DASSAULT SYSTEMES | The 3DEXPERIENCE® Company

# DIGITALLY ACCELERATING ADDITIVE MANUFACTURING

While Additive Manufacturing (AM) has opened up possibilities for product design that were not even contemplated before, the industry still struggles with unknowns: part distortions, residual stress, and microstructure defects. The **3D**EXPERIENCE® platform provides a digital thread from design to simulation to production. Within this framework, engineers can perform detailed thermal-mechanical analyses to predict complex physics, such as microstructure, as-built material properties, and buckling. A faster eigenstrain-based simulation method is also available to obtain distortions for part compensation iterations. These simulation tools were awarded first place in residual stress prediction by the recent NIST AM Benchmark, and have been validated for a range of process types and materials.

## MAKING PARTS THAT WORK

This eBook focuses on simulation of additive manufacturing processes. Read papers and watch presentations from our customers that demonstrate how they leverage our simulation solutions to:

- Advance adoption of additive manufacturing technology
- Predict as-built material properties of additively manufactured parts
- Understand build part distortions and residual stresses to ensure a successful build

Continue reading to view these paper and presentation abstracts —then **download the complete papers!**

3DEXPERIENCE®

Image courtesy of Revolve NTNU

## ADDITIVE MANUFACTURING: HELPING BUILD AEROSPACE'S FUTURE

Nyle Miyamoto, Additive Manufacturing Chief Engineer in Boeing Commercial Airplanes will share insights into Boeing's additive manufacturing journey. He will discuss progress the company is making, and describe some of the challenges of implementing Additive Manufacturing in the highly regulated Aerospace industry. Finally, he will communicate how Boeing is leveraging the **3D**EXPERIENCE platform to accelerate the development and implementation of this ground breaking technology.

CLICK HERE TO SEE THE FULL PRESENTATION

*Courtesy of Nyle Miyamoto,*
*Boeing Commercial Airplanes,*
*2018 Science in the Age of Experience Conference*

## ADVANCED COMPOSITES – A VISION FOR SIMULATION IN 2040

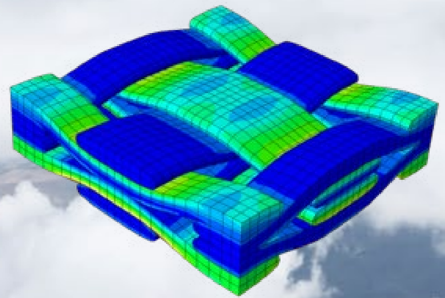
Dr. Pipes will present an overview of research and development of new composite materials using aerospace, marine, and automotive examples. The role of simulation to develop the virtual twin in performance and manufacturing will be explored with thirteen work flows that use **3D**EXPERIENCE Design, Simulation, and Biodesign (materials) to develop end-to-end composite manufacturing processes, including validation, to achieve "manufacturing informed performance." Finally, barriers to pervasive simulation use in future product development, such as tool accessibility, adaptability, interoperability, traceability and usability, as concluded by NASA's "Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems," will be discussed.

CLICK HERE TO SEE THE FULL PRESENTATION
*Courtesy of Dr. Byron Pipes, Purdue University, 2018 Science in the Age of Experience Conference*

CLICK HERE TO READ MORE ABOUT RESEARCH FROM DR. PIPES' LAB
*Simulation of Semi-Crystalline Composites in the Extrusion Deposition Additive Manufacturing Process, 2017 Science in the Age of Experience Conference Proceedings*

CLICK HERE TO READ MORE ABOUT RESEARCH FROM DR. PIPES' LAB
*Prediction of the Degree of Bonding in the Extrusion Deposition Additive Manufacturing Process of Semi-Crystalline Polymer Composites, 2018 Science in the Age of Experience Conference Proceedings*

CLICK HERE TO READ MORE ABOUT RESEARCH FROM DR. PIPES' LAB
*Simulation of Polymeric Composites Additive Manufacturing using Abaqus, 2017 Science in the Age of Experience Conference Proceedings*



## HOW TO BRIDGE THE GAP BETWEEN NUMERICAL SIMULATION AND EXPERIMENTAL ANALYSIS

Weight reduction, whilst maintaining the performance of structures, is a fundamental driver in the automotive, aerospace and energy sectors. Manufacturers are continuing to seek improvement in structural efficiency and reduction in component cost via integrated assembly whilst striving to meet stringent emissions targets and reducing material wastage. Drawing from her research in the field of lightweight design, Dr. Feih's presentation will focus on case studies utilizing Abaqus to predict performance and failure of lightweight structures, particularly for fiber reinforced composites, metallic alloys and hybrid connections between dissimilar materials. For each case study, the journey will be shared to achieve synergistic numerical and experimental analysis outcomes in order to drive, and successfully validate, innovative design solutions.

### CLICK HERE TO READ MORE ABOUT RESEARCH FROM SIMTECH

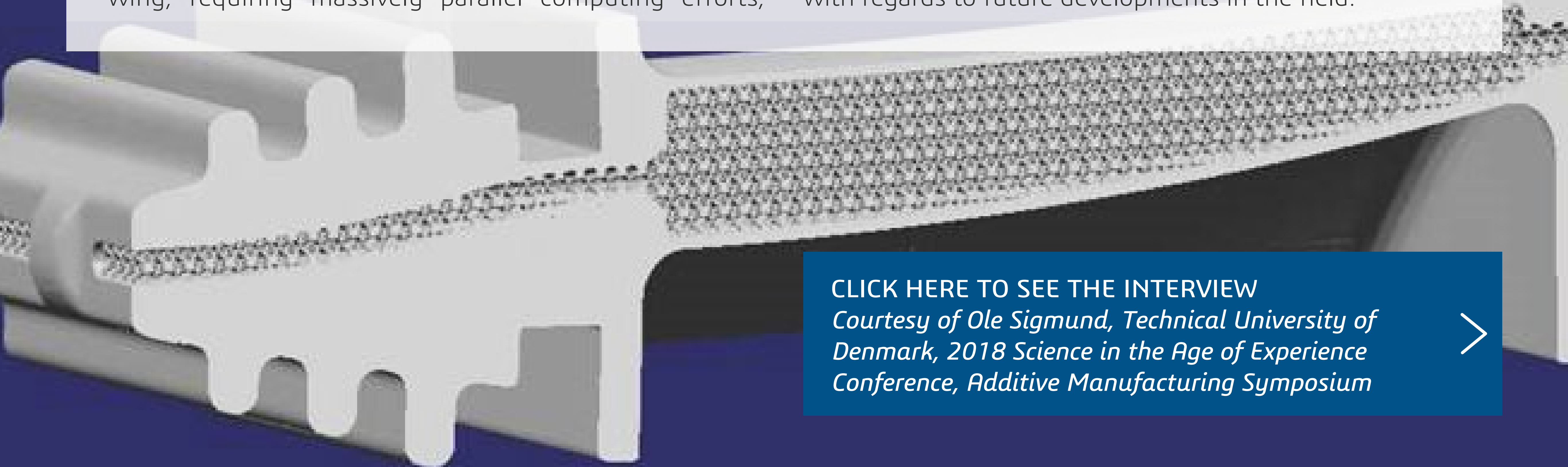
*Influence of Surrounding Powder Bed and Build Platform on Thermal Cooling Characteristics in 3D Printed Parts via Selective Laser Melting, 2017 Science in the Age of Experience Conference Proceedings*

### CLICK HERE TO SEE THE FULL PRESENTATION

*Courtesy of Stefanie Feih, SIMTech, 2018 Science in the Age of Experience Conference, Additive Manufacturing Symposium*

## TOPOLOGY OPTIMIZATION OF STRUCTURES AND INFILL FOR ADDITIVE MANUFACTURING

Topology optimization (TO) and additive manufacturing (AM) constitute an ideal marriage. Highly optimized designs coming out of TO or generative design approaches often have intricate or organic looking shapes that only can be manufactured using AM technologies. On the other hand, AM offers unique manufacturing capabilities such as complex lattice structures and infill that may have advantages over traditional solid structures but also require reformulation of TO approaches to release their full potential. The talk gives an overview of recent TO developments, starting with a giga-voxel design study for a full airplane wing, requiring massively parallel computing efforts, and continuing to more efficient multi-scale projection approaches that allow design of open and closed-walled lattice or infill structures, directly aimed at AM-based realizations. Contrary to common belief, however, lattice structures are not stiffness optimal. Nevertheless, lattice structures may be a good choice if buckling stability, transparency, requirements to permeability or other alternative mechanical or multiphysics aspects play a role in the optimization problem. After a discussion of these aspects, the talk ends with a few examples of alternative TO/AM applications within thermofluidics and an outlook with regards to future developments in the field.



CLICK HERE TO SEE THE INTERVIEW

*Courtesy of Ole Sigmund, Technical University of Denmark, 2018 Science in the Age of Experience Conference, Additive Manufacturing Symposium*

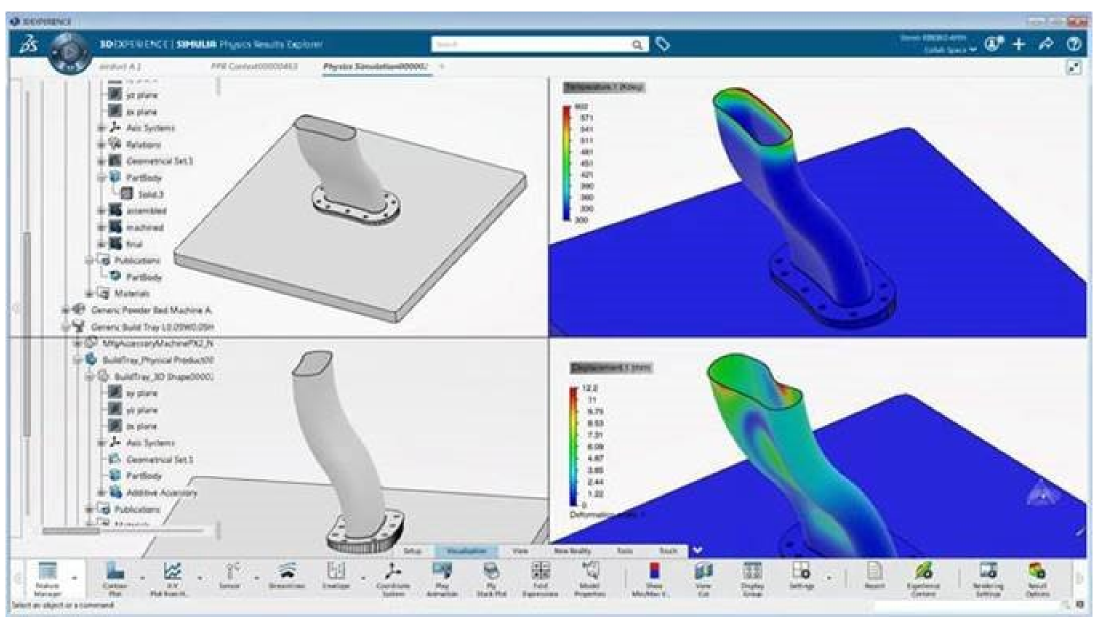
## VALIDATION OF A GENERIC METALLURGICAL PHASE TRANSFORMATION FRAMEWORK APPLIED TO ADDITIVE MANUFACTURING PROCESSES

While significant progress has been made in the last few years, the reliability of Additively Manufactured (AM) parts is often questionable as they suffer from manufacturing defects and hence subpar strength and fatigue life. Like in many other fields before, numerical methods are sought to provide insight into the process and help accelerate progress in raising the quality of AM parts, including predicting thermal evolutions, part distortions and residual stresses. In addition, in metal applications, assessing the amount of unfused powder, melt pool volumes, and metallurgical phase transformations are often of interest. In this work we introduce a generic framework for assessing metallurgical phase transformations, building on a previously developed general simulation framework for predicting temperature evolution, distortions and residual stresses. Phenomenological plasticity models based on the predicted microstructural evolutions are used to predict yield strength, ultimate strength and ductility limit. Experimental work was conducted in order to validate numerical predictions and included temperature measurements, EBSD/XRD microstructural examinations, and tensile tests on dogbone specimens. Additional publically available experimental test data was used to validate melt pool sizes and unfused powder predictions. Comparisons between experiments and numerical predictions suggest that such modeling techniques, with minimal calibration efforts, can be used to predict strength behavior including softening behavior beyond the uniform elongation limit.

CLICK HERE TO READ MORE ABOUT RESEARCH FROM TWI TECHNOLOGY CENTER (NORTHEAST)
*Predicting the Properties of Additively Manufactured Parts, 2017 Science in the Age of Experience Conference Proceedings*

## ADDITIVE MANUFACTURING PART LEVEL DISTORTION SENSITIVITY ANALYSIS WITHIN ABAQUS ON A THIN-WALLED, TUBULAR STRUCTURE

As additive manufacturing (AM) evolves to become a more viable production solution in terms of cost, quality, and time, the need for predictive simulation of the process grows as well. After testing several commercial offerings to see how well they could predict deformation of various parts, Abaqus was found to be the most promising option and chosen for a more in depth analysis. The scope of this particular project was to examine the effects of certain simulation choices – from basics (mesh, timestepping, element type) to unique AM convergence techniques (full/partial activation, expansion time constant, follow deformation, etc.). Hundreds of simulations were run in Abaqus with various permutations and the resulting response on the final deformation and stress state was tracked. The results will be presented with charts and images to showcase the patterns (or lack thereof) produced by isolating each of these modeling choices on a thin-walled, tubular structure. The findings and conclusions are of value to anyone using Abaqus to simulate part-level distortion due to AM: for some – the study can provide a model or launching point for other in-depth sensitivity studies, for others – confidence in established procedures, or others still – insight to the myriad of options available with Abaqus's AM capabilities.



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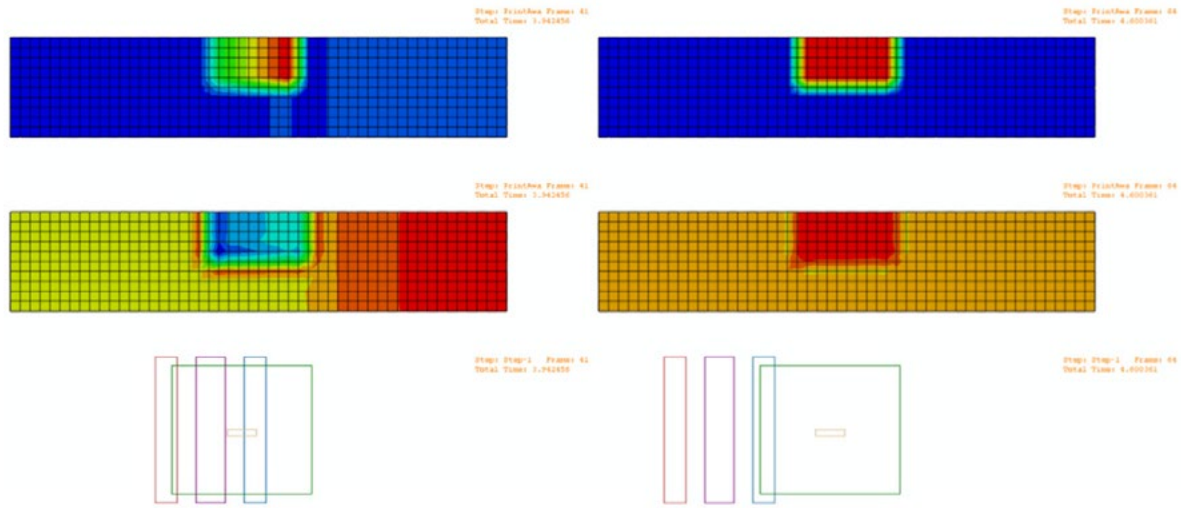
*Courtesy of Richard Deering, The Kansas City National Security Campus, 2018 Science in the Age of Experience Conference*

## FINITE ELEMENT SIMULATION OF THE MULTI JET FUSION (MJF™) PROCESS USING ABAQUS

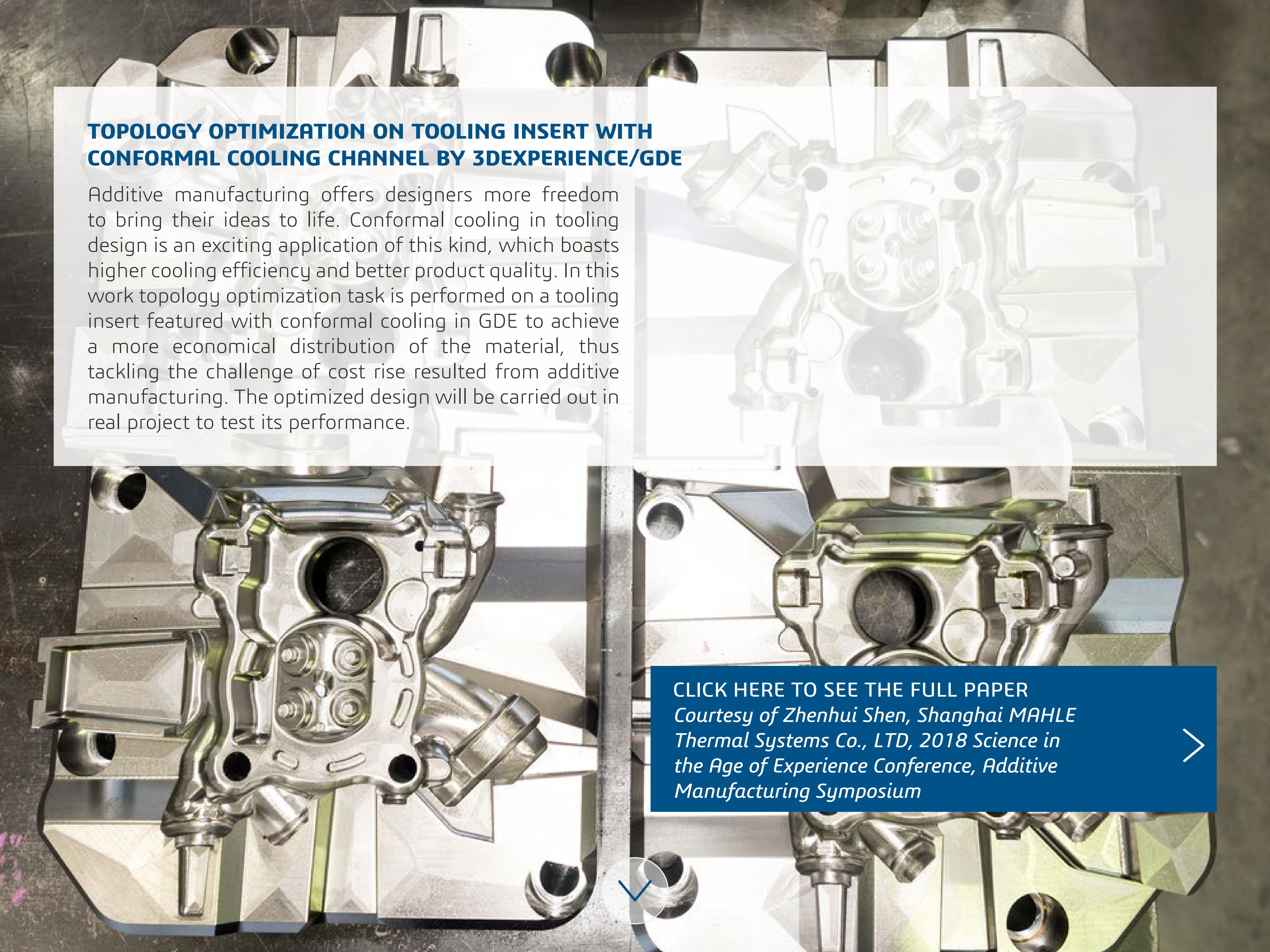
In this paper, we adopt some of the latest technologies developed in the commercial finite element software package - Abaqus - to effectively simulate the Multi Jet Fusion (MJF™) printing process. We first characterize the independent physical events using the event series data; including event time, event location, and material status information. These independent events could be powder material deposition, heating and cooling events or chemical agent deposition events. Abaqus solves for the dependent events such as the powder melting, evolution of cooling surfaces, and material temperature, stress and distortion. Materials and elements are progressively activated according to the powder deposition events. We then use a user defined moving distributed flux subroutine to model multiple moving heat sources. The Abaqus keyword interface and user subroutines are customized to account for different types of moving heating sources and different chemical agent additions. MJF™ uses two functional agents; a fusing agent and a detailing agent during the multipass print process. Once the keyword interface and user subroutines are defined, the cost for modeling different parts and geometries is significantly reduced. This results in significant simplification of modeling effort as well as much shorter simulation time as compared to actual printing time. This makes finite element simulations effective for print process development and functional part production.



CLICK HERE TO SEE THE FULL PAPER
*Finite Element Simulation of the Multi Jet Fusion (MJF™) Process using Abaqus, 2017 Science in the Age of Experience Conference Proceedings*

## TOPOLOGY OPTIMIZATION ON TOOLING INSERT WITH CONFORMAL COOLING CHANNEL BY 3DEXPERIENCE/GDE

Additive manufacturing offers designers more freedom to bring their ideas to life. Conformal cooling in tooling design is an exciting application of this kind, which boasts higher cooling efficiency and better product quality. In this work topology optimization task is performed on a tooling insert featured with conformal cooling in GDE to achieve a more economical distribution of the material, thus tackling the challenge of cost rise resulted from additive manufacturing. The optimized design will be carried out in real project to test its performance.



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*Courtesy of Zhenhui Shen, Shanghai MAHLE Thermal Systems Co., LTD, 2018 Science in the Age of Experience Conference, Additive Manufacturing Symposium*

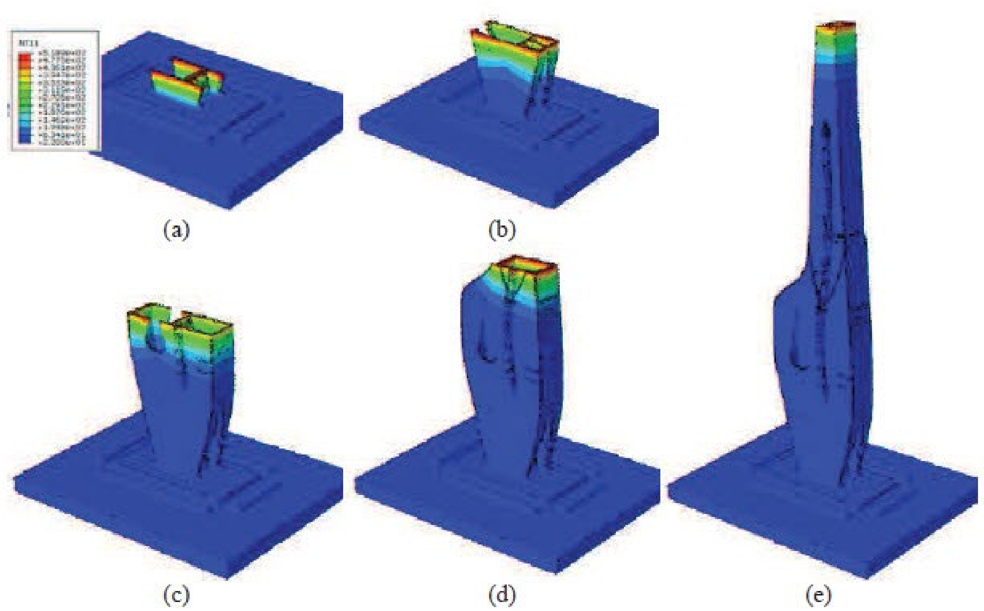
## PREDICTION OF PRINTING FAILURE OF A 3D PRINTED DRONE PROPELLER USING FUSED DEPOSITION MODELING

Fused Deposition Modeling (FDM) is a 3D printing process where thermoplastic materials are deposited layer by layer through an extrusion nozzle. One of the main advantages of an FDM process is that any complex shape geometry can be printed directly from a CAD model. However, the process also shows disadvantages such as air-gap, porosity, weak inter-layer bonding due to thermal gradient, which lead to unwanted print failure at the time out of the machine or under in-service conditions. Therefore, it would be beneficial to model and predict possible print failures early at part and process design stages in order to reduce the scrap rate and decrease product development cycle. In this paper, a drone propeller is used as an example to illustrate the print failure modeling strategy. The commercial finite element software package ABAQUS is used to simulate the FDM printing process and in-service performance of the propeller. In order to analyze the printing process, a heat transfer analysis is done first to predict the temperature history of the part, which drives the stress analysis for distortion and residual stress predictions. The tool path patterns dictate how material is added during the printing and it also have direct influence in the residual stresses in the part. Abaqus uses machine tool path as a direct input and solves the local orthotropic material properties and evolving cooling surfaces using the event series and progressive element activation technologies. With residual stresses and strains mapped from virtual printing simulation, in-service loading is also applied to predict the high stresses and displacements zone, which have higher possibility of failure. The results of the in-service condition of a 3D printed propeller is compared with a non-3D printed propeller, having same material properties and dimensions and in-service conditions. The comparison clearly shows that the 3D printed propeller has more stress all over the propeller body than the non-3D printed one, which make them more prone to breakage.

CLICK HERE TO SEE THE FULL PAPER
*Prediction of Printing Failure of a 3D Printed Drone Propeller using Fused Deposition Modeling, 2018 Science in the Age of Experience Conference Proceedings*

## PROCESS MODELING AND VALIDATION FOR METAL BIG AREA ADDITIVE MANUFACTURING

Metal Big Area Additive Manufacturing (mBAAM) is a new additive manufacturing (AM) technology based on the metal arc welding. 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. Objects are manufactured one layer at a time starting from the base plate. The final properties of the manufactured object are dependent on its geometry and the metal deposition path, in addition to depending on the basic welding process parameters. Computational modeling can be used to accelerate the development of the mBAAM technology as well as a design and optimization tool for the actual manufacturing process. We have developed a finite element method simulation framework for mBAAM using the new features of software ABAQUS. The computational simulation of material deposition with heat transfer is performed first, followed by the structural analysis based on the temperature history for predicting the final deformation and stress state. In this formulation, we assume that two physics phenomena are coupled in only one direction, i.e. the temperatures are driving the deformation and internal stresses, but their feedback on the temperatures is negligible. The experiment instrumentation (measurement types, sensor types, sensor locations, sensor placements, measurement intervals) and the measurements are presented. The temperatures and distortions from the simulations show good correlation with experimental measurements. Ongoing modeling work is also briefly discussed.



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*Process Modeling and Validation for Metal Big Area Additive Manufacturing, 2017 Science in the Age of Experience Conference Proceedings*

## SIMULATION OF RESIDUAL STRESSES AND DISTORTIONS IN A 17-4 PH PART PRODUCED BY LASER POWDER BED FUSION

Mitigation of residual stresses and distortions in additive manufactured parts is of great interest to industry. In this study, an arch-shaped geometry is simulated using the general purpose finite element code Abaqus® in order to predict stresses and distortions for a laser powder bed fusion (LPBF) manufacturing process. A sequential thermal-mechanical coupling is adopted, in which temperatures are predicted first and then used as inputs in the static stress analysis. The printed part is modeled as an elasto-visco-plastic material, whose parameters are estimated using high temperature mechanical measurements from the literature. The layer-by-layer printing process is simulated by progressive element activation in conjunction with a moving heat source. After removal from the build plate, the simulations predict an outward distortion of the arch legs which qualitatively matches experimental observations of a similar geometry.

CLICK HERE TO SEE THE FULL PAPER
*Simulation of Residual Stresses and Distortions in a 17-4 PH Part Produced by Laser Powder Bed Fusion, 2017 Science in the Age of Experience Conference Proceedings*

## SOLUTION FROM LATTICE SIZING OPTIMIZATION TO ADDITIVE MANUFACTURING

Lattice structures bear many desirable characteristics from design standpoints, such as stable designs with large network of structural members, desirable weight characteristics, custom mechanical behavior and porous nature that could facilitate bone and tissue growth on medical implants. To efficiently optimize the structure of lattices, we can use Tosca structure to vary the lattices thickness to reach certain design objectives. However, the radii in Tosca are associated with beams which are not optimal to have a smooth stress transition on connected nodes. Additionally, the optimized results can not be meshed smoothly enough in Abaqus for additive manufacturing. In order to avoid these limitations, we proposed a workflow combining the Tosca structure and Element Free (nTopology) using python scripts. As a demonstration, a bike stem model was created in solid. By meshing it in Abaqus and reconstructing it in Element Free, a basic lattice structure with internal supporting beams was created and imported into Tosca for sizing optimization. Other than Tosca which has radii associated with beams, Element Free has nodal radii. To deal with this difference, the optimization results were converted into nodal radii models in Element Free. Then a STL file was created in Element free based on the converted results. Additionally, a method to design the initial RVE lattice structure using topology optimization was mentioned for those who might be interested. This whole process enabled the additive manufacture on optimized lattices and reduced the design time to one or two hours.

CLICK HERE TO READ THE FULL PAPER
*Solution from Lattice Sizing Optimization to Additive Manufacturing, 2017 Science in the Age of Experience Conference Proceedings*

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