simunovic, Andrzej Nycz, Mark W. Noakes (Oak Ridge National Laboratory, Oak Ridge, TN, USA) Charlie Chin and Victor Oancea (Dassault Systemès SIMULIA Corporation, Johnston, RI, USA) at 2017 Science in the Age of Experience

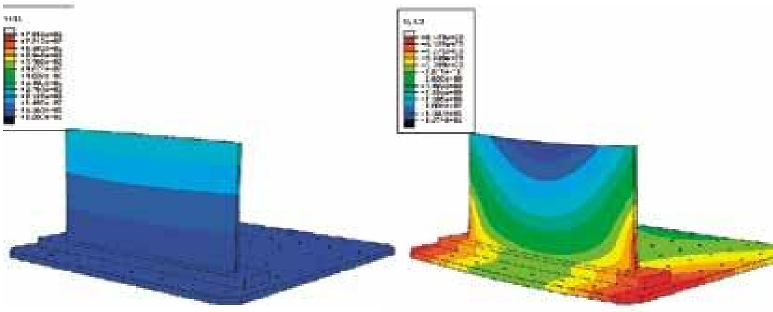
The AM process simulation framework lately developed by Dassault Systèmes is validated for the Laser Direct Energy Deposition (LDED) process. ORNL used the new simulation framework to simulate another large-scale metal additive manufacturing process that uses a wire fed arc process and then ORNL validated the simulation results against experimental measurements as part of research activities that are funded by the Department of Energy's Advanced Manufacturing Office. A continuously fed metal wire is melted by an electric arc that forms between the wire and the substrate, and deposited in the form of a bead of molten metal along the predetermined path. This process is modeled by computational simulation of material deposition with heat transfer first, followed by the structural analysis based on the temperature history for predicting the final deformation and stress state.

A partially clamped curl bar was printed with six thermocouples drilled into each side of the build plate and three additional thermocouples attached to the table on each side of the build plate. The temperature from thermocouples was compared to simulation results. With simple choices of constant convection coefficients, the curves compare well. The temperature histories from heat analysis were mapped into subsequent structural analysis. The overall upward bending distortion at the top of the bar caused by material contraction during cooling was captured well with simulation.

A bigger thin-wall structure was also printed and simulated. In the early stages, there is more conduction into the massive build plate and positioning table which is reflected in lower temperatures. As the print builds up, the intensity of the heat conduction from the heat source into the build plate and table is reduced, so that the overall temperature increases. Using the constant film coefficients for the printed part and the build bar, respectively, the simulated temperatures again matched well the experimental thermocouple data for the first hour of simulated printing. Afterwards, the simulations exhibited slower cooling rates which is associated with increasing effect of the radiative heat transfer as the wall grows higher. Using the temperature dependent combined heat transfer model, developed for a similar AM process, good correlation with the experiment was then found.

Finally, a 2.1m high excavator arm was printed. The real-world printing time for this part is around 4.6 days. Simulation is a clear incentive to replace the physical print of this part (a demonstrative model with ~2.2 million elements takes ~6 hrs. of simulation time). It was shown that simulations can be effectively used to assess the temperature history, final distortions and the residual stresses in the printed part, and investigate efficiency of various printing strategies.

In summary, validated parts range from small (0.01m high) to large (2m high). The small parts were used to develop the best simulation practices and to calibrate the process and boundary condition models. Large parts demonstrated the feasibility of computational modeling for simulating practical large-scale metal systems manufacturing problems. Results show that with minimal calibration efforts a good correlation with the physical experiments was achieved.



Thinwall: Thermal (left) vs. Mechanical

ABOUT OAK RIDGE NATIONAL LABORATORY

Oak Ridge National Laboratory is managed by UT-Battelle for the Department of Energy's Office of Science, the single largest supporter of basic research in the physical sciences in the United States. DOE's Office of Science is working to address some of the most pressing challenges of our time.

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