SIMULIA COMMUNITY NEWS

#17

PRINT TO PERFORM: DIGITALLY ACCELERATING ADDITIVE MANUFACTURING

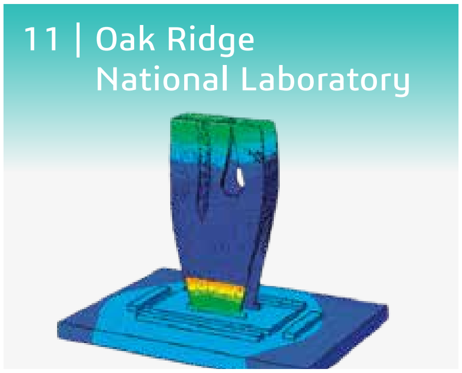
COVER STORY

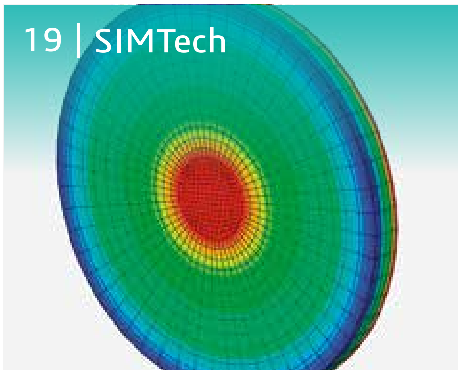
SINGAPORE INSTITUTE OF MANUFACTURING TECHNOLOGY

DASSAULT SYSTEMES | The 3DEXPERIENCE® Company

In this **Issue**

September 2017





Contributors: Parker Group, TWI, Ltd., Oak Ridge National Laboratory, Purdue University, SIMTech, 3Degrees, Aerolytics, LLC., The Pennsylvania State University

On the Cover: Dr. Stefanie Feih, Senior Scientist, Polymer Joining Technology Group, Singapore Institute of Manufacturing Technology (SIMTech)
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LOOKING DEEPER INTO ADDITIVE MANUFACTURING SIMULATION

As many of you know, additive manufacturing (AM) is receiving a great deal of attention these days. Prototyping has finally given way to functional, industrial 3D-printed parts that can fly in aircraft engines, power a car on a race track, generate energy in power plants, replace worn-out joints in human beings, and do many other things not previously thought possible. Everyone is talking about this disruptive technology and its potential to replace—or at least complement—conventional manufacturing, first with low-volume parts but increasingly in higher-production quantities.

Additive manufacturing, empowered by generative design, is revolutionizing how production parts are being conceived and produced. This new technology is nevertheless still ***manufacturing***. As engineers, we know that making things, no matter how, will always remain a process subject to the laws of physics. But additive manufacturing involves more, different, complex physics than just about any other form of manufacturing. So how do you predict material behavior and validate AM designs when optimizing for manufacturing? Through the power of simulation.

Since the earliest days of FEA, customers like you have needed the best tools in order to advance in your industries. Identifying the optimum design alternatives and having an end-to-end solution are critical to your ability to innovate and bring products to the market faster. Designers, simulation analysts and manufacturing specialists require a rich set of AM applications for generative design, build planning, virtual print and shape compensation. We believe the **3D**EXPERIENCE® platform, backed by multiphysics-based simulation, enables such a transformation through a unified and simplified interface.

No matter where you are in your thoughts about additive manufacturing, I think you'll find this edition of ***SIMULIA Community News*** of particular interest. We have gathered a collection of customer stories, expert opinions, and other insights that will expand your knowledge on the subject.

Experts contributing to the conversation include Stefanie Feih of SIMTech, our cover interview (p. 19); Bill Bihlman of Aerolytics (p. 4); and Mike Vasquez of 3Degrees (p. 30). The additive manufacturing team at SIMTech works on a range of AM technologies for both polymer and metallic components, while Bill Bihlman's article focuses on the potential—and the challenges—of additive manufacturing in the aviation industry. Interested in the processing and materials technology for 3D printing? Mike Vasquez provides helpful insights for companies considering the adoption of this technology.

Academic institutions, including Purdue University (p. 27), and Penn State (p.10), are key hotbeds of AM research, as are government laboratories such as ORNL (p. 11). If you were unable to join us at the 2017 Science in the Age of Experience conference, you can still read about the innovative work presented by three Purdue students, and others. There's much more inside, so please read on.

Additive manufacturing will be featured at several of our Regional User Meetings this fall. We hope to hear how you are addressing the AM challenges in your own industries.

Best wishes,

SCOTT BERKEY,
SIMULIA CEO

WHAT'S THE FLIGHT PATH FOR ADDITIVE MANUFACTURING?

An aviation engineer looks at the future of 3D-printing technology

As a mechanical engineer and licensed pilot, Bill Bihlman found the perfect first job at Beech Aircraft after graduate school. "My passion was always aviation," he says. "My work gave me access to time in the air."

Yet he soon realized that although he liked engineering, he wanted to expand his horizons further. "Engineering is the quarterback of the field, but there're other elements that make for smart business strategy and a sound product," he points out. "So I went back to business school, worked for several firms, then went into consulting—where I combine engineering insight and acumen with business principles."

Bihlman formed his own company, Aerolytics, LLC, in 2012, to help aerospace companies with decisions that impact design, material selection and supply chain structure. Advising clients about different production processes, he has gained significant perspective about the potential—and the challenges—of additive manufacturing (AM). He is also currently honing his expertise by working on a Ph.D. in industrial engineering. A panelist and speaker at the AM Symposium at the 2017 Science in the Age of Experience conference, he has big-picture opinions about the future of the technology as well as realistic insights into its plusses and minuses.

"We're over the early hype about additive now and people are cautiously optimistic," he says. "Like any new technology there's a certain paradigm and anybody with a strong tech background is going to be a bit skeptical. Additive still has to mature more—and I believe it is doing so."

The use of additive manufacturing in aviation began a couple decades ago, with laser cladding employed by government and commercial aviation for turbine blade-tip repair. Early adopters then began using it for tooling, where there was less emphasis on precision and integrity. "Of course those issues become much more important when you start talking about production parts and flight-critical components," Bihlman points out.

The breakthrough moment for industrial AM was considered by many to be GE's announcement several years ago about the Leap Engine fuel nozzle—the first additively manufactured component cleared by the FAA to fly in an aircraft. "That was absolutely pivotal because it legitimized additive and showcased the adaptiveness of the technology," Bihlman agrees. "It was a big bet on the part of GE. This is a reminder to suppliers that to remain competitive they needed to be aware of technological advancements, not just price."

> "Given Dassault Systèmes' position in connecting the digital thread from functional generative design to process planning and simulation on the **3D**EXPERIENCE platform, they look to be one of the leaders in this space for years to come."
>
> —Bill Bihlman, President, Aerolytics, LLC

With metal additive manufacturing machines running in the neighborhood of $600,000 to $1 million apiece, not to mention the expense of advanced alloy powders of titanium and aluminum, unit cost is important to evaluate, notes Bihlman. “Whatever your production methodology, you need to amortize that over a certain number of units. Now when you’re talking about cost/benefit of additive, the ability to customize is a big plus. But in aerospace we’re not as interested in customization, with the exception of cabin interiors. We’re looking for repeatability and predictability of mechanical properties.”

So particularly in the case of flight-critical, load-bearing aircraft components, additive won’t be competing with closed-die forging for large, simple aircraft parts any time soon, Bihlman feels. “We won’t get away from the 50,000-ton press in the near future,” he predicts. “However, the design flexibility that is the genius of additive will support complex structures with hollow geometries, made out of exotic alloys such as titanium aluminide. And that makes additive’s powder-bed fusion technology more competitive against investment casting for things like engine turbine blades—something we’re already beginning to see with GE/Avio. Part-count reduction is another area in which additive offers benefits that can go far beyond traditional design thought.”

While wire-fed AM is also being used in aerospace, powder-bed AM will continue to dominate the field of research and development, Bihlman feels. Of course, any additive technology brings with it the attendant challenges of microstructure quality and process repeatability. And in powder-bed, spherosity, size and particle distribution are additional critical variables. So the ability to precisely predict and control material behavior is the goal of every AM technology.

This is where simulation enters the equation. But it’s no easy task. “Metal AM involves extremely complex physics,” says Bihlman. “You start with either a solid (wire) or powder, superheat it, essentially melt it into a liquid, and then let it cool back to a solid. It’s basically a controlled explosion, an incredible process involving extreme temperatures at a rate of heating and cooling on the order of tens of thousands of degrees per second. So it’s very complex to model properly.”

Simulation is coming along, Bihlman notes. “I know Abaqus is one of the more powerful tools and that’s an area that continues to improve. We’ve got the computational power to be able to do very fine, intricate meshes for microstructure prediction as well as part- or build-tray level part distortion and residual stress prediction, so it’s just a matter of time to where we can discretize the whole AM process and map it all the way through, and then include post-processing factors. Given Dassault Systèmes’ position in connecting the digital thread from functional generative design to process planning and simulation on the **3D**EXPERIENCE platform, they look to be one of the leaders in this space for years to come.”

The reduction in experimental time and testing costs that simulation provides is well understood in aerospace, says Bihlman. “As confidence with AM modeling grows in this industry, we’ll be able to reduce our certification costs as well; the FAA has long since recognized instances where testing can be supplanted by analysis.” And as AM matures, this will become increasingly more common because of the prohibitive costs of full-scale and component-level testing.

With manufacturing of all kinds becoming increasingly automated (as underscored by the ubiquitous concept of “Industry 4.0”), maintaining the digital thread that tracks part pedigree all the way from early design through supply chain logistics is particularly critical in the case of additive, Bihlman feels. The complexity of AM demands mastery over a lot of data: there are well over 100 known characteristics that can affect the integrity of a final part—including machine settings, laser intensity, sweep pattern, particle distribution and many more. “Perhaps 20 percent of those characteristics account for 80 percent of the final part’s mechanical properties,” he points out. “But there’s so much hard science that remains in terms of build modification that we’re still learning and trying to tweak it.”

Learning-curve lessons, discovery and intellectual property are being kept close to the vest by many equipment manufacturers at this point in time. “Competition is understandable, due to the right to primacy,” Bihlman says. “But it’s unfortunate that we don’t really have an open forum through which the information is fed back properly so everyone can learn from it.” He describes the experience of a small, tier 3 parts manufacturer that spent months figuring out the optimum configuration of settings for their new AM machine. “When they fed that information back to the AM machine provider, telling them exactly what control settings and processes were required to produce the desired result, the provider said, ‘Well, that’s what GE told us!’”

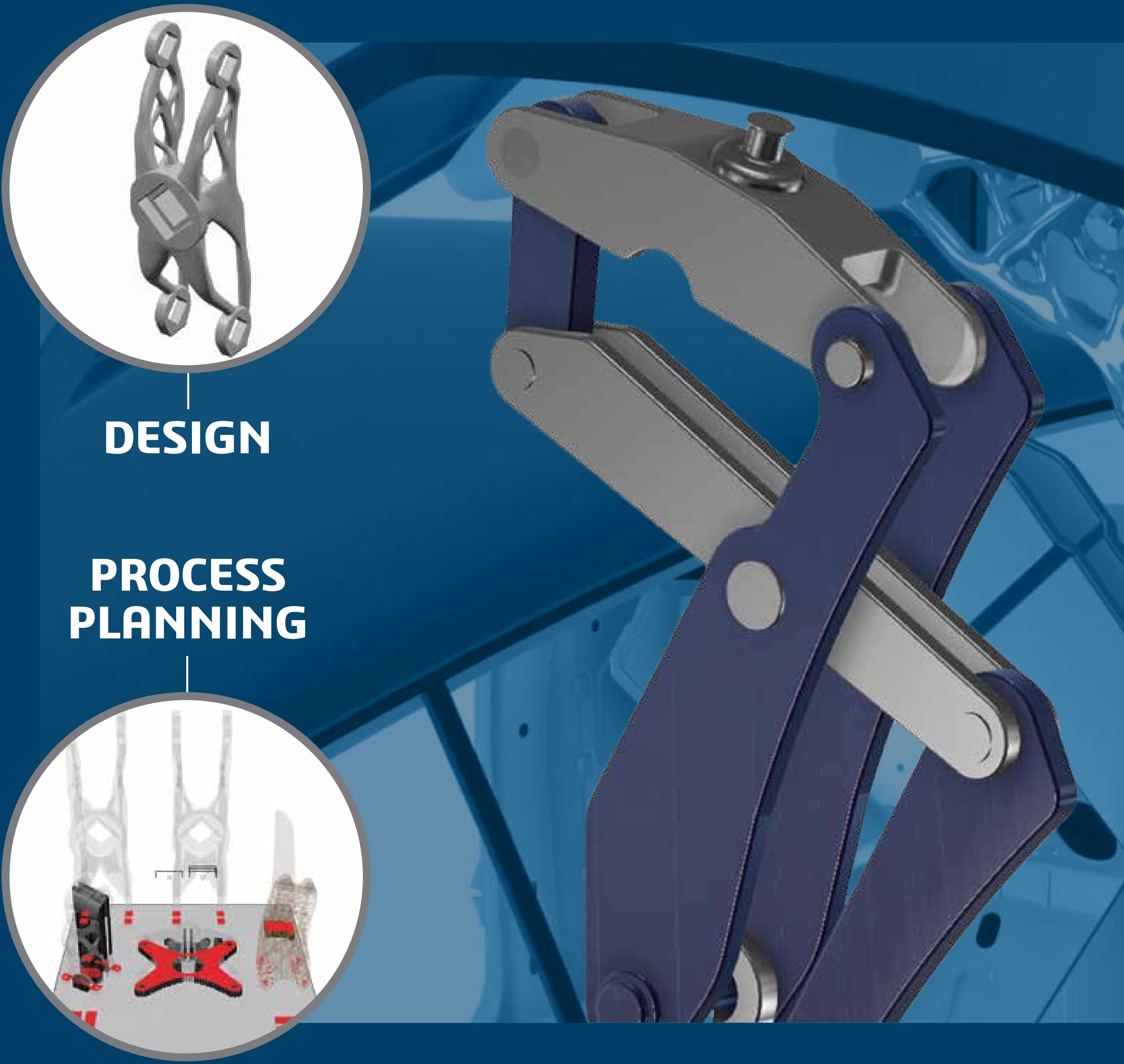
Progress is being made. U.S. government labs and universities are working to provide publicly available data about AM, and the SME and the ASME have set up standardization committees. “We all need to agree on what to define in terms of critical path and share that information so that people can commercialize additive based on proper nomenclature and fundamental characteristics,” says Bihlman. “That is absolutely essential, not just to generate standards but to take a lead in public research as well.”

For More Information

www.aerolyticsllc.com

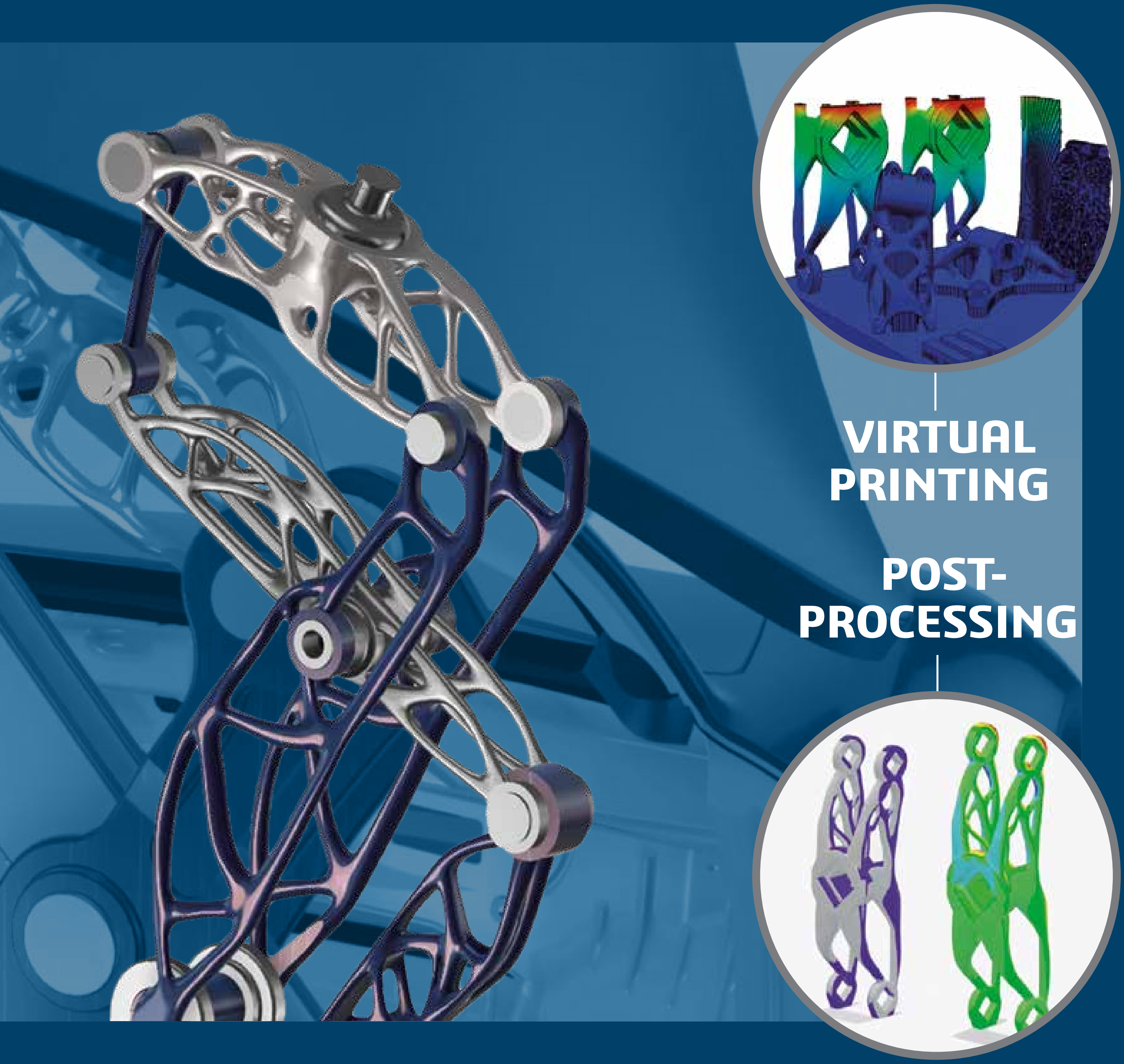
DIGITALLY ACCELERATING ADDITIVE MANUFACTURING

MAKING PARTS THAT WORK



ADDITIVE MANUFACTURING FOR GENERATIVE DESIGN

Dassault Systèmes offers a full portfolio of integrated applications for additive manufacturing that works seamlessly across design, manufacturing, and in-service performance.



AM AND GENERATIVE DESIGN REVOLUTIONIZE HOW PRODUCTION PARTS ARE CONCEIVED AND PRODUCED

3DEXPERIENCE

- Additive manufacturing empowered by generative design is revolutionizing how production parts are being conceived and produced
- A digital thread that connects, integrates and intuitively captures design, materials and manufacturing, is key for functional parts
- **3D**EXPERIENCE, backed by multiphysics-based simulation, enables such a transformation through a unified and simplified interface
- Provides designers, simulation analysts and manufacturing specialists a rich set of additive manufacturing applications for generative design, build planning, virtual print and shape compensation

GENERATIVE DESIGN WITH THE FUNCTIONAL GENERATIVE DESIGNER ROLE

- Design with topology optimization in a single environment
- Create parts in context of the manufacturing process using guided workflows
- Automatically generate variants of conceptual and detailed organic shapes
- Make informed business decisions based on physics-based analytic tools

PROCESS PLANNING WITH THE ADDITIVE MANUFACTURING PROGRAMMER ROLE

- Define and customize the manufacturing environment
- Automatically nest parts on the build tray
- Design and generate optimal support structures
- Create machine specific slicing and scan path, ready for print

VIRTUAL PRINTING WITH THE ADDITIVE MANUFACTURING RESEARCHER ROLE

- Automatically includes machine inputs for energy, material and supports into the simulation
- Access built-in simulation best practices with minimal user-level intervention
- Simulate at layer, part and build levels for any additive manufacturing process
- Accurately predict part distortions, residual stresses and as-built material behavior
- Evaluate and correct for build failure because of interferences such as recoater collision

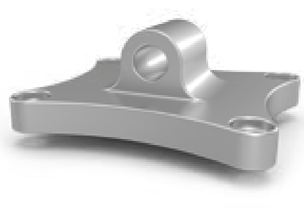
POST PROCESSING WITH THE REVERSE SHAPE OPTIMIZER ROLE

- Use simulation to guide support-structure strategy for enhanced build yield
- Guide post-processing efforts such as removal from build plate and heat treatment
- Compensate distortion effects without the need to redesign the product tooling
- Produce high-quality morphed surface geometry with unchanged topology
- Perform final in-service performance validations of manufactured part

SUMMARY VALUE

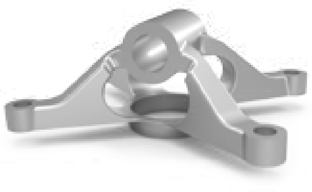
- Native integration of design, manufacturing and simulation applications
- On-premise and on-cloud with high-performance computing and visualization
- Define reusable rules for each step of the additive workflow.
- Make informed business decisions based on physics-based analytic tools

For More Information
www.3ds.com/simulia

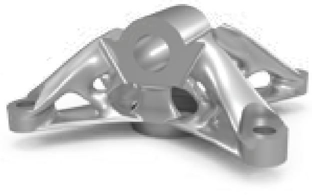


LEGACY
0.7 kg

3-AXIS MILLING
0.45 kg



CASTING
0.36 kg



ADDITIVE MANUFACTURING
0.295 kg

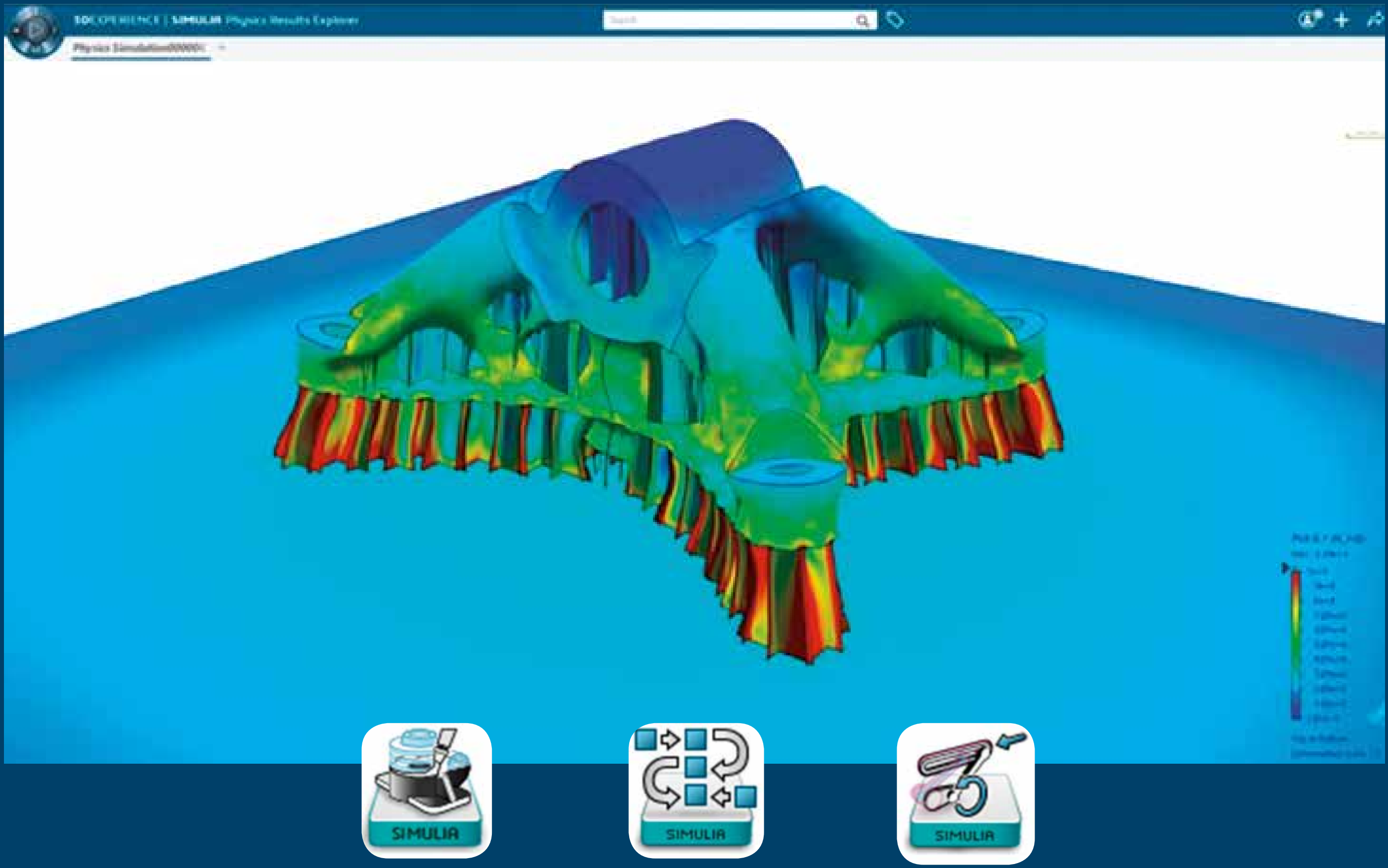
ADDITIVE MANUFACTURING RESEARCHER ROLE OVERVIEW

HIGHLIGHTS

- Physically realistic simulation of 3D printing of parts including laser scan paths, material deposition and solidification, thermal distortion and residual stress, and support structures
- Allows powder bed, polymer extrusion, and direct energy deposition (plus user defined) manufacturing process simulation
- Offers a high level of automation and guidance to allow the user to easily setup complex simulations
- Provides an easy-to-use experience on top of the sophisticated technology of the Abaqus solver while allowing customization for more advanced users
- A guided user assistance panel provides a step-by-step workflow to set up a simulation
- Uses part build information, automatically set build times and populate supports for some features

USER VALUE

- Seamless integration to design and manufacturing
- In-built simulation best practices to allow usage by additive experts
- Automatically applies settings to conform to additive manufacturing simulation best practices
- Process-level, part-level and build-level simulations in a single environment for metals or polymers.
- Reduce residual stress and distortion in completed parts
- Increase dimensional accuracy
- Optimize part orientation
- Minimize print time and material usage
- Post-processing methods for build plate removal and heat treatment
- In-service performance validations of functional part



Virtual Printing using **3D**EXPERIENCE Platform

DISRUPTING MANUFACTURING AS WE KNOW IT

Timothy W. Simpson, Ph.D., Paul Morrow Professor of Engineering Design and Manufacturing Director, Additive Manufacturing & Design Graduate Program, Co-Director, Penn State CIMP-3D, The Pennsylvania State University

Why are holes round? A question with an answer that many just take as an eternal fact: holes have always been round. The practical reason holes are round is because we have always used a subtractive process in manufacturing to remove what we want to create the part or product we need. The problem with subtractive processes is that they create limitations during manufacturing, which limits what we can design.

Additive manufacturing (AM) is changing this notion. Layer by layer we are able to create objects we couldn't before. This is frequently done by a laser melting powders to create solid parts. We are also able to change materials with some AM processes allowing for the most optimal and efficient design of an object that is corrosion-, fatigue-, and wear-resistant, for instance.

AM is synonymous with 3D printing which has actually been around for about 30 years. Traditionally, 3D printing was mostly done with plastics and polymers; however, with technological advances over the past five to ten years we are bringing metals into the mix. We can think of AM as adding material rather than subtracting material to optimize a design. The current process allows us to print layers thinner than the human hair!

Adding material using AM allows us to be more efficient with material choice and with our designs. This is desirable because we can create parts that are lighter in weight, stronger in design, and better in fuel efficiency. A lattice design that is impossible to make in a subtractive process is easy with AM, which changes the way parts are designed and materials are selected. In fact, we can now mimic cellular design with the lattice structure and print titanium hip implants closely resembling bone structure allowing blood vessels and tissue to integrate more quickly around the implant which speeds recovery for patients.

Printers range in size allowing for printing parts such as wing spars for airplanes. These large printers print via a wire as opposed to metal powder. An electron beam bombards the wire with electrons thereby heating the wire to melt it into the desired shape. This type of AM process is akin to robotic welding…on steroids!

Well now we've discussed the benefits of the AM process, which is disrupting manufacturing as we know it. Disruption is both positive and negative. There are, of course, challenges that arise when a new technology emerges in the market. Now, if companies want to buy a 3D printed part, do they have that part shipped to them or can they just have a CAD file of the part emailed to them and then print it on site? What about customs? Border control? Import taxes? Furthermore, a CAD file can't be patented so how is the IP protected? Data shows that this form of open manufacturing means that manufacturing is the highest susceptible industry to be cyber attacked, even greater than energy, water, and IT systems that are used to dealing with cyber threats. What about worker safety? Small particles used in the printing can be inhaled or even explode depending on its composition, which disrupts our current fire and safety codes. How about the companies that lead the way? Their stock prices tend to soar with the excitement of the new technology and then drop drastically when the realities of the problems are discovered. Eventually, their stock prices will even out and hopefully climb as the technology matures, but it all depends on the way the disruption is handled by the companies who are willing to take risks and redefine their industry and the markets they serve.

The great thing about this new technology is that it gives rise to more startup companies and opportunities. We are truly only limited by our imagination. Only time will tell how long holes will remain circular.

For More Information
https://sites.psu.edu/edog

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

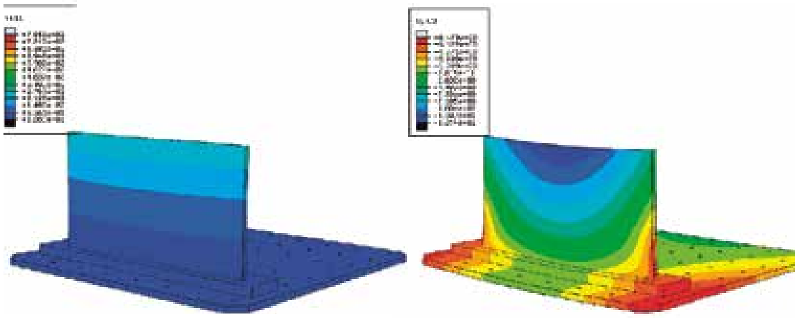
The AM process simulation framework lately developed by Dassault Systèmes is validated for the Laser Direct Energy Deposition (LDED) process. ORNL used the new simulation framework to simulate another large-scale metal additive manufacturing process that uses a wire fed arc process and then ORNL validated 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.

This research is supported by DOE's Office of Energy Efficiency and Renewable Energy-Advanced Manufacturing Office under the Manufacturing Demonstration Facility at ORNL. AMO supports early stage applied research and development of new materials, information, and processes that improve American manufacturing's energy efficiency, as well as platform technologies for manufacturing clean energy products.

For More Information
http://science.energy.gov

SIMULATION DRIVEN DESIGN AND 3D-PRINTING WITH SIMULIA AND STRATASYS

Stratasys has been at the forefront of 3D printing innovation for more than 25 years, shaping lives by revolutionizing the way things are made. Many successes have been achieved with the added value of using additive manufacturing (AM) realized through supply chain benefits associated with eliminating the need for tooling and lengthy manufacturing processes. While these success stories show promise for the technology, a behind the scenes look at the workflow used to create them reveals a treacherous and cumbersome journey, from concept to design to print of final part.

Figure 1: Stratasys Fortus 3D Production Systems.

For example, the topology-optimized structures may not adhere to 3D printing design rules and cause part cost to skyrocket. Costly iterations involving physical part printing are needed to get to a high quality part. Weight savings can be significantly reduced due to lack of accurate characterization of the behavior and performance of FDM materials. The partnership between Stratasys and Dassault Systèmes rapidly addresses such gaps in the concept-to-production workflow and empowers engineers to realize complex designs for a cost-effective, functional, and high-performance part. At Dassault Systèmes, we provide solutions for studying and designing polymer material microstructural architecture, optimizing realistic design concepts that consider FDM constraints and support structure requirements, and planning polymer extrusion processes to achieve predictable and reliable builds using process simulation.

IN-SILICO MATERIAL ENGINEERING

Predicting part distortions and residual stresses are critical missions of AM simulations. In order to do this accurately, we need a complete understanding of the material as it goes through the dramatic temperature cycles of production. Understanding the physics at the lower scales is an important driver for the part-level Finite Element (FE) simulations.

At Dassault Systèmes, we can leverage polymer material design from the molecular scale all the way to in-service performance simulations at the part level. Constituent properties and microstructure morphology can be estimated with molecular dynamics and mesoscale simulations, which can then be used to construct mesoscale FE models that allow us to connect to the continuum scale. Material behavior can be homogenized using mesoscale RVE models, then leveraged to higher scale thermal and mechanical simulations. Part level simulations are performed to predict the distortions and residual stresses and use them as initial conditions for in-service performance prediction.

Many factors in the FDM process affect the material properties of the final printed part including patterning direction, bead aspect ratio, air gap size and slice height. In order to perform accurate finite element process simulations, the mechanical and thermal properties of these FDM materials must be tested and characterized either physically, with coupons, or virtually with RVE models. The Abaqus micromechanics plugin, available as a download in the Dassault Systèmes Knowledge Base QA00000046185, can be applied to understand voids and bonding behavior, simulate and characterize FDM printed parts (see figure 2).

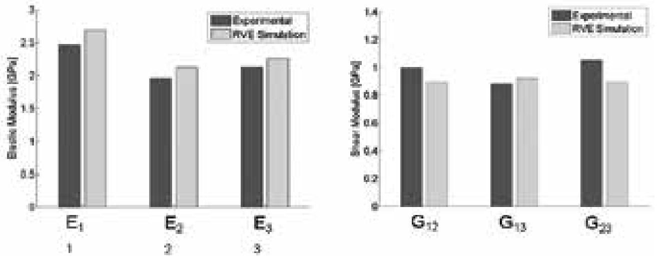


Figure 2: Comparing virtual testing using Abaqus micromechanics plugin with physical testing [1].

FUNCTIONALLY DRIVEN GENERATIVE DESIGN

With design no longer constrained by the subtractive manufacturing restrictions, a part designer must use new methodologies to determine the most efficient part design. The Functional Generative Design available on the **3D**EXPERIENCE platform delivers topology optimization while considering the print direction and overhanging members, thereby reducing the number of supports required during manufacturing. Regions of high-stress concentrations can be identified by performing a basic stress analysis on the resulting geometry. To reduce stresses in these locations, an optimum shape can be selected by performing shape optimization with consideration of optimum member size for post processing. The **3D**EXPERIENCE platform provides powerful tools that help the user re-parameterize and reconstruct the geometry to efficiently obtain a lightweight and a functional design (see Figure 3a).

Non-parametric lattice/infill sizing optimization can also be performed in the design space to achieve even lighter designs. We developed tools for beam and shell sizing optimization, material-behavior interpolation, and multiscale topology optimization eliminating, the need for geometry reconstruction (see Figure 3b).

PROCESS DEFINITION & PRODUCTION PLANNING

At the SIMULIA brand of Dassault Systèmes, we've developed a single solution with an open and customizable process-simulation framework for all existing and new process types.

Goals of process simulation:

- Take independent events (e.g., material addition according to tool path) as inputs, capture the correct physics
- Predict residual stresses and distortions and calculate tolerances with sequentially coupled thermal-mechanical analyses
- Calibrate material and build to close the gap between your design and your build
- Process mapping and optimization for cost and build quality control

Considerations for FDM process:

- Detailed path data defining the deposition of the molten material; tool-path data conversion from Stratasys software to SIMULIA simulation input; schematic generation of simulation input in the **3D**EXPERIENCE platform
- Support simulation of actual part together with support structures and heated base; complex shapes with different element types or generalized voxel based mesh (eliminating the need for support geometry generation)
- Mechanisms of heat transfer on the evolving outer surface of the part that defines cooling during the thermal process; progressive elements activation and heat transfer surfaces evolution according to the tool path as material is deposited
- Material characterization considering process parameters such as bead height and width; material orthotropy and local orientation assignment according to detailed tool path with tool path Event Series API and user orientation subroutine.
- Capture different void effects. Equivalent material properties for voids between deposition beads; progressive elements activation for voids between tool path styles and voids designed for lightening
- Time increment size and mesh size necessary to capture thermal gradients, cooling rates, and stress gradients; fidelity and performance control with simple change of time increment size; layer-by-layer analysis for distortion and residual stress prediction; single-layer analysis to analyze bonding and delamination

(see Figures 4 and 5)

Our initial validation results show good agreement without additional calibration. Stratasys and Dassault Systèmes have an ongoing collaboration for FDM printed parts, temperature history and part distortion/tolerance prediction validation. Stay tuned for future validation results !


Figure 3a: Topology optimized circuit box for space rocket.

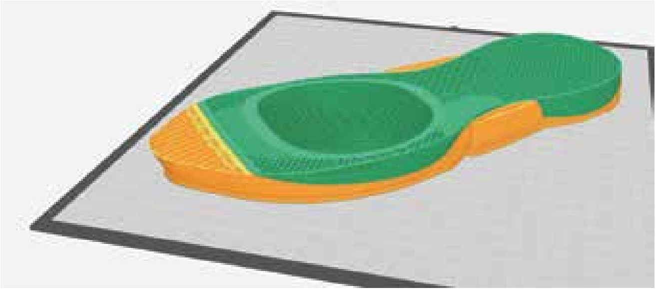


Figure 3b: Direct tool path generation in Stratasys software from infill optimization result.

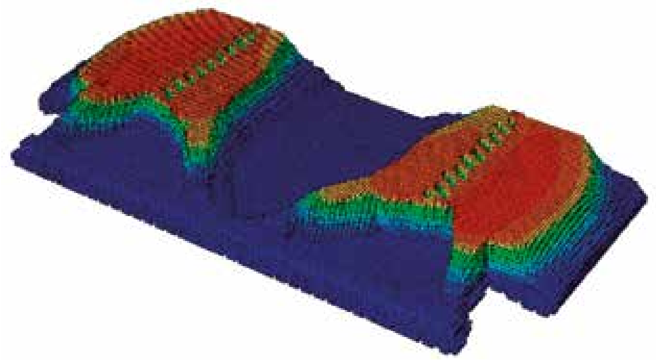


Figure 4: Process simulation of a circuit box for space rocket.

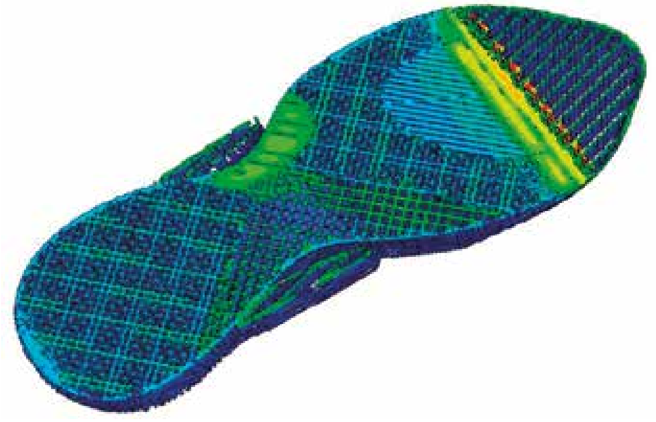


Figure 5: Process simulation of an infill shoe sole.

For More Information

www.stratasys.com

[1] Mechanical Testing of FDM Parts for Process Simulation, Siddharth Dev, Christopher J. Hansen, Blake Courter, Jing Bi, Vishal Savane, Proceedings of NAFEMS World Congress, Stockholm, June 2017.

[2] Finite Element Simulation of the Fused Deposition Modeling Process, Blake Courter, Vishal Savane, Jing Bi, Siddharth Dev, Christopher J. Hansen, Proceedings of NAFEMS World Congress, Stockholm, June 2017.

TWI SIMULATES WELDING AND ADDITIVE MANUFACTURING

Welding is one of the oldest metal arts known to man. Additive manufacturing (3D printing) is one of the newest. Yet the two technologies have more in common than you might think. And few people understand this better than the experts at TWI, Ltd. (formerly The Welding Institute), established in Cambridge, U.K. in 1946.

TWI is one of the world's foremost independent research and technology organizations, with expertise in materials joining and engineering processes as applied in industry. Its teams of consultants, scientists, engineers and support staff work with over 1,800 industrial members in 80 countries. Five U.K. and 13 overseas facilities serve both TWI members and some 25,000 students trained each year in welding and inspection technologies.

"Additive manufacturing [AM] can be thought of as a series of micro-welds," says Tyler London, Regional Team Manager for TWI's Numerical Modeling and Optimization group. A Chartered engineer, scientist, mathematician and professional simulation engineer, London has an MSc in mathematical modeling from Oxford and a background in offshore, aerospace and oil & gas fracture-integrity assessments. Simulation was a core tool during his student years and has proved particularly useful since he joined TWI in 2010 and began partnering with the additive manufacturing team.

"AM and welding are not very different in how one approaches their simulation," he says. "Of course, the number of 'micro-welds' in an AM simulation can be enormous, so simulation run times and memory become significant. But you are definitely investigating many similar phenomena in both technologies, such as phase transformations of metals, cooling rates, tool paths, residual stresses and distortion."

TWI began working on computational weld modeling, with SIMULIA's Abaqus software as their primary FEA tool, in the 1990s. They have deep expertise in material (constitutive) models, the modeling of different heat sources, and calibration and validation exercises—all of which have in turn informed their recent involvement in additive manufacturing. "Having both modeling expertise and the ability to manufacture, measure and test samples in-house has allowed us to use a multi-disciplinary approach to integrate AM process simulations into our portfolio of R&D and consultancy services," says London.

Putting their AM expertise to work, TWI consults with numerous oil & gas, aerospace and medical organizations to help prove out the viability of designs for various additive manufacturing processes such as powder-bed fusion (selective laser and electron beam melting), laser metal deposition, and wire-arc additive manufacturing. Applications have included everything from medical and dental implants (hip, cochlear and dental bars) to automotive turbochargers and aircraft components.

HOW SIMULATION SUPPORTS ADDITIVE MANUFACTURING

London says that 3D printing simple parts can be fairly straightforward if someone is very familiar with a particular AM machine's capabilities and can make a good guess about what build orientation, process parameters, and layer thickness are required to get a good, low-distortion build with a nice surface finish. "But when you get a very complicated part, or one that needs a lot of support during the build, the best-practice knowledge you need is still pretty non-existent in industry," he says. "You're left doing a lot of trials, trying to build at different orientations with different support structure strategies and laser powers—and ultimately that turns out to be expensive and time consuming." While AM pre-processing software has improved greatly over the past few years, the choice of optimal processing parameters is seen as a barrier requiring more research to better understand the fundamental physics of AM processes.

The new solution features enable the exact machine formation about the powder recoating sequence, laser scan path, and process parameters to be directly input in the FE model.

So what TWI is working toward along with their members, and the wider AM community, is a simulation capability that delivers an optimal design envelope for whatever they are trying to manufacture. "We help people take advantage of the various benefits and design freedom that AM offers," says London. "You want to balance light weight and function with ease of manufacture. Once you arrive at your new design, we perform process simulations to determine optimal layer thicknesses or the build orientation that will minimize distortion and residual stresses. This in turn enables you to reduce the build time and, importantly, the amount of post-processing required.

"Trying to balance all these things using Abaqus for both the mechanical analyses as well as the thermal process simulations is a huge area of interest for us right now," he says. "We're seeing a lot of demand for that kind of activity from both industry and funding bodies."

PUTTING AM SIMULATION CAPABILITIES TO THE TEST: SELECTIVE LASER MELTING

Selective Laser Melting (SLM) is a powder-bed fusion AM process by which a layer of powder is deposited onto a substrate, spread uniformly by a wiper, and then a high power-density laser fully melts the powder layer according to a specific computer-generated 2D slice of the 3D part being built. The melted particles fuse and solidify to form a layer of the component. The substrate then retracts vertically and the next layer of powder is deposited, with the fusion process repeated until the 3D part is completely built. A wide range of material can be used including metal alloys like Titanium alloys (Ti-6Al-4V), stainless steel, nickel-based alloys (Inconel) and Aluminium alloys (6061). The design freedoms of the SLM process enable complex, light-weight parts with optimal material distributions to be produced (Figure 3) that could not otherwise be made using conventional manufacturing methods.

However, the extreme temperature cycles and rapid cooling rates that parts see during SLM processing tend to lead to unfavorable metallurgical structures, high residual stresses and undesirable levels of distortions (shape imperfections). In the worst-case scenario, the process-induced residual stresses can cause cracking during the build process, or the distortions may be so large as to cause damage to the wiper during recoating. Hence, enhancing the as-manufactured quality of SLM parts is a major milestone to enabling the wide-scale adoption of SLM as a manufacturing process. To address this challenge, TWI is undertaking validation activities, in collaboration with the SIMULIA brand of Dassault Systèmes, to improve the fundamental understanding of the SLM process.

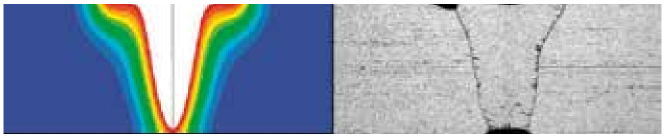


Figure 1. Conventional welding simulation comparing fusion zone size and shape.

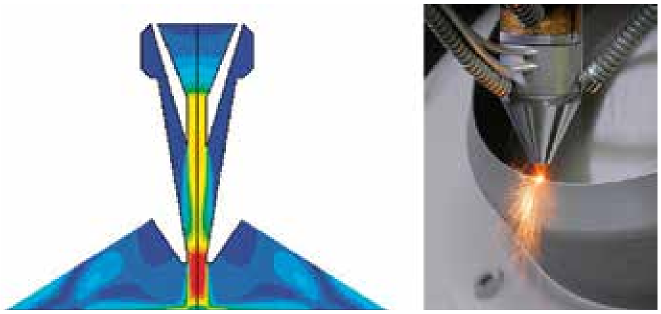


Figure 2. Thermal simulation[1] used as input to Abaqus for multi-physics AM predictions of Laser Metal Deposition.

Figure 3. SLM part designed using Tosca topology optimization and produced using the SLM process[2].

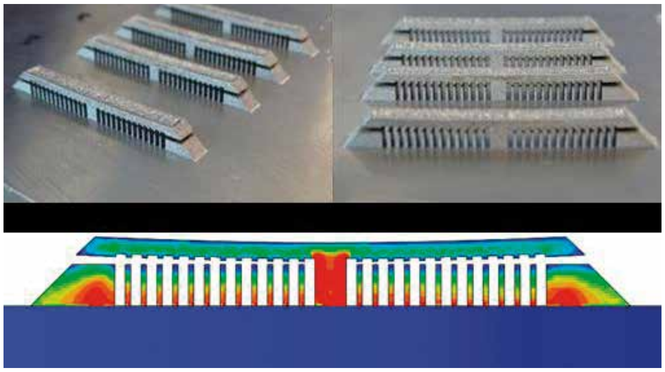


Figure 4. SLM double cantilever samples (top) and simulation (bottom)[3].

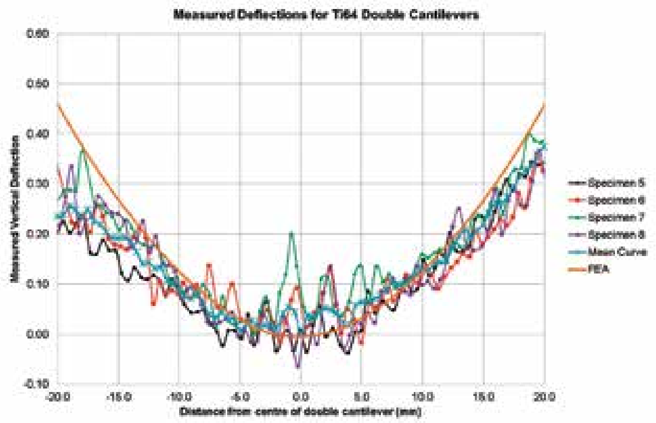


Figure 5. Comparison between experimental measurements and FEA predictions for cantilevers.

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[1] He W, Zhang L and Hilton P (2009): 'Modeling and validation of a direct metal deposition nozzle', Presented at ICALEO 2009.

[2] Undertaken as part of the European Commission project "MANSYS" funded under FP7-NMP Project ID 609172.

[3] Tripathy S, Chin C, London T, Anakalkhope U and Oancea V (2017): 'Process modeling and validation of powder bed metal additive manufacturing', NAFEMS World Congress 2017, 11-14 June 2017, Stockholm, Sweden.

Case Study

Could finite element analysis meet the challenge posed by AM? Using new physics-based FEM formulations available in Abaqus 2017, London and his colleagues created heat transfer models of the process using Abaqus/Standard on a "double cantilever" test piece. The new solution features enable the exact machine information about the powder recoating sequence, laser scan path, and process parameters to be directly input into the FE model. These state-of-the-art capabilities enable progressive element activation, progressive heating computations and cooling of the evolving solid surface of the part as the build progresses.

"Using CAE, we created the CAD geometry and exported an STL file that we sent to the laser AM team. They then specified how they were going to build the part—layer thickness, laser power, scan strategy and so on," says London. "This process information was used to construct the heat transfer model, which was then used to drive a mechanical model from which distortions and residual stresses were calculated." The double cantilevers themselves were then printed using Ti-6Al-4V powder with a Renishaw AM250 machine.

After manufacturing the double cantilevers, TWI used wire electrical discharge machining to cut the support structures just below the solid beam surfaces. Upon cutting, the locked-in residual stresses generated deflections of the remaining beam structure. The out-of-plane deflections were measured and compared with the model predictions. Strong agreement between the predictions and measurements was observed leading to confidence in the use of this new modeling approach.

OUT OF THE POWDER BED: ELECTRON BEAM WIRE-FED ADDITIVE MANUFACTURING

"While powder-based additive manufacturing techniques allow complex geometries to be fabricated, they are inherently slow processes," says Nick Bagshaw, a consultant and simulation engineer in the Electron Beam group at TWI. "Wire-fed additive processes enable a large volume of material to be deposited rapidly, but typically a final machining or distortion correction operation is required to reach the final dimensional tolerances." However, this offers a significant reduction in material wastage compared to machining the final component from solid. High deposition rate processes have been associated with distortion and for industrial applications, it is important that distortion is minimized.

To better understand the quality of Wire-Electron Beam Additive Manufacturing (W-EBAM) components and to help define the potential commercial application areas for W-EBAM, TWI simulated, built and measured Ti-6Al-4V parts built using the W-EBAM process. Trials were conducted on a Hawker Siddeley Dynamics 6kW beam power EB welding machine. The machine is fitted with an in-chamber CNC controlled wire-feeder that is equipped to feed 1.6mm diameter wire. Bespoke tooling was developed and a clamping procedure defined to hold the plates during processing as shown in Figure 6.

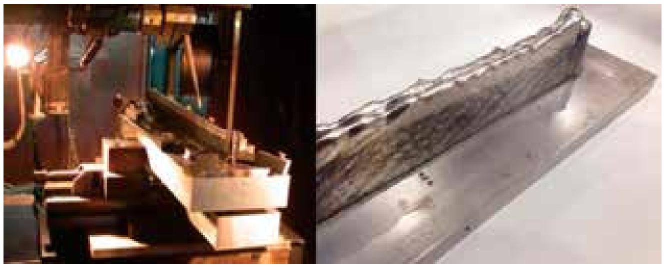


Figure 6. Wire EBAM test set-up (left) and example of W-EBAM test piece.

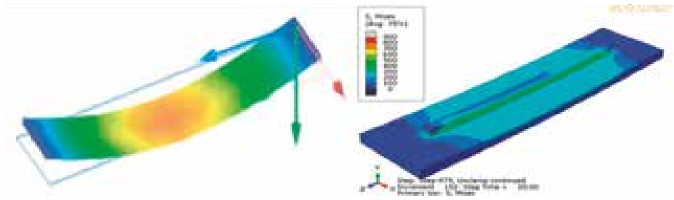


Figure 7. Comparison of coordinate measuring machine (CMM) measurement (left) with FEA predictions from Abaqus (right).

A conventional welding simulation approach was used to model the W-EBAM process, leveraging the "model change" and element activation capabilities of Abaqus. Each 1.5mm layer comprised of two parallel passes; simulations were used to predict the thermal history and resulting distortion of structures ranging from 12mm-to-50mm high depositions. The model was successfully validated across all ranges of build height investigated and the simulations were able to accurately capture the stiffening effect caused by the structure as its height increases.

NEXT STEPS

"Regardless of the AM process, we are looking into having robust and reliable means to predict temperature evolutions, distortion and residual stresses," says London. "Ultimately, we are looking to calibrate and validate metallurgical phase transformation models in the advanced process simulation capabilities in Abaqus so we can predict phase fractions, grain sizes and shapes, and the microstructural evolutions that occur during printing. The aim is to be able to predict the mechanical performance of AM parts."

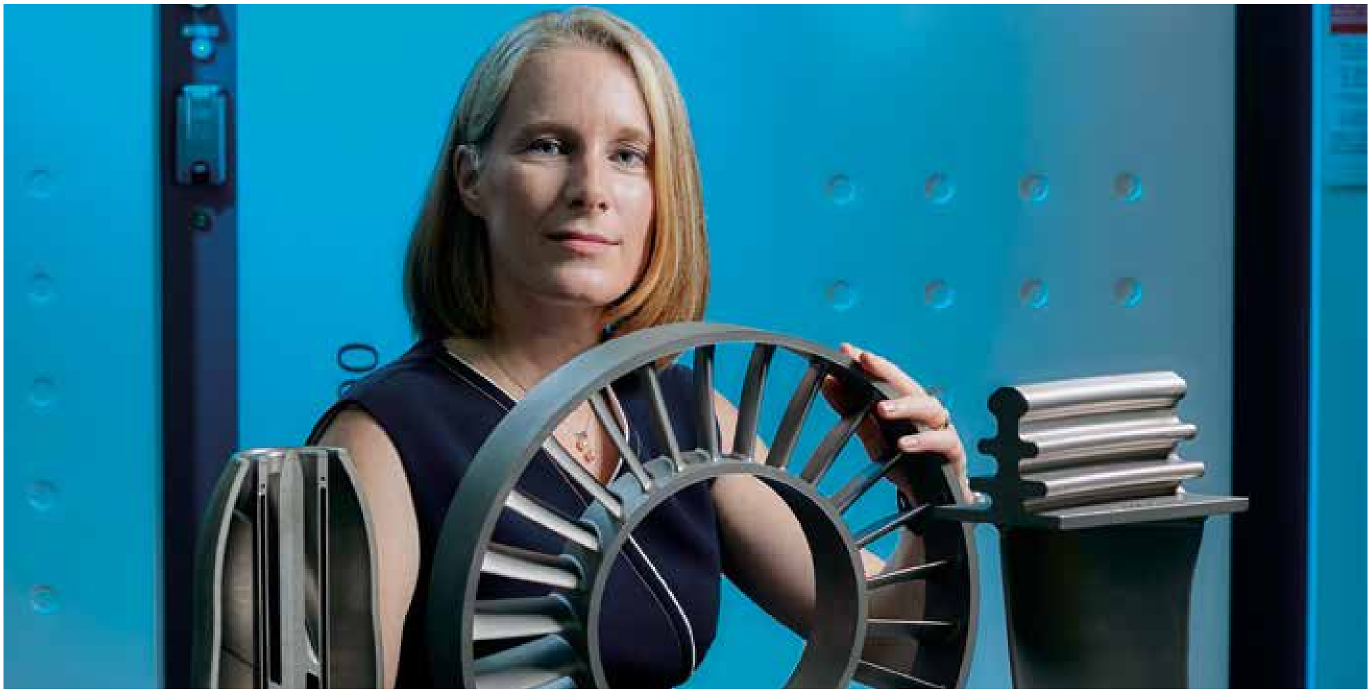
Validation work presented at this year's Science in the Age of Experience conference shows that progress is being made. The collaboration between TWI and Dassault Systèmes is helping us achieve the goal of having a comprehensive capability validated over the next few months.

ACKNOWLEDGEMENT

This work has been undertaken as part of TWI's Core Research Programme for the benefit of TWI Industrial Members.

For More Information

www.twi-global.com



CUSTOMER INTERVIEW: STEFANIE FEIH, PH.D., THE SINGAPORE INSTITUTE OF MANUFACTURING TECHNOLOGY

Dr. Stefanie Feih can be described as a citizen of the world, based on all the places she has studied, worked and lived. She grew up in Germany with a love of STEM topics, got her M.E. in her native country but also participated in an international exchange program with Cornell University in the U.S. She pursued her Ph.D. in Engineering at the University of Cambridge, U.K., in collaboration with TWI (The Welding Institute), and began a research career that took her from Denmark to Australia with a strong focus on design of lightweight materials (both composite and metal) for wind, aerospace and maritime applications. Dr. Feih joined the Singapore Institute of Manufacturing Technology (SIMTech) in 2014 to work in a more industry-focused research environment. Singapore has strong ties to the Aerospace OEM and MRO industry, a sector that drives exploration and implementation of weight-saving material strategies. Additive manufacturing is a key topic of study for Dr. Feih and her colleagues.

What kinds of projects is your team at SIMTech involved with?

Feih: SIMTech develops high-value manufacturing technology and human capital to enhance the competitiveness of Singapore's manufacturing industry. We collaborate with multinational and local companies in the precision engineering, electronics, semiconductor, medical technology, aerospace, automotive, marine, logistics and other sectors. SIMTech is a research institute of A*STAR. (www.SIMTech.a-star.edu.sg)

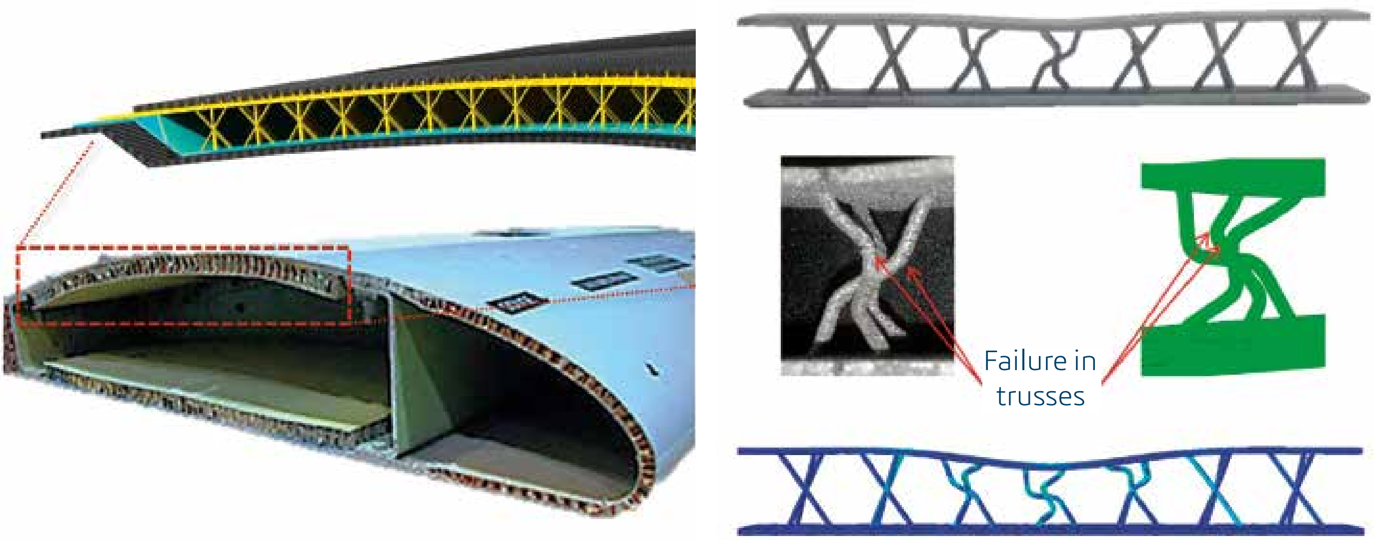
The additive manufacturing (AM) team at SIMTech works on a wide range of AM technologies for both polymer and metallic components. The team focuses on (i) fundamental understanding of 3D AM technologies, (ii) exotic and non-proprietary material development for use in 3D AM systems and (iii) new applications for 3D AM technologies to complement or replace conventional manufacturing processes. SIMTech also supports local SMEs and multinational industry clients with AM technology adaption solutions and provides industry training courses for AM technology.

How long have you been an Abaqus user?

I have used Abaqus software for the past 20 years for materials research and have also taught FE theory in both university and industry courses. In Singapore, SIMTech staff have participated and presented at the local SIMULIA user conferences over the last eight years to highlight our research outcomes and industry solutions. Abaqus has the ability to conduct highly nonlinear analysis, both in explicit and implicit formulations, and offers a wide range of material and failure models along with the option to program customized user subroutines to interact with the main code. This makes the software a very versatile research tool used widely by both research and industry organizations.

How does your study of lightweight composite materials inform your current work on additive manufacturing technology?

We are currently working on lightweight materials that combine a metal AM lattice core with a fiber-reinforced composite skin. The numerical work on the AM structural investigation is done with Abaqus, and we have published



Figures 1 & 2 (above). Ductile Failure Modeling Under Static and Dynamic Loading Of 3D Additively-Manufactured Metallic Kagome Core Structures. Credit: This work was undertaken by Dr Stefanie Feih's former Ph.D. student Dr. Inam Ullah under co-supervision of Professor Milan Brandt at the Additive Manufacturing Centre at RMIT University, Australia.

extensively and also presented at the Abaqus user conference in Singapore on this topic (see Figure 1).

Metal AM has the potential to create lightweight structures that exceed the performance of traditionally manufactured composites, but this approach is currently limited by printing size and printing accuracy—hence our paper addressing these parameters, delivered to Science in the Age of Experience this past May (see Figure 2).

SIMULIA's new AM process simulation framework allows for separate modeling of solid material, powder bed and platform as well as the evolving heat-transfer surfaces of a part as it is built. Why is it important to take all of these components of a build into account when creating a simulation? How can simulation help AM users with quality assurance and cost control?

It is necessary to develop a systematic understanding of factors potentially influencing the print results. Due to time constraints during the simulation, most researchers currently neglect the influence of the surrounding powder bed and platform. It is also unclear whether neighboring parts influence the cooling rates within the metallic structure and what distance should be kept between individual parts. Finally, it is also difficult to establish realistic thermal properties for the powder bed for a large range of temperatures. In our simulation research we showed that the surrounding powder bed material influences the thermal cooling rates of the build part, and the platform, which is normally pre-heated prior to build, contributes as a finite heat sink to the temperature distribution within the build part. Both are therefore important to consider, and the platform should always be modeled. The powder influence may be accounted for by adjusting the film coefficient governing surface convection of the print part to simplify the model complexity.

For how long, and in what ways, have SIMTech and Dassault Systèmes SIMULIA been cooperating in developing simulation capabilities for additive?

Dassault Systèmes and SIMTech started collaborating on additive manufacturing simulation three years ago following a seminar from Dassault Systèmes at SIMTech on the new AM capabilities. We quickly determined a mutual interest in terms of validation and prediction of distortion of our printed parts. Especially with larger build platforms, print failure is one of the greatest cost factors in terms of time and material waste, hence enhancing our simulation capabilities to allow optimization of print orientation, support structures and print parameters for parts with minimum distortion and print defects is a key priority.

Your paper, delivered at Science in the Age of Experience 2017, compared different ways to account for the moving heat source (see figure 3) and also looked at the sensitivity of solution to the mesh. You also did a study on using HPC to scale your simulation times. Are you developing best practices so that you can deliver recipes for AM simulations and make it easier for others in your organization to leverage?

Simulation time is currently the biggest obstacle for AM process simulation. The new concentrated heat-flux model approach developed by SIMULIA allows for multiple print layers to be simulated within one element, which reduces computational time considerably. Elements are then partially activated every time the laser path passes through an element. In contrast to this we also have the more established Goldak-type heat source models, which require very fine mesh resolution for each print layer and hence much longer simulation times. Abaqus offers both approaches within the same modeling framework. From a research point of view it is therefore important to establish validated outcomes for the concentrated heat flux model in terms of predicted temperature and stress distributions,

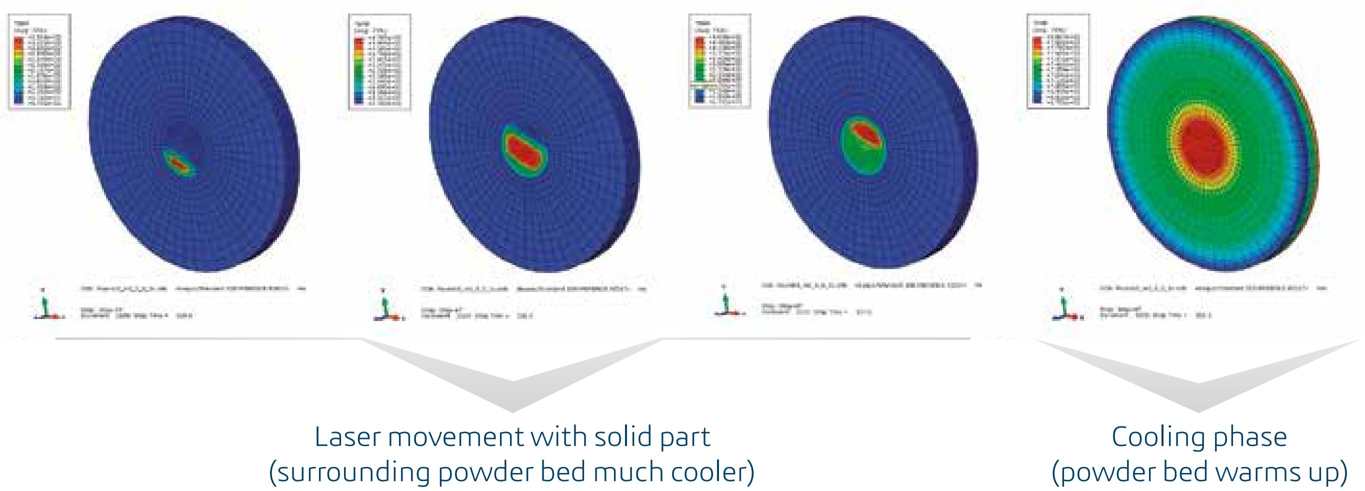


Figure 3 (above). Images from Dr. Stefanie Feih's presentation on "Influence of Surrounding Powder Bed and Build Platform on Thermal Cooling Characteristics in 3D Printed Parts via Selective Laser Melting."

hence allowing for significant reduction in simulation time. Long-term we would then like to train our engineering staff operating AM equipment to use these available tools prior to print scheduling for print set-up validation.

What's on your "wish list" for additional simulation functionality? How do you think this would connect to the overall design and manufacturing and final build workflow?

Ideally I wish to link optimized part design (i.e., topology optimization) to process simulation. During the design process, we need to determine best geometry with best print orientation, including optimized support structures. We then envisage potential compensation of the initial geometry via process simulation to allow for near net-shape printing. Process simulation also needs to interface with AM printing equipment to allow unique machine parameters, such as heat source movement, speed and power, to be used as input for the simulation. While work has started on all these individual stepping stones, a unified concept with a reasonable simulation time frame for industry projects has so far not been realized. The one-stop solution remains an ambitious task for software developers and the AM community.

You previously worked on light-weighting composites. How does AM fit into the light-weighting and/or parts consolidation narrative and why is this important for the future of so many industries?

AM offers the opportunity to design and manufacture highly complex and integrated parts, hence reducing the need for costly assembly processes and material waste. The AM process is tool-less, hence design iterations are quickly implemented and validated through changes in virtual CAD files. The Aerospace and MedTech industries are currently at the forefront of industry adaption. Especially in the aerospace industry, high cost-to-fly parts with small build volume can benefit from AM technology. Equally, as medical devices move to bespoke design rather than mass-produced standard sizes, the product demand for AM increases. Lastly, the spare parts market is expected to benefit significantly from AM technologies to reduce cost associated with making, storing and shipping spare parts and hence reduce lead time for international customers.

You also teach at universities. What is your advice for young engineers looking for interesting fields in which to work?

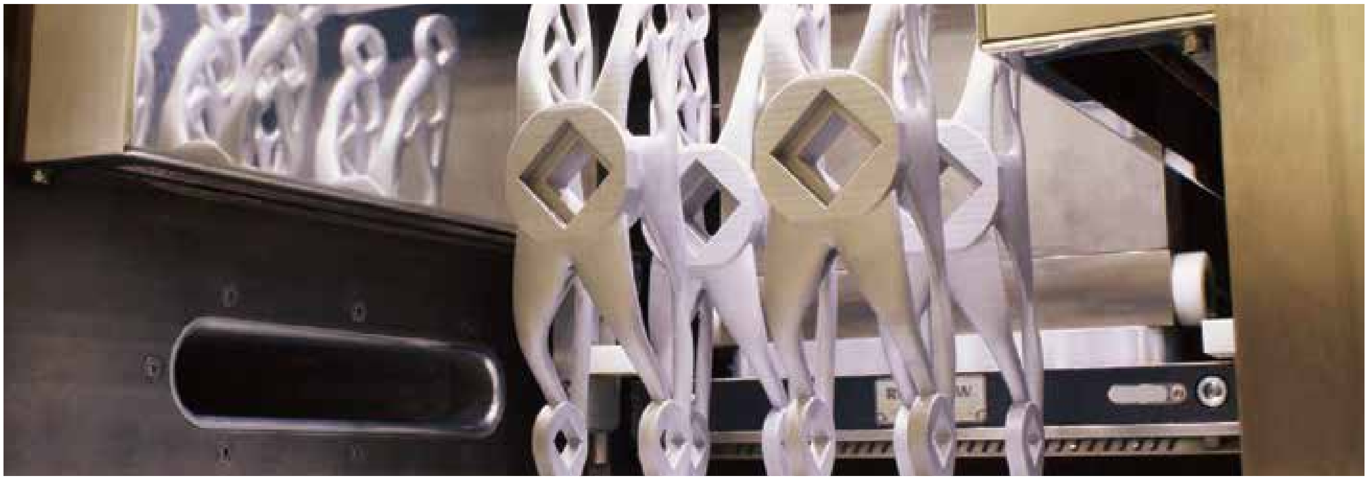
Emerging research and engineering fields open up constantly due to today's rapid progress in manufacturing technologies, data analytics and process control. In my opinion, it is therefore important to keep an open mind and be willing to change and adapt research interests throughout one's career to embrace new challenges. The expertise gained from working in different fields and application areas will always be useful for future projects.

You've written a great number of papers in a wide variety of engineering disciplines. What are the benefits you've experienced from collaborating with others and publishing the results of your work?

I have worked on large international projects and collaborated with research institutes and universities in the UK, Switzerland, Australia and the US. In my opinion, international and cross-disciplinary collaboration is crucial to progress research and develop original contributions. Collaboration also has the advantage of utilizing unique experimental set-ups and equipment at other research institutions to widen the scope of possible research. Publication of low TRL research outcomes is very important to allow for the dissemination and uptake of novel ideas and outcomes in future technology development.

For More Information

www.a-star.edu.sg/simtech



Bleu car hinge component in RenAM 500M build chamber

ENHANCING THE ADDITIVE MANUFACTURING PROCESS CHAIN

The design freedom provided by additive manufacturing (AM) or 3D printing technology is an important enabler in cutting- edge product innovation. As part of the revolution in digital manufacturing, AM can radically simplify the production of complex parts, while simultaneously improving functional performance, reducing part weight and minimising component counts.

To take full advantage of AM's unique capabilities, however, complementary software tools need to be optimized to satisfy the new requirements of 'design for additive manufacturing' (DfAM) rules and guidelines. Dassault Systèmes, a world-leading provider of 3D design software, 3D Digital Mock Up and Product Lifecycle Management (PLM) solutions, collaborated with Renishaw to streamline its **3D**EXPERIENCE platform to deliver a no-compromise end-to-end AM design experience.

BACKGROUND

The **3D**EXPERIENCE platform comprises a whole suite of 3D software applications supporting the complete product life cycle, from design and development to simulation and reliability analysis.

Available to users on premise or on-cloud, and accessible via a single user interface, it enables the creation of 'social enterprises' where collaboration in the product innovation process becomes simpler and more efficient.

Topological optimization is a key step process in the manufacture of 3D parts, ensuring material usage within a defined space is fully optimized. Dassault Systèmes' CATIA applications for generative design provide product modeling powered by the **3D**EXPERIENCE platform. Dassault Systèmes' companion DELMIA software application then enables users to design and test a product in a simulated production environment. Importantly, the software manages product build set-up and the generation of laser (scan) tool paths required by the AM systems.

Simulation of the complete AM build process, including full product stress analysis and distortion prediction, is carried out using the **3D**EXPERIENCE platform's simulation application.

In its close collaboration with Dassault Systèmes, Renishaw employed a broad range of its state-of-the-art precision manufacturing and metrology products. These included the flagship RenAM 500M metal additive manufacturing systems with laser powder bed fusion technology, QuantAM build preparation software, machine tool probing systems, EquatorTM gauging systems and CMM with REVO 5-axis measurement system.

Renishaw applied its technologies for characterization of the build process, design validation and automated process control of a final subtractive machining operation. These, combined with the **3D**EXPERIENCE platform's applications, delivered a seamless AM process and the end-to-end manufacturing solution required.

CHALLENGE

The key challenge faced by Dassault Systèmes and Renishaw engineers was to achieve alignment of their respective virtual and real worlds—of 3D design, test and analysis software and metal 3D printing. Software needed to follow real AM build rules.

The collaboration aimed to rationalize the AM design and manufacturing process so manufacturers can move away from an expensive 'design–build–test' approach to a 'right-first- time' approach.

> Renishaw applied its technologies for characterization of the build process, design validation and automated process control of a final subtractive machining operation.

Dassault Systèmes (USA)

More specifically, the project ultimately aimed to remove any need for the export of native CAD source files in a universal .STL triangulated file format—an export long proven to introduce manufacturing errors and a prime cause of loss of quality control in successive product versioning.

SOLUTION

Using 3D design innovations in the automotive industry as a demonstration and test mechanism, this software enhancement project was based around the design and manufacture of a futuristic door hinge for Dassault Systèmes concept car, Bleu.

A complex, lightweight, double-wishbone type component, the hinge presented Dassault Systèmes and Renishaw engineers with an authentic production scenario demanding close attention to structural optimization, multi-material design and part consolidation.

Working within the **3D**EXPERIENCE platform, a radical 3D hinge design was produced using the CATIA generative design capabilities. Associated tool paths generated by DELMIA applications were imported into QuantAM for additional processing prior to output to the RenAM 500M system.

Following an iterative, closed-loop sequence of hinge design adjustment, simulation, printing and precision inspection, the specific AM build rules that needed to be integrated within the **3D**EXPERIENCE platform's software to achieve optimal 3D design and printing were determined.

Renishaw made an application programming interface (API) for its QuantAM software available to Dassault Systèmes for integration within the DELMIA application for the generation of right-first-time 3D printing tool paths.

RESULTS

As a direct result of the collaboration between Dassault Systèmes and Renishaw, **3D**EXPERIENCE platform users can now print directly to the complete range of Renishaw AM systems from within the existing native CAD environment. There is no need to export data files to an external system for additional post-processing.

The enhanced CATIA, SIMULIA and DELMIA applications mean that innovative 3D product designs are now automatically optimized for both manufacture on Renishaw AM systems, and end functional performance. As a result, parts are produced more accurately from the outset, bringing lead time and material cost savings.

The focus of attention for the 3D design software developments and the ultimate by-product of the project, the conceptual hinge for the 'Bleu' concept car, also provided further real-world evidence of the benefits to be achieved by 3D design and printing.

The evolution of the component design is shown most dramatically in Figure 1 and Figure 2, where the original CATIA product design can be compared with the final product tool path generated in QuantAM. While in this case the original and optimized part volumes were virtually identical, all of the support structures were removed from the hinge design, creating a more elegant, more reliable and yet far simpler automotive product.

Subham Sett, Director of Additive Manufacturing and Materials, SIMULIA, commented, "Like Renishaw, Dassault Systèmes is committed to providing solutions which simplify the integration of 3D design and printing technology into all manner of production environments. This common thinking was instrumental in the project's success. Dassault Systèmes provides the functional generative design and physics-backed manufacturing simulations that are a key part of the metal 3D printing process chain."

For More Information

www.renishaw.com

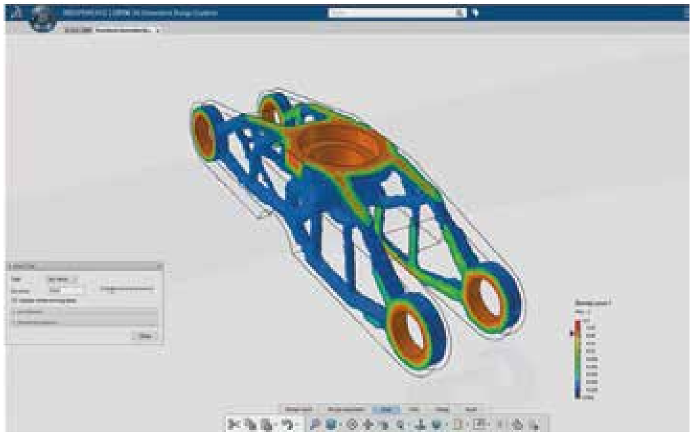


Figure 1: Bleu car hinge component in CATIA.

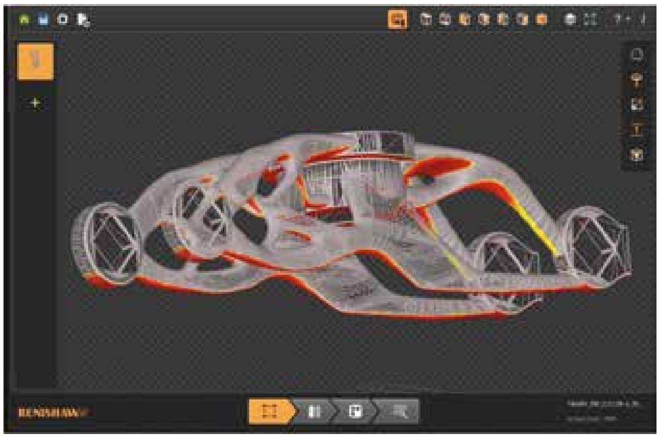


Figure 2: Bleu car hinge component in QuantAM build preparation software.

LATTICE DESIGN WITH ABAQUS AND nTOPOLOGY ELEMENT

Until recently, designing lattice structures was a long, difficult process. Conventional design tools don't allow enough flexibility, and conventional analysis & optimization methods have struggled to integrate well into engineering workflow. But with a new collaboration between Abaqus and nTopology, lattice design, analysis, and optimization is a seamless and repeatable process.

TOPOLOGY

Lattice design begins with topology—the locations and connectivity of nodes and beams in the structure. Topology design determines the load paths and structural rigidity of the design. Lattice topologies can be generated by a number of methods—some periodic/repeating and some aperiodic/stochastic.

Regardless of the topology generation method, we begin by understanding our design space. By using Abaqus to analyze the solid region that we'll be generating a lattice in, we can create a topology that is effective and efficient (see figure 1).

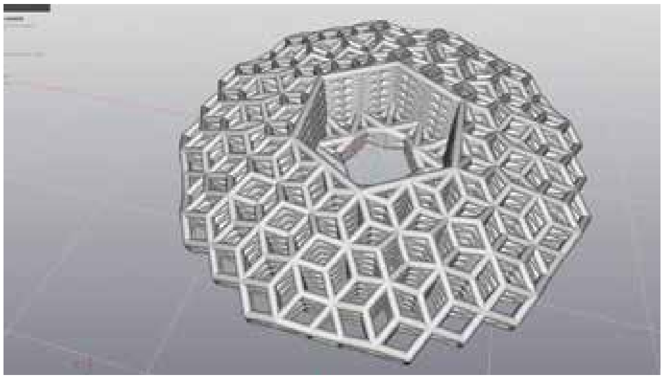


Figure 1.

Using this result, we can use nTopology Element to design a topology. Stochastic topologies will vary beam density based on Abaqus field outputs, whereas periodic topologies will use different lattice cells in different regions of the part. Here, we'll use variable periodic topologies (all based on a hex prism cell) to create regions with different properties in our part (see figure 2).

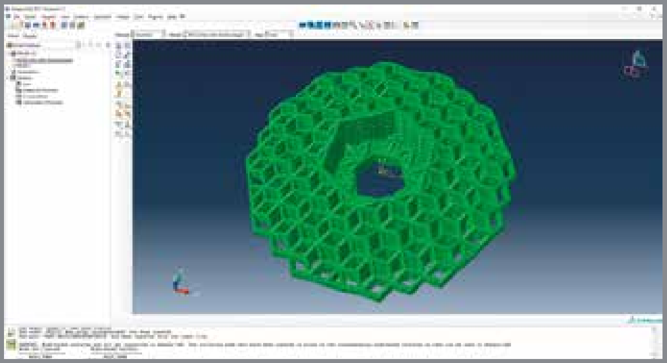


Figure 2.

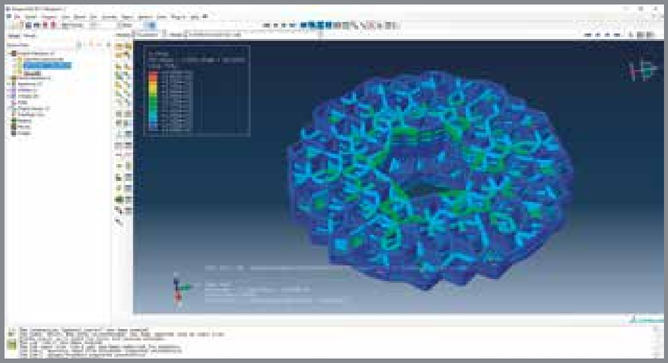


Figure 3.

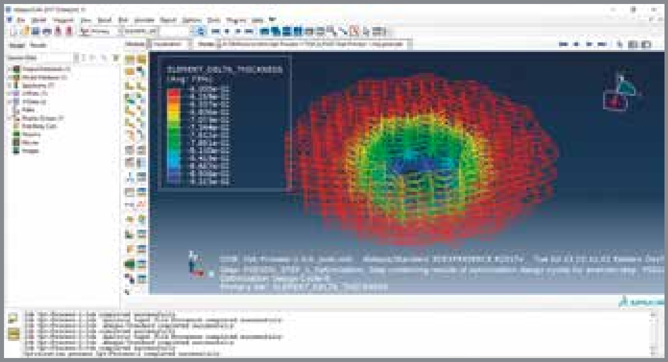


Figure 4.

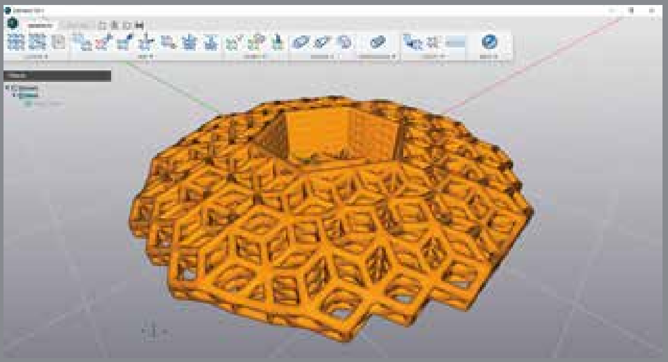


Figure 5.

Once we have a topology, we can reanalyze the part to understand how that topology will perform. Using nTopology Element to export an Abaqus input file, apply a default beam thickness based on the 3D printing process. Finally, run a simple beam analysis on the part (see figure 3).

If necessary, we can use these analysis results to modify the topology design. Otherwise, we can use Tosca to optimize beam sizes. We limit the beam thickness to the printable range of our printing process, staying thick enough to print successfully and thin enough to not require support structures. Even with tens of thousands of beams, these optimizations run very quickly. We can be confident that the results are efficient and reliable because we use Tosca's time-proven optimization methods (see figure 4).

Once the optimization has run and we're happy with the results, we export the design back out as an LTCX file and bring it into nTopology Element. At this stage, we can make any necessary design edits before converting the part into a printable mesh (3MF or STL are preferred) (see figure 5).

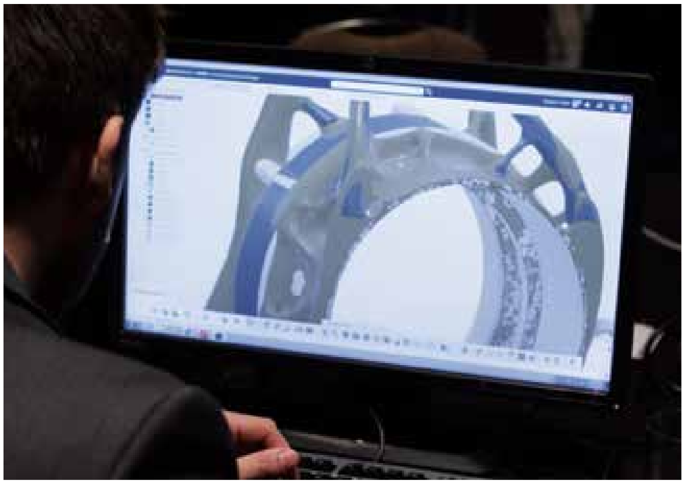
Through this process we can create parts that have extremely high strength to weight ratios, efficient mass distributions, and variable mechanical properties (stiffness/compliance, etc). Whether you're designing for aerospace, medical implants, or consumer tech, this workflow can be tuned to meet the key metrics that your customers require. Regardless of your specific goals, the workflow is smooth and flexible. Learn more about nTopology Element , Abaqus and Tosca.

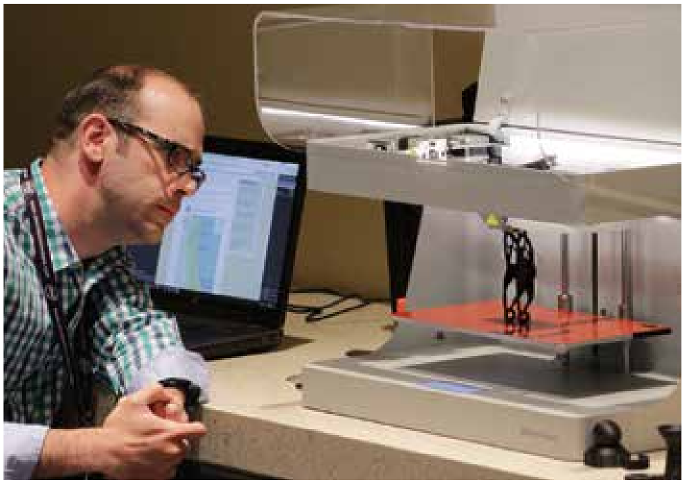
ABOUT THE AUTHOR

Spencer Wright manages integrations & R&D at nTopology in New York City. He writes about additive manufacturing at pencerw.com and about the engineering industry at theprepared.org.

For More Information

www.ntopology.com





TEAMS TAKE ON DESIGN CHALLENGE DURING ADDITIVE MANUFACTURING HACKATHON AT SCIENCE IN THE AGE OF EXPERIENCE

This year at Science in the Age of Experience, we hosted our first-ever Hackathon in conjunction with our Additive Manufacturing Symposium. We invited students from all over the globe to participate and were joined by participants from Purdue University, University of North Carolina Charlotte, Northwest, and Norwegian University of Science and Technology.

We provided the teams with four design challenge statements or the opportunity to bring their own engineering challenges to hack. With support from partners including nTopology and Adaptive Corporation along with our best-in-class **3D**EXPERIENCE platform, including functional generative design, students tackled real engineering problems within the additive manufacturing space including lattice, infill and topology optimization to build process simulation.

Over the course of two days the students feverishly worked away on the workstations we provided. They had access not only to all the software needed but also industry experts there to answer questions in person. At the end of the hackathon, all groups presented their work to a panel of judges from NNSA's Kansas City National Security Campus, TWI Technology Center and Dassault Systèmes. A panel judged each project on design aesthetics, originality, product performance, manufacturability, and usability.

While the decision was tough, the ultimate winners were students from Purdue University. Luyao Cai, Ke Huo, and Subramanian Chidambaram, who brought their own design challenge with them to the event and designed a patient specific arm cast.

Congratulations to all the teams. Each contribution was unique, well planned, and well executed. It was a joy to host the students and teach them about what Dassault Systèmes is doing in the AM space. With contributions like theirs it's easy to see that the future of AM is a bright one.

PRINTING IN PURDUE

University researchers and students use SIMULIA software tools to improve 3D-printed composites

Since its introduction as a limited prototyping technology scarcely three decades ago, additive manufacturing (AM)'s capabilities have grown to the point where it's not only today's leading prototype parts-making solution, but is also beginning to compete with traditional manufacturing methods in low- to medium-volume end-use parts production. This is especially true in the automotive and aerospace sectors, where the need for lightweight, robust components will only increase as consumers, governments, and manufacturers everywhere continue their pursuit of ever-smaller carbon footprints.

One way to accomplish this is the use of composite materials in AM (aka 3D printing). When combined, carbon fiber and engineering-grade plastic offer the potential for exceedingly strong yet lightweight products, especially when constructed of complex geometric shapes that until now were impractical—if not impossible—to manufacture. AM is a truly disruptive technology—yet some significant engineering hurdles still need to be overcome.

HELLO CAMRI

This is the work of researchers at Purdue University's Composites Manufacturing and Simulation Center (CMSC) in West Lafayette, Indiana. Together with professor R. Byron Pipes [see SCN issue #15], graduate students Eduardo Barocio, Bastian Brenken, Anthony Favaloro, and others have designed and built the Composites Additive Manufacturing Research Instrument (CAMRI), and are using tools from Dassault Systèmes SIMULIA to understand what makes this and other 3D-printing processes tick.

But what is CAMRI, and why does the world need yet another 3D printer? To understand that, it's first necessary to define another acronym, EDAM, short for extrusion deposition additive manufacturing. Several commercially available flavors of EDAM printer exist on the market today. Most work by extruding a thin filament of heated thermoplastic through a nozzle, in essence drawing sections of a thinly-sliced CAD model, filling in one layer at a time and working from the bottom of the workpiece up. Upon extrusion, the filament binds with the material below and adjacent to it before hardening, allowing subsequent layers to be laid atop one another until complete.

Purdue's CMSC might have used one of these commercial printers but for one thing: because the goal of the program is to understand and develop composites technologies, the team needed their own machine that could print a customized 50-50 blend of carbon fiber and polyphenylene sulfide (PPS), an engineering grade thermoplastic that offers excellent chemical and mechanical properties in a variety of applications.

GOING "ORGANIC"

As mentioned earlier, AM's greatest strength is its ability to build novel part geometries that are both strong and light. Spider web and helical shapes, self-supporting lattice

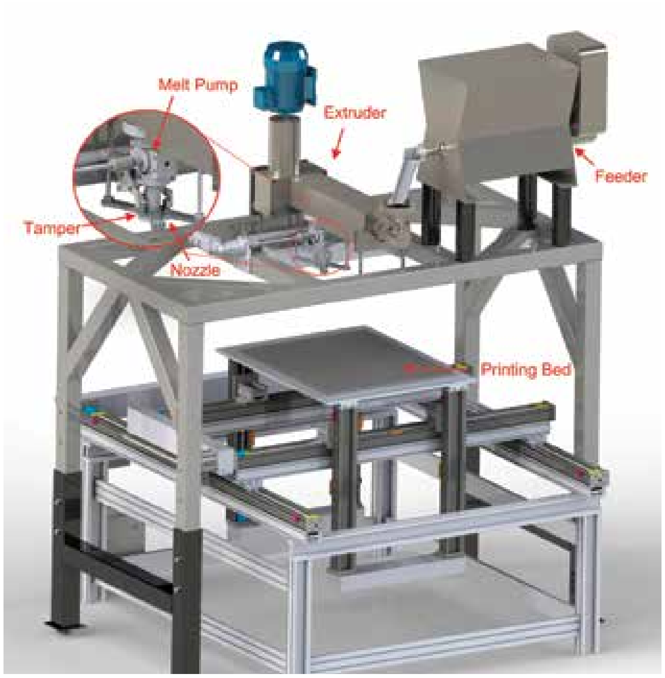


Figure 1a: A SOLIDWORKS rendering of Purdue's CAMRI 3D printer, showing the feedstock hopper, extrusion and heating mechanisms, and print bed.

Figure 1b: The CAMRI system in action. Note the movable X-Y-Z axes platform beneath, on which the 3D printed parts are constructed.

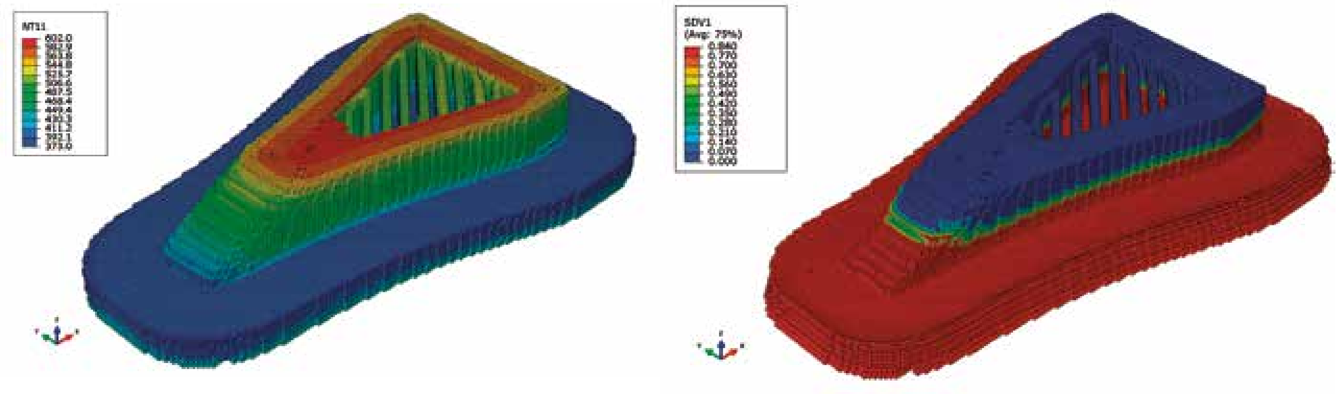


Figure 2a/2b: In-Situ temperature (left) and crystallinity simulations (right) in Abaqus.

arrangements, cellular constructions mimicking bones or honeycombs—these and other organic structures are child's play for AM. What's not so easy is determining how to design products that leverage these structures, to understand what exactly is going on at the boundary where hot and cold meet, and how the carbon fibers mesh with the surrounding thermoplastic. To this end, the team turned to simulation tools from SIMULIA.

MOVING CLOSER TO AS-DESIGNED

"Unlike a typical stress analysis, simulating the EDAM process requires modeling of the system throughout a large temperature range, using a complex, phase dependent, anisotropic thermo-viscoelastic material model," says research assistant Anthony Favoloro. "Additionally, this simulation requires a finite element framework in which individual elements can be progressively added so that the model grows in a way that mimics reality."

Simply put, there's a lot going on in there. The EDAM process uses pelletized feedstock that is mixed, heated and forced through the extruder onto a build platform. Because of the complexity of the 3D shapes being made, together with the continuous addition of molten material to a moving workpiece, numerous challenges exist to making structurally sound yet accurate products. Enough heat must be applied to assure a cohesive bond between layers, but at the same time achieve sufficient stiffness so that the model is self-supporting and avoids the thermal distortion that can affect 3D-printed parts. Most importantly, notes Favoloro, there should be minimal differences between as-designed and as-manufactured parts, an oftentimes significant process gap.

Fortunately, all of this was made a little bit easier thanks to several new additive manufacturing features from SIMULIA. "Our team has been able to implement an element-activation algorithm in Abaqus that uses the same machine path information as the CAMRI," Favoloro says. "For a precise representation of the path, the CAMRI is sampled through a physical print job such that the dynamics of extrusion rate and table speed are captured. Additionally, we are able to automatically assign machine-path dependent material orientations through an ORIENT subroutine. Finally, the full thermoviscoelastic model is captured through user material models."

These types of simulations allow for a virtual investigation of the infill percentage, infill type, print speed, and other parameters used when 3D printing a part, he adds. Analysis of part deformation can also be used to compensate the original machine path, minimizing the "as-designed vs. as-built" process-gap, and to identify potential weak areas. "In this way, these simulations play a critical role in accelerating confident adoption of the EDAM process," says Favoloro.

KEEPING COOL

Graduate student Bastian Brenken enjoyed similar results. "We were able to develop a user-subroutine toolset in Abaqus and use it to model the EDAM process," he says. "It combines a non-isothermal dual crystallization kinetics model with a statistical melting model to describe the simultaneous solidification and re-melting behavior of 3D printed parts. In this way, both the crystallization process of the cooling material as well as local re-melting upon deposition of new, hot and molten material can be modeled during a printing simulation."

Brenken and his colleagues employed an Abaqus user-developed subroutine to study the behavior of semi-crystalline fiber-reinforced thermoplastics during the 3D printing of a tool used in the autoclave process of NACA (National Advisory Committee for Aeronautics) air ducts, small plastic scoops that attach to an aircraft fuselage and direct cool air into the engine.

Figure 3: The upper left part of the photo shows the "as printed" NACA duct tool; the section below is the finished product after machining.

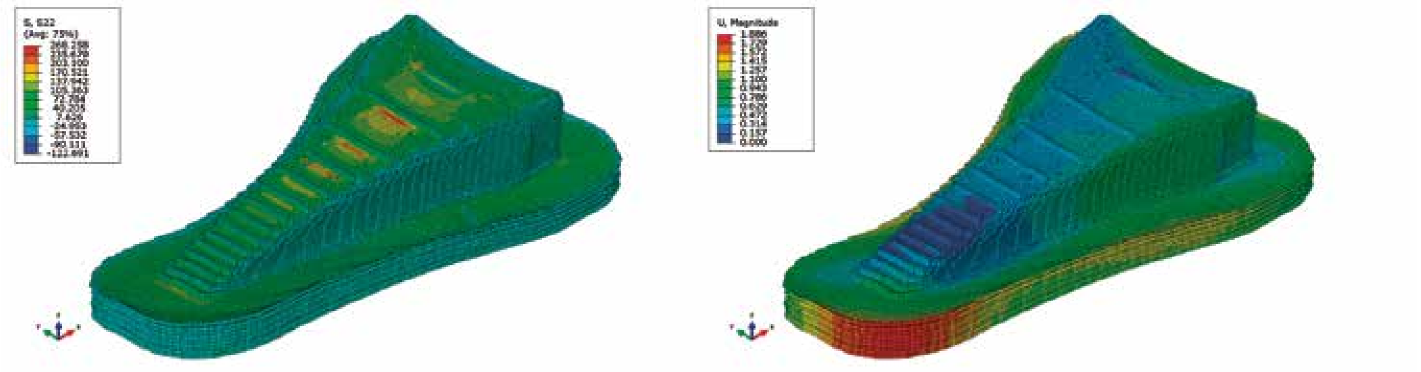


Figure 4a/4b: Abaqus models showing the final residual stress (left) and deformation (right).

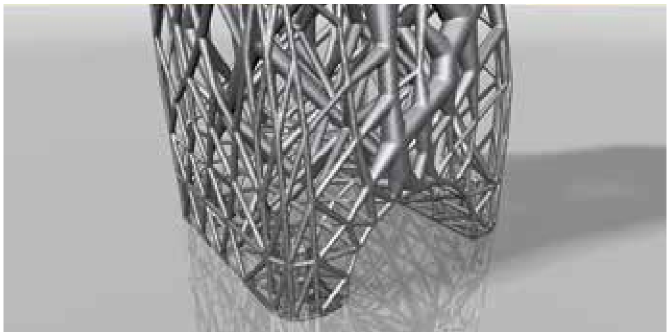
Another Abaqus model was built of rod-like shapes stacked atop one another like firewood, representing the extruded beads of material within each layer. Convection, radiation, and thermal contact boundary conditions were established between the individual beads, and detailed thermal and crystallization histories recorded for bond formation analyses.

"These simulations clearly demonstrated how crystallization and re-melting occurs during the extrusion deposition (EDAM) process, not only at the local bead level but also globally, throughout the entire part," Brenken explains. "We observed that the crystallization behavior is very dependent on the utilized material—in this case, we modeled both a composite of PEEK (polyetheretherketone) and PPS. It would have been difficult to identify these material characteristics without the new AM functionality in Abaqus."

WORKING WITH LATTICES

Despite AM's extensive potential, substantial work remains in determining the optimal design for printed products in a way that fully utilizes 3D printing's freeform manufacturing capabilities. Quite often the ideal structure is lattice-like, resembling an inverted tree, or a randomized version of the Eiffel Tower. And while these complex yet seemingly delicate geometries are simple enough to construct additively, understanding the best size, orientation, and shape of the various support beams within is mathematically challenging, to say the least.

Luyao Cai, from Purdue's Weldon School of Biomedical Engineering, has tackled this problem head on. Their lattice-sizing optimization project attempts to determine the best combination of weight, mechanical stability, and surface area of 3D-printed support structures in applications ranging from hip and knee replacements to rugged but lightweight bicycle components.



Says Cai, "Lattice structures bear many desirable characteristics from a design standpoint. This includes stable designs that utilize a large network of structural members, with desirable weight characteristics and mechanical behavior that can be customized to fit a specific application—for example, development of medical implants with a porous nature that facilitates bone and tissue growth. It wasn't until recently however, with the evolution of additive manufacturing technology, that fabrication of these complex lattice structures has been made possible."

LOOKING WITHIN WITH TOSCA

Using Tosca design optimization tools and plugins, Cai can easily convert the surface mesh common in most CAE models to a lattice structure, which was then optimized before being converted into the STL language used by 3D printers. They tested the optimization routine on a bicycle handlebar stem, which after 17 iterations delivered a structure that showed improved stiffness under horizontal load, and was "print ready" in less than two hours.

Cai also used Abaqus to simulate cartilage and soft tissue in humans, which he says is virtually impossible to measure accurately "in vivo." He developed models based on MRI displacement maps and then used Tosca to vary mechanical properties of each element to match those displacements, thus determining its relative stiffness distribution. Cai says such models can be used to test cyclic loading of knee joints, for example, and enable researchers to design implants that will closely mimic the human body's own internal structures. "The ability to simulate the interaction between tissue and a stent or other medical device is very exciting," he says. "Abaqus can solve problems very quickly, and has saved me a lot of time. It's fantastic."

For More Information

https://engineering.purdue.edu/engr

THREE THINGS YOU SHOULD BE DOING WHEN SETTING UP A PRODUCTION 3D PRINTING

Mike Vasquez, Ph.D., CEO, 3Degrees, LLC

The processing and materials technology for 3D printing has continued to evolve and improve, enabling significant expansion of production use cases for the technology.

As adoption of the technology moves beyond its prototyping heritage, the needs of companies deploying the technology are rapidly changing, too. No longer are 3D printed parts just for the use and testing of R&D or innovation teams; printed products are now finding a number of end uses that bring them into the "for commercial use" realm. As more applications become financially and technologically feasible, a real effort needs to be undertaken to match the sophistication of existing manufacturing processes for documenting critical variables, process characteristics, materials and inspection.

Having worked with organizations in the aerospace, automotive, medical and consumer products industries as they operationalize 3D printing for production parts, we advise keeping in mind three key things as you make the jump to production.

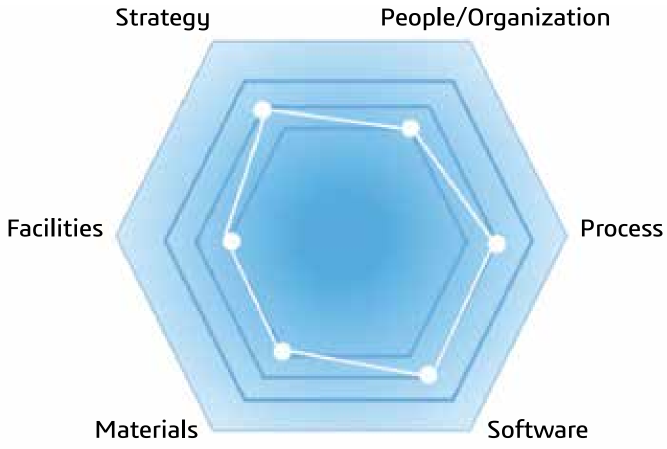
SWEAT THE FACILITY STARTUP DETAILS

Once you invest $10,000, $100,000 or $1 million dollars into a machine, you quickly will realize that much more is needed to create a safe, effective 3D printing capability. Additional cost items include materials, post-processing equipment, safety equipment and training. This can be especially true for metal 3D printing technologies, as once the part is built in the machine it still may require heat treatment, removal from a build plate, surface treatments and polishing before it's finished.

As you go down this path, having internal alignment on the business case for the created parts as well as how the organization will operate can make the difference between getting ramped up quickly and costly delays. We often work with companies at these early stages to do a Production 3D Printing Readiness evaluation that takes a look at the following categories: AM Strategy, People/Organization Structure, Processes, Materials, Software, and Facilities. It is important to make sure that these topics are discussed and thoroughly thought-through during your production planning.

DESIGNING FOR 3D PRINTING IS CRITICAL

If your idea of a great application for 3D printing is to create a screw or a standard bolt for your business, you probably don't need to invest in the technology. The biggest advantage that 3D printing has over other manufacturing technologies is the fact that you can create complexity in your parts without adding cost. This means that in order to use 3D printing effectively, you need to be comfortable redesigning your parts to take advantage of this. Companies often struggle trying to achieve their return on investment for 3D printing because it requires going back to the drawing board, literally.



Mapping Your AM Production Strategy

DEVELOP A SMART WORKFLOW TO MANAGE QUALITY

Another challenge that we've seen as companies start to operationalize their 3D printing capabilities for production is trying to formalize a workflow that ensures both efficiency and quality part development. There are a number of factors that impact part quality throughout the process including design, material feedstock, processing, post-processing and inspection. Within each of these broad categories there could be dozens of variables that need to be documented and controlled. This is made more complex by the fact that the development of industry specifications and standards is still in its infancy.

The bottom line is that companies—large and mid-size alike—are just starting to incorporate this technology into their production processes. As a result, there's still a lot to learn... and a lot of opportunities for companies who do it right to create competitive advantages.

ABOUT THE AUTHOR

Dr. Mike Vasquez is a 3D printing expert specializing in pushing the boundaries of advanced 3D printing technology. He is the Founder of 3Degrees, a Chicago-based consulting company focused on helping organizations maximize their investment in the technology. He completed his Ph.D. in Additive Manufacturing at Loughborough University and received both his Bachelors and Masters from MIT in Materials Science and Engineering. Recently he published a best practice guide titled *How to Make 3D Printing Work for You and Your Business*.

For More Information

www.3degreescompany.com

ADDITIVE MANUFACTURING PROCESS SIMULATION: A 2-DAY TRAINING COURSE

We are introducing a 2-day training course for Additive Manufacturing (AM) process simulation. In this class, you will learn how to set up the entire AM workflow from manufacturing planning to process simulations. Through lectures, live demonstrations and hands-on self-contained workshops, attendees will become conversant with applications available through the following roles: Additive Manufacturing Programmer and Additive Manufacturing Researcher.

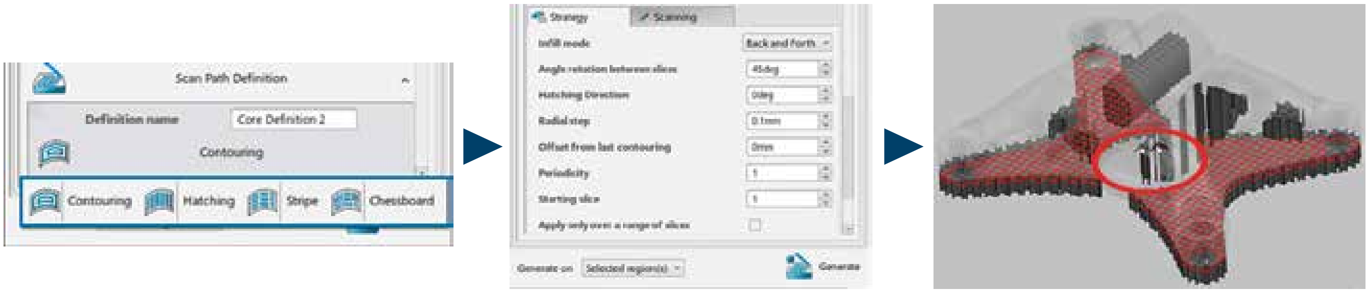
The manufacturing applications, central to the Additive Manufacturing Programmer role, allow you to plan the build for metal powder bed fabrication, which includes nesting, support structure generation and slicer strategies. A guided step-by-step lecture walks you through the following steps in the workflow.

1. Under build setup, select or create the machine and build tray.
2. Orient the part(s) and position them using automated or manual nesting.
3. Create the support structures for the part(s) from a library or manually.
4. Specify and generate the scan paths based on machine-specific parameters and hatching strategies.
5. Export the data in standard or vendor-specific formats.

The above exercise only covers those portions of the applications that are relevant to the subsequent process simulations.

The Additive Manufacturing Researcher role allows you to conduct finite element simulations based on the generated AM process parameter. The goal is to predict part distortions, residual stresses and microstructure evolutions that occur during the layer-by-layer build of the additive part. A guided step-by-step lecture guides you through the steps involved in setting up the simulation model for metal powder bed application with information coming from the manufacturing applications. After the manufacturing simulations (thermal, stress) are complete, the next step is to simulate build plate removal and predict the final deformations in the part. Finally, you will learn how to customize the interface for other manufacturing processes (e.g.: LDED, FFF) and include external tool/scan path data.

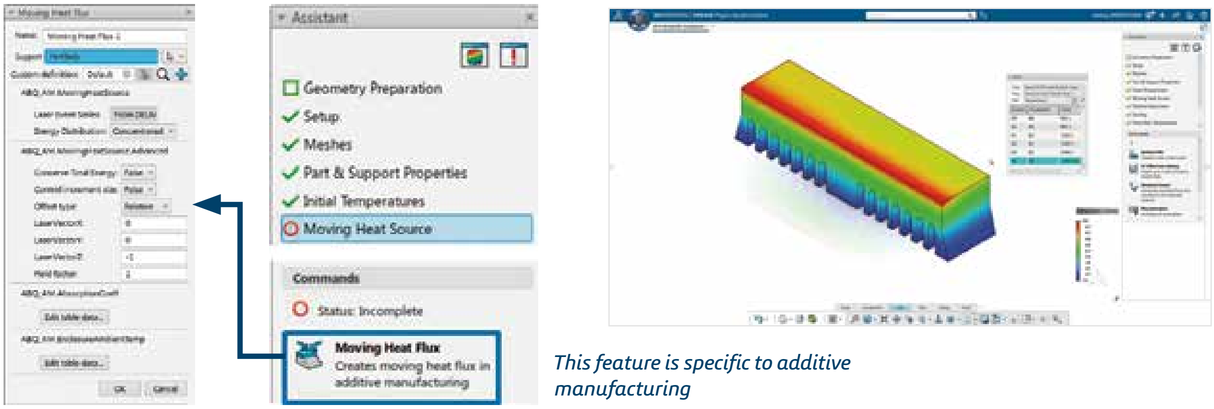
This 2-day course has been constructed to give you as much hands-on training as possible. Attendees are encouraged to bring their own parts and geometries to the class or select from a suite of different workshops to accelerate their digital additive journey!



Definition name: Core Definition 2

Infill mode: Back and forth
Angle rotation between slices: 45deg
Hatching Direction: 0deg
Radial step: 0.1mm
Offset from last contouring: 0mm
Periodicity: 1
Starting slice: 1
Apply only over a range of slices ☐
Generate on: Selected region(s)

Defining Hatch Sequences in the Powder Bed Fabrication application



○ Status: Incomplete

Moving Heat Flux: Creates moving heat flux in additive manufacturing

This feature is specific to additive manufacturing

Specifying moving heat source (laser) in the Additive Manufacturing Scenario application

ATTEND A USER MEETING NEAR YOU!

Each fall, SIMULIA provides a place for industry and academia to gather and learn about the latest simulation technology and methods that can accelerate and improve product innovation. Last year, more than 4,100 users attended Regional User Meetings (RUMs) and user group meetings around the globe. Because these are local meetings, we are able to tailor content toward trends and marketing conditions where you are, and present information in native languages.

See the meeting schedule and register today at www.3ds.com/rums

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