NSRP | National Shipbuilding Research Program

Ship Design and Material Technologies Virtual Panel Meeting

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Simulation Workflow Development for Additive Manufacturing

PTR: Monika Skowronska (NASSCO)
PM: David Najera (ATA Engineering)

ATA Team Introduction

NSRP Simulation Workflow Development for Additive Manufacturing

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Why Use Additive Manufacturing?

How will AM benefit the naval shipbuilding enterprise?

- New production parts with improved quality, innovative design features, domestic sourcing, and reduced cost and lead time
  - Wire-fed DED/friction stir processes for replacement of large, porous castings
  - Powder bed or powder-fed DED for smaller components with fine features
- Maintenance and repair
  - Reverse engineering and replacement of out-of-production or obsolete parts
  - Remote fabrication of replacement parts for improved readiness and $B in parts and logistics cost savings through reduced replacement part inventories

Images Courtesy Lincoln Electric & nTopology

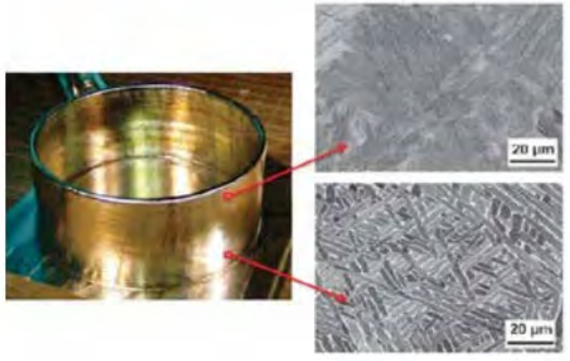
What are The Challenges to AM Implementation?

AM for critical or structural parts is impeded by strenuous seaworthiness requirements

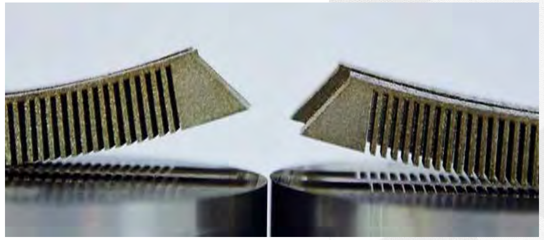
- Certification of critical parts requires detailed understanding of part performance and reliability. **For AM, performance and reliability is driven by the manufacturing process unique to each part**
- Without predictive modeling and simulation tools to understand how part design and print settings impact manufacturing outcomes (porosity, mechanical properties, residual stress, net shape), **design and qualification is more costly than conventional manufacturing**
- AM part design requires trial-and-error studies to establish design and print parameters that result in adequate quality. Studies may need to be repeated for new part geometries/features
- AM part qualification requires exhaustive testing at the feedstock, printer, process, and part levels to form a statistical characterization of all aspects of the part performance and reliability

Parameters → **Process** → **Performance**

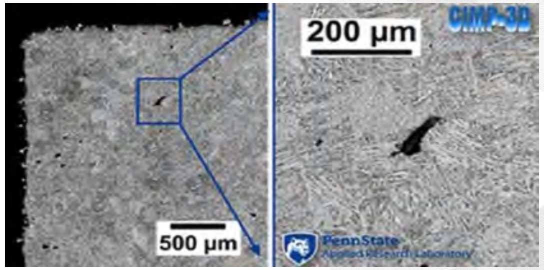
Grain Structure – Mechanical Properties



Residual Stresses – Distortion



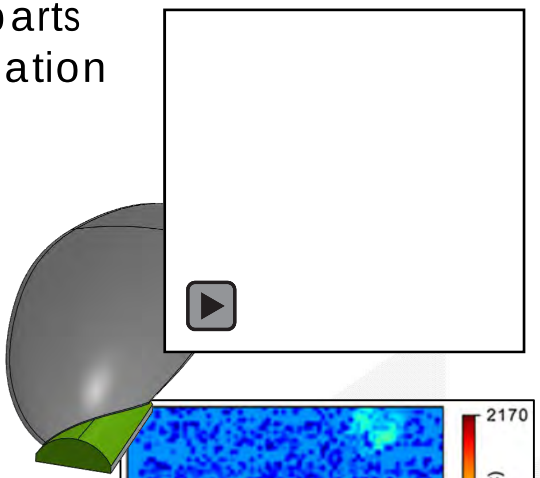
Porosity – Defects

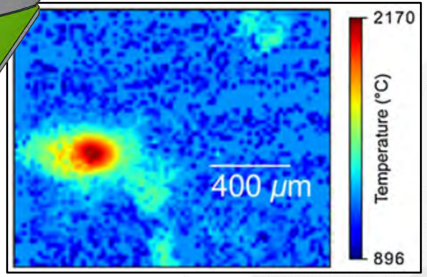


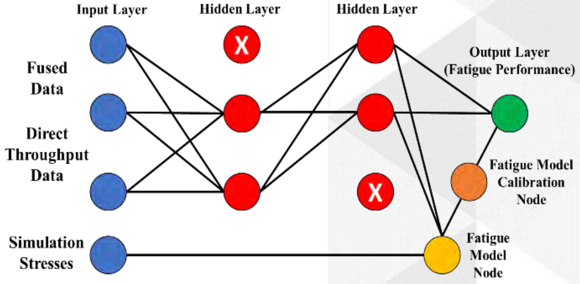
Our Goals for Additive Manufacturing

Develop and provide predictive modeling capabilities to ensure AM parts reliably meet requirements for simulation-supported design and qualification

- In this panel project, ATA has developed **foundational** physics-based modeling capabilities that are readily adaptable to a variety of AM processes and material systems of interest to our commercial and government customers
- In future work, ATA seeks to build upon these simulation capabilities through integration of empirical data and application of machine learning tools to solve major industry challenges and **reduce reliance on trial-and-error prototyping and exhaustive qualification testing**
  - Rapid identification of optimal print process parameters
  - Data-driven models to predict defects and porosity, and subsequent prediction of fatigue life and damage tolerance
  - Characterization and propagation of uncertainty to capture statistical performance of parts
  - Help define the Digital Thread for AM and a minimum viable part data package from a solution-driven perspective
  - Use in modeling a variety of AM processes and alloys

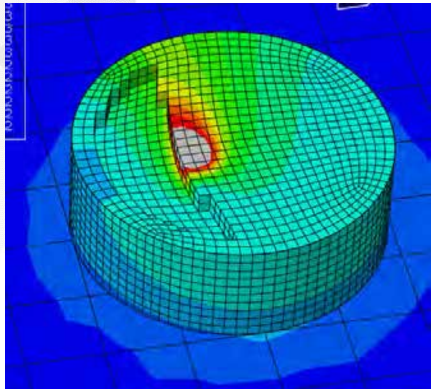




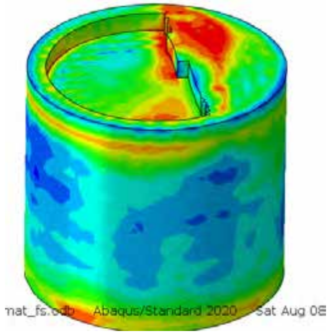


Project Outcomes

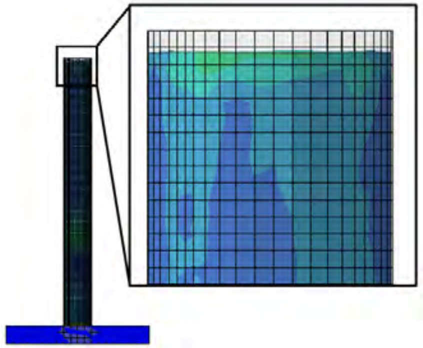
An integrated workflow that leverages validated simulation tools to characterize part temperature history, residual stress, net shape, microstructure, and resulting mechanical properties for LENS printing of 316L parts



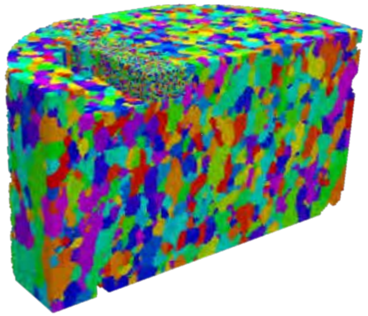
Thermal Simulations (Abaqus)



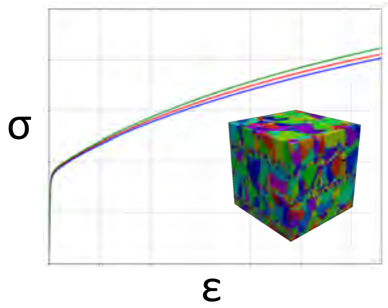
Residual Stress Prediction (Abaqus)



Net Shape Prediction (Abaqus)



Microstructure Evolution (SPPARKS)



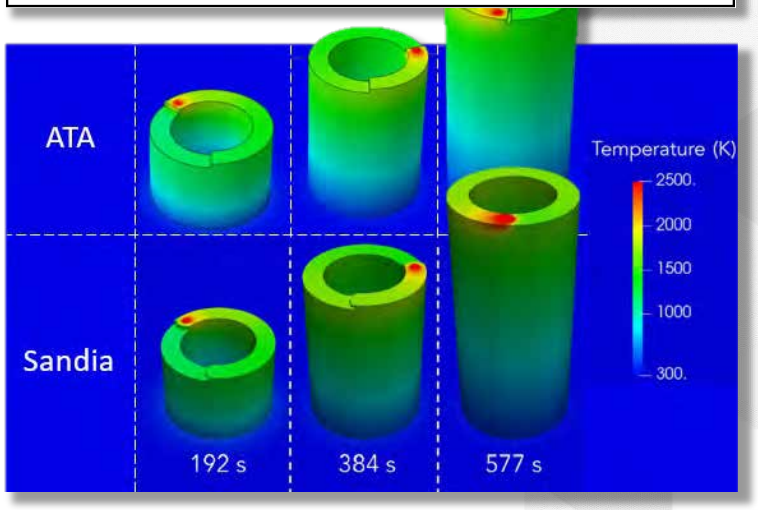
RVE Mechanical Response (DAMASK)

Part-Level FEM with As-Built Residual Stress, Net Shape, and Mechanical Properties (Abaqus)

Additive Manufacturing Process Modeling Strategy

Sequentially coupled thermomechanical simulations

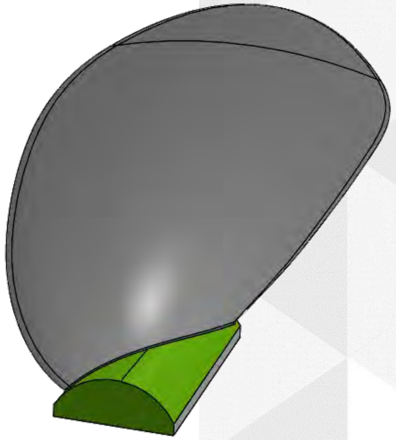
- **Process parameter inputs:**
  - Laser speed, laser power, heat source shape & size, and print path
- **Thermal simulation:**
  - A thermal simulation is performed in Abaqus by solving the heat transfer equations.
  - The material deposition is simulated by activating elements following the prescribed print path.
  - The output is the thermal time history of each element in the FEM.
- **Mechanical simulation:**
  - A mechanical simulation is performed in Abaqus by solving the static equilibrium equations.
  - The mechanical simulation takes the thermal time history as input and solves for the displacements in each element.
  - Given a temperature-dependent material model, the stresses & strains are computed for the entire part.
- **Initial work validated against Sandia high-fidelity simulations**



Process Modeling Approach Pros & Cons

Direct simulation of heat transfer on part geometry

- For a powder-fed DED process where the melt-pool size (2-3mm) is usually reasonable compared to the part size, we decided to directly simulate deposition heat transfer on part geometry.
- **Pros – Accuracy:** Competing tools use lower-fidelity methods
  - Layer agglomeration: deposition heating is applied layer-by-layer onto a part geometry, losing effects on print path definition on local heat build-up
  - Breakout models: heat transfer from a laser track is simulated on a semi-infinite volume, losing effects of part geometry and boundary conditions, e.g. printing on part edges
- **Con – Computation Cost:** Thermal simulations can take one week for even small parts.
  - Heat transfer simulations directly on part geometry will be intractable for smaller-scale AM processes, like powder-bed fusion, or for large-scale parts without implementation of some cost reduction strategy.
  - We have some ideas...



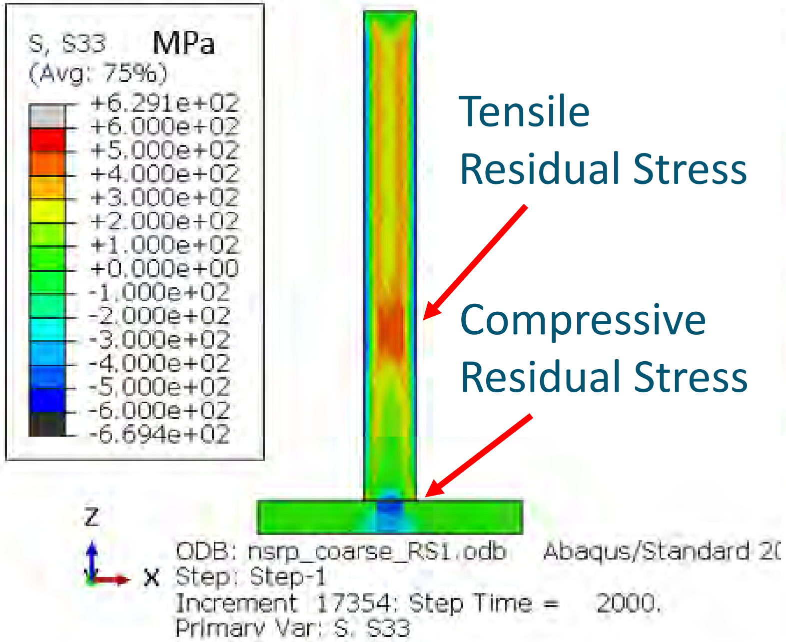
Accurate Prediction of Temperature History is Necessary to Predict Part Performance

Differences in AM Process Impact Temperature History and Residual Stress

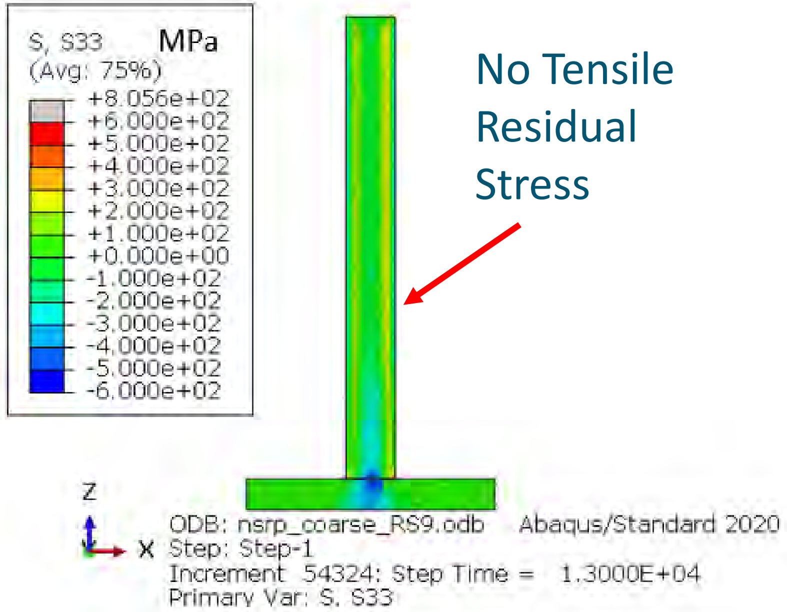
Thermal Simulation

Structural Simulation: Final Residual Stresses

Printing of One Cylinder (Continuous Deposition)



Printing of Nine Cylinders (Delay Between Layers)

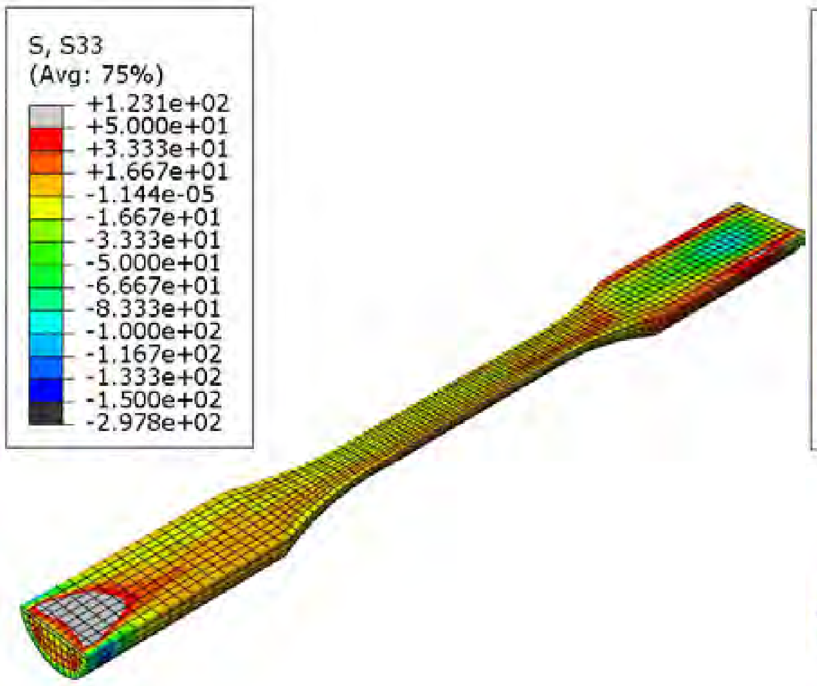


Residual Stress Differences Between Single and Nine Cylinder Configurations

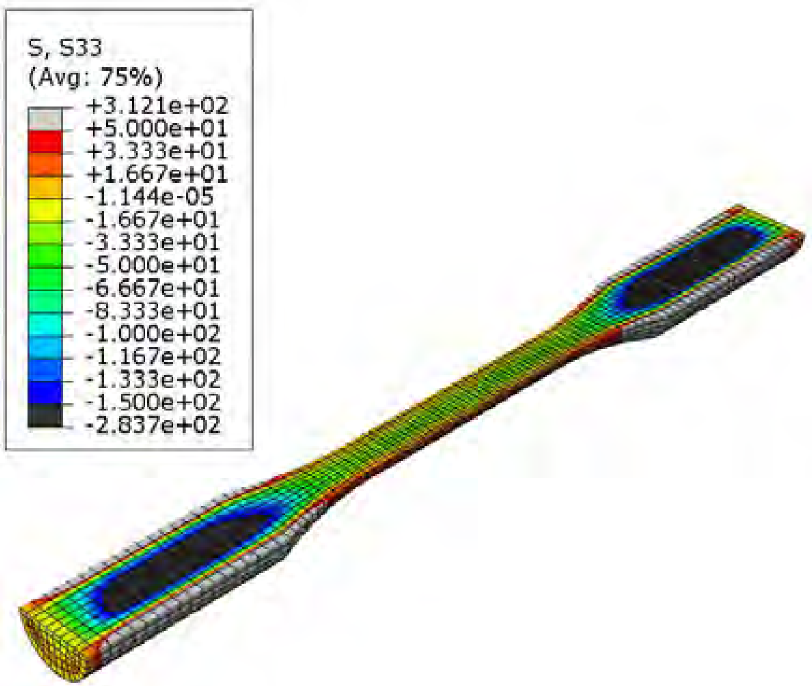
Residual stress prediction post-machining of as-built tensile specimens

Observations:
The (A) cylinders have tensile stresses primarily, while the (B) cylinders have low tensile, or high compressive stresses. This difference effectively shifts the yield strength of the coupon, highlighting the important effect that residual stresses have on *apparent* strength.

A. Single cylinder



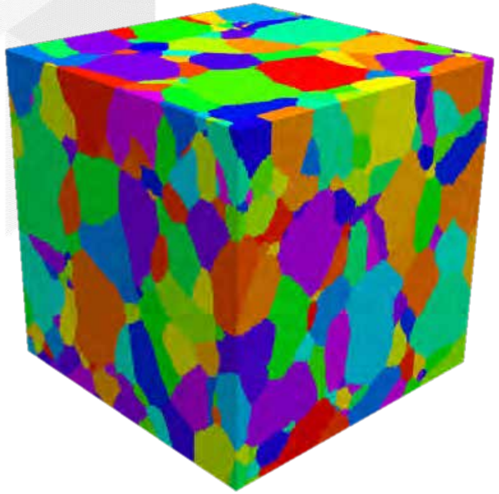
B. Nine cylinder



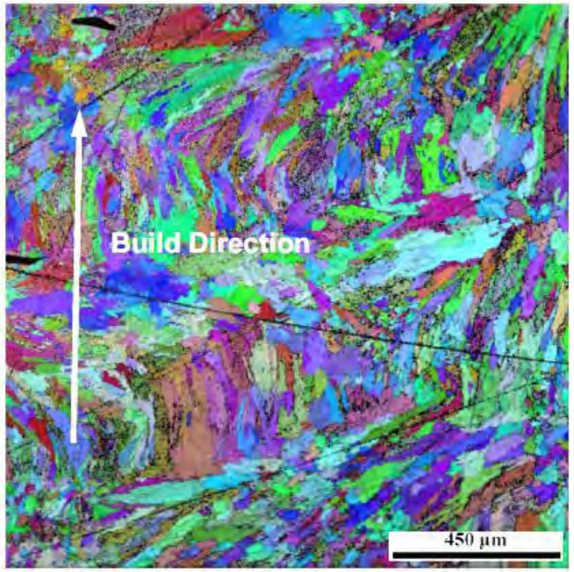
Accurate Prediction of Temperature History is Necessary to Predict Part Properties

Predicted differences in layer boundaries and grain morphologies are qualitatively similar to EBSD

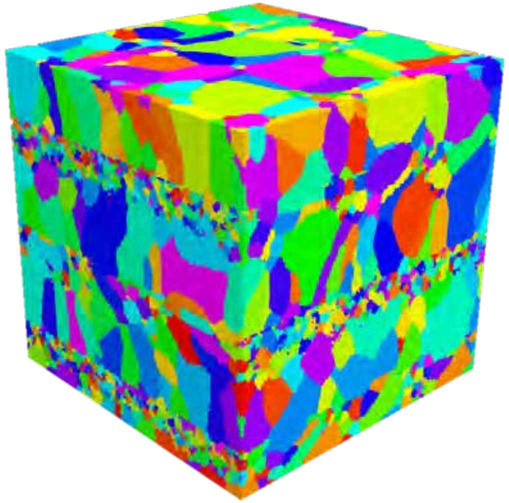
Single-Build Cylinder

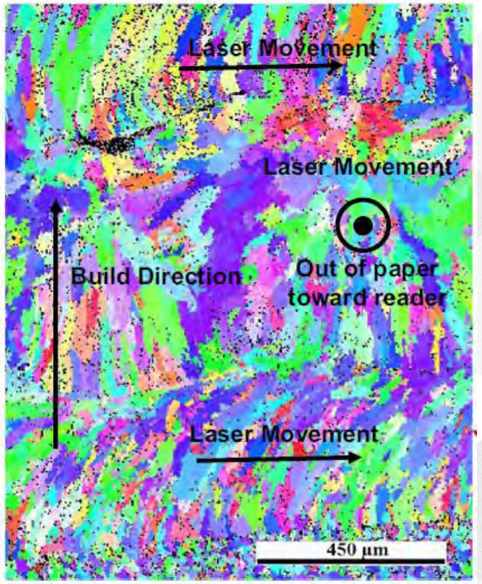


Representative volume element (RVE)



Nine-Build Cylinder

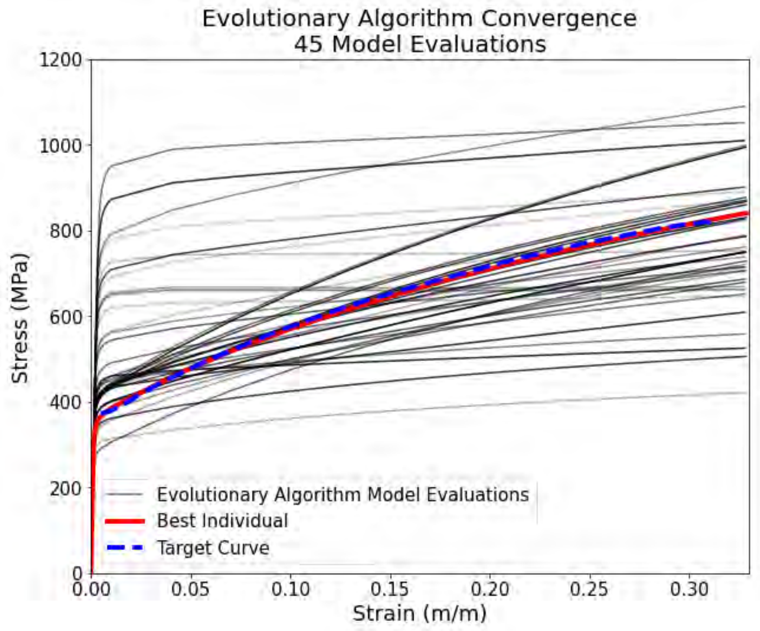




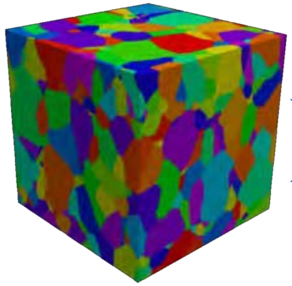
Derivation of Spatially-Varying Mechanical Properties

An Evolutionary Algorithm is used to find crystal plasticity simulation model parameters to match test data

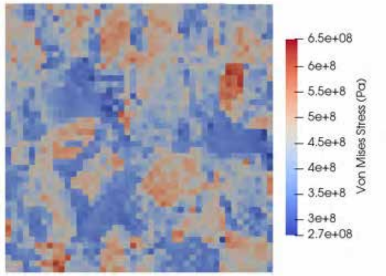
- Microstructure results from SPPARKS are automatically fed to the DAMASK crystal plasticity solver to calculate nonlinear anisotropic mechanical properties
- ATA developed an Evolutionary Algorithm to calibrate crystal plasticity parameters to fit experimental test data from heat-treated stress-strain response from Yadollahi et al.
- Model evaluations were carried out using DAMASK by solving for the deformation gradient response of an equiaxial, untextured RVE with the respective material model parameters
- The automated algorithm converged on a solution after only 45 model evaluations with a total run-time of just under 7 hours
- Results are automatically translated to Abaqus material models and mapped to associated part microstructure regions



Microstructure Topology

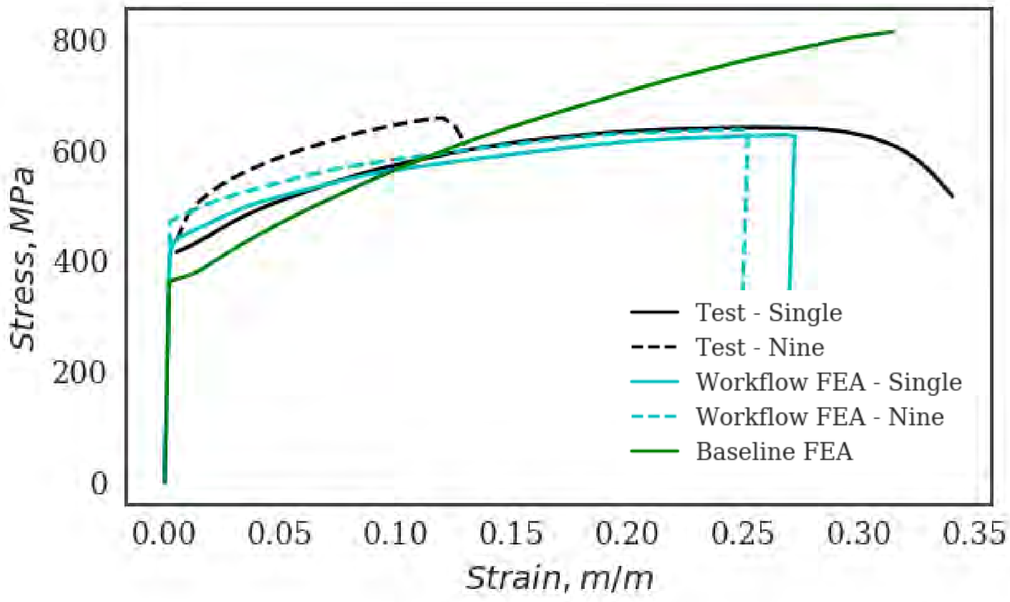


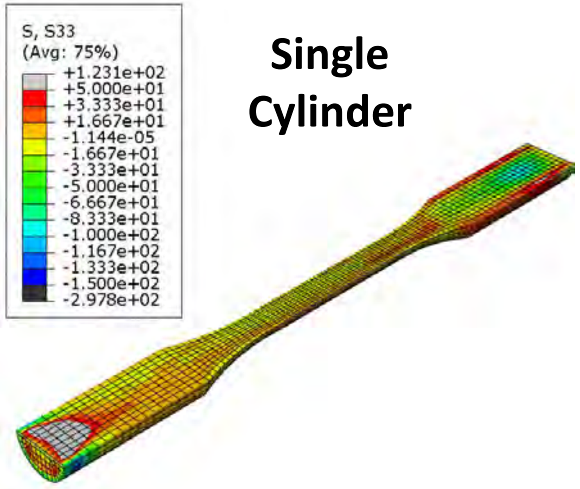
Stress-Strain Response Under Applied Tractions

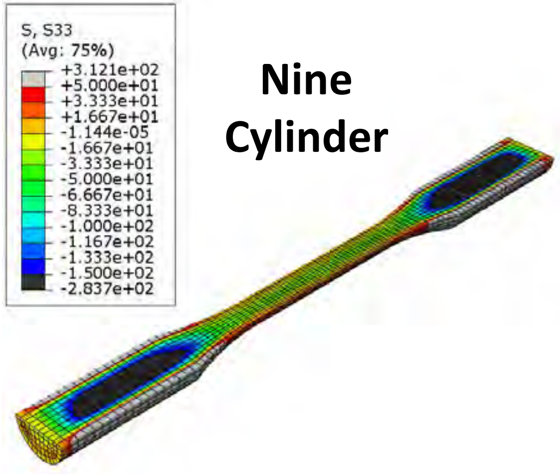


The Workflow Results in Significant Improvement Over Baseline Approaches in Predicting Response & Strength

Additional IRAD efforts are ongoing for improved robustness and accuracy







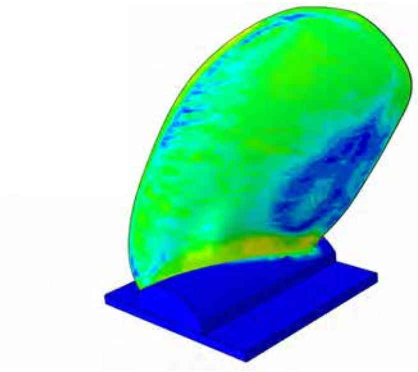
Main Takeaways

- **Accurate residual stress prediction is critical for yield strength and hardening modulus prediction.**
- **Ultimate strain is driven by microstructure mechanisms that our models are still unable to consider. More work is needed to refine crystal plasticity models and improve the existing models.**
- **Our existing modeling approach captured general trends, such as the difference in yield strength, and higher ductility in the single-cylinder case, as well as yield strength, hardening modulus, and ultimate strength for the single-cylinder case.**

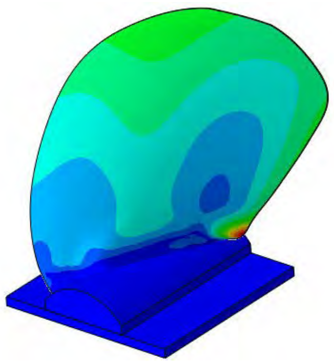
ModSim Workflow Applied to Representative Part Geometry

Selection of similar process parameters creates similar part thermal histories, allowing reuse of calculated microstructure properties, thereby saving cost and schedule for evaluation of new part geometries

Thermal Simulations

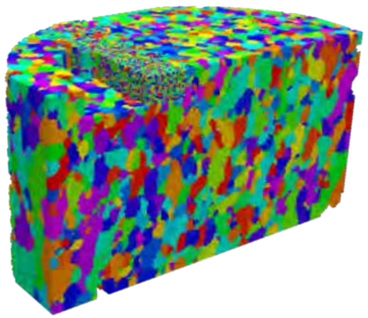


Residual Stress Prediction (Abaqus)

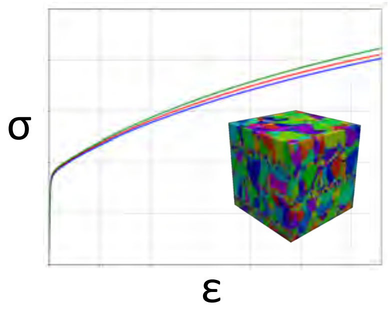


Max deformation on the order of blade thickness

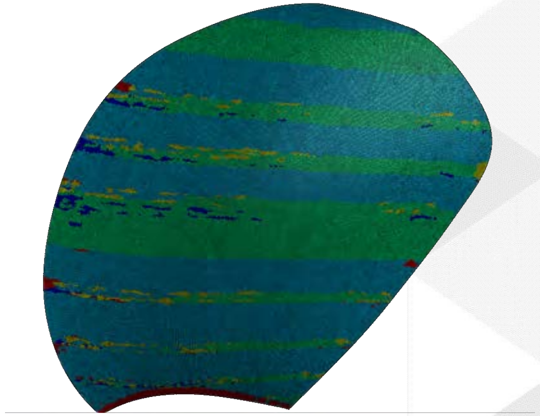
Net Shape Prediction (Abaqus)



Microstructure Evolution (SPPARKS)

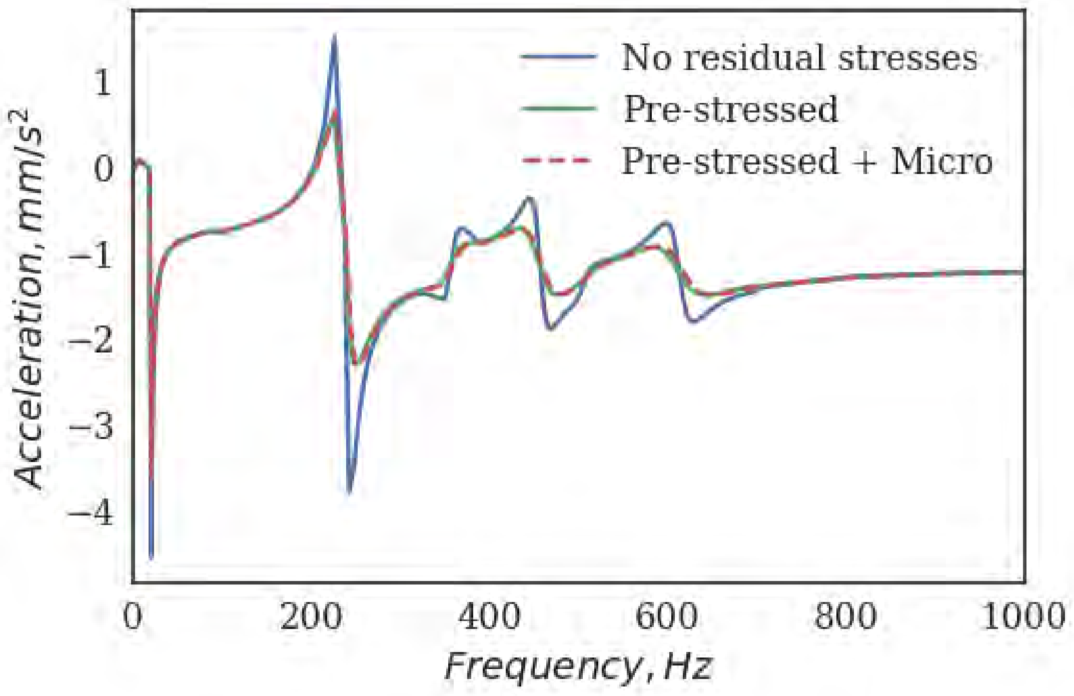


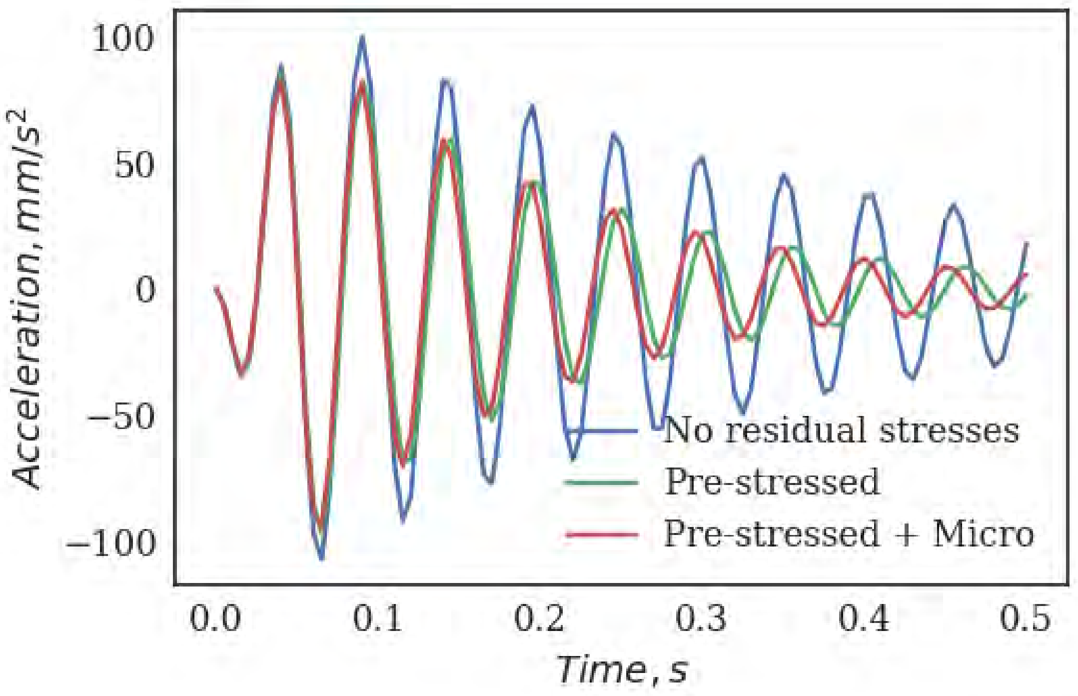
RVE Mechanical Response (DAMASK)



Part-Level FEM with As-Built Residual Stress, Net Shape, and Mechanical Properties (Abaqus)

Effect of Residual Stresses and Microstructure on Structural Dynamic Performance of Blade Response

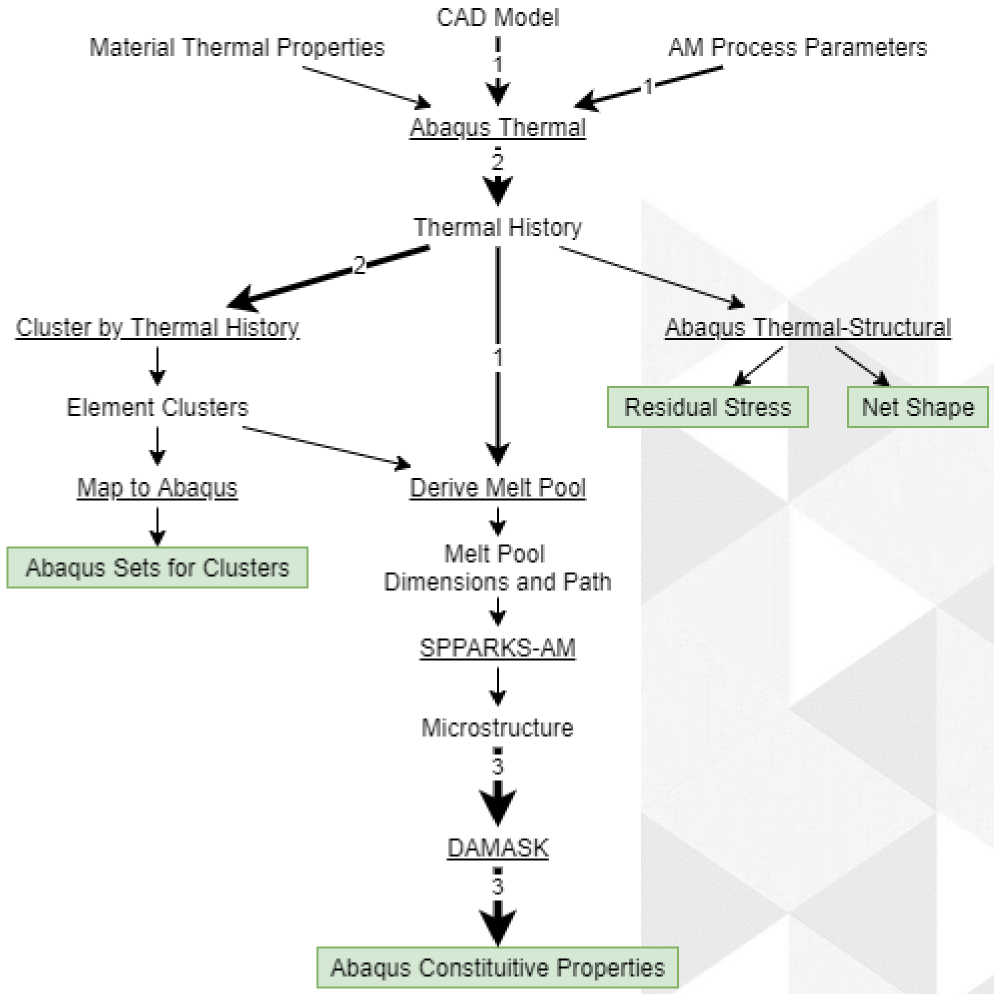




Differences in response between pre-stressed and unstressed model are due to slight shifts in natural frequency, and increased damping ratio due to plastic response.

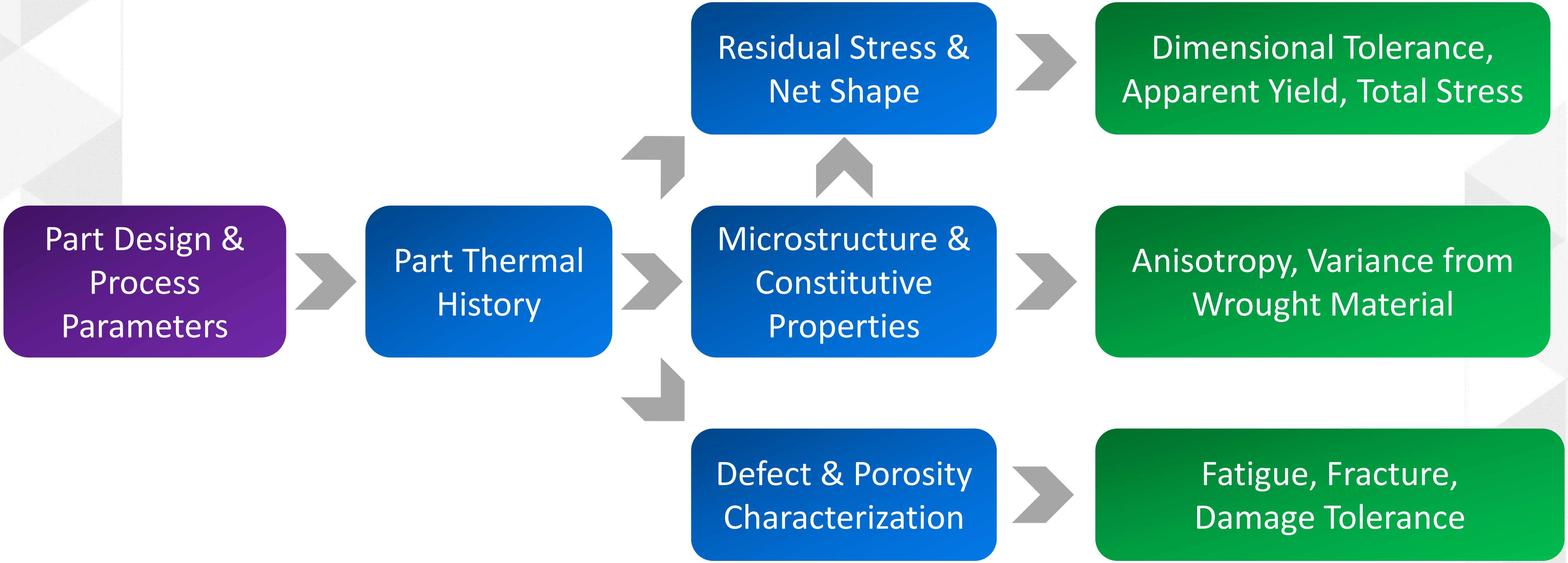
The AM Modeling and Simulation Workflow Integrates a Set of Diverse Tools Through Automating Scripts

- ATA has integrated a set of state-of-the-art tools from diverse pedigrees to provide a comprehensive AM part characterization workflow.
- ATA has streamlined and automated much of the workflow through Python scripts
- Use of the workflow currently requires background expertise because of the different codes involved, each having different technical pre-requisites. ATA plans to improve the workflow through graphical user interfaces in the future.



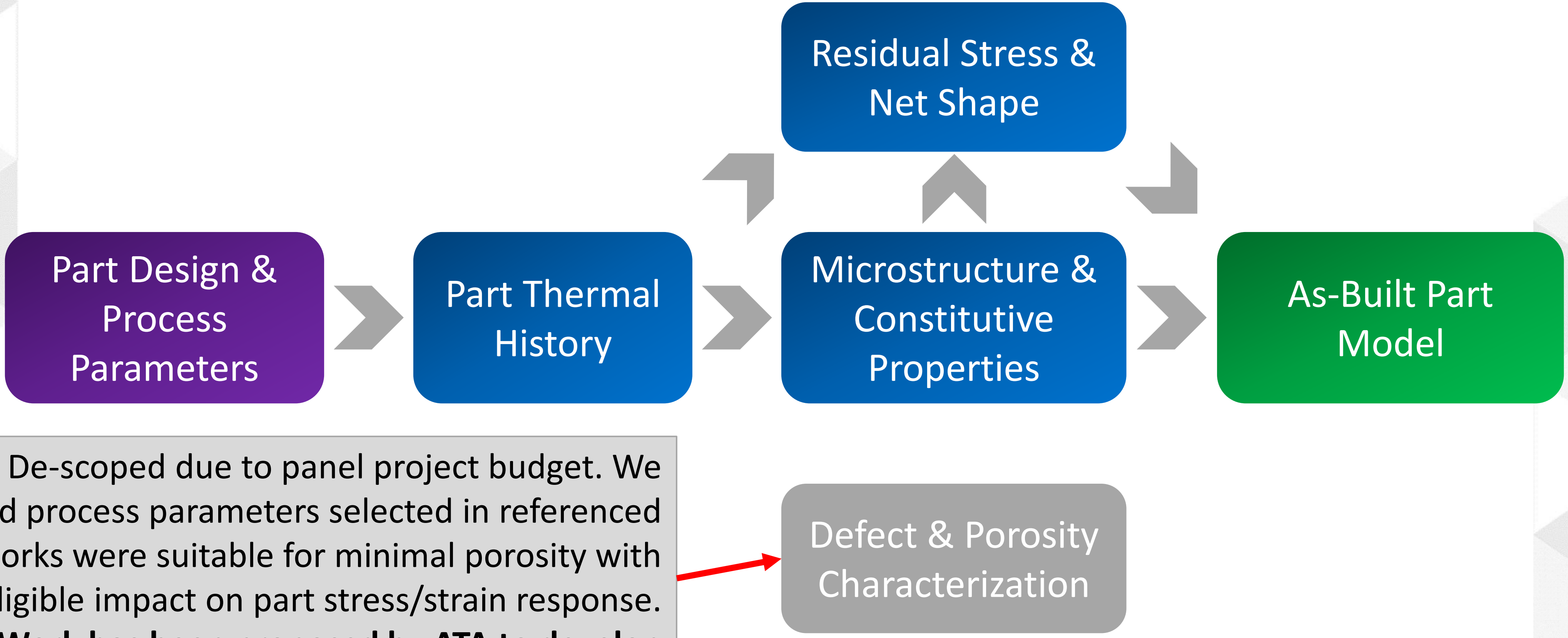
How Do These Tools Fit Into The Big Picture?

The process physics in blue must be addressed at some level of detail in order to characterize AM processes and predict performance of an as-built part



Process Physics for AM Modeling & Simulation

The developed toolset for prediction of as-built part mechanical response and strength captures the highlighted process physics



De-scoped due to panel project budget. We assumed process parameters selected in referenced works were suitable for minimal porosity with negligible impact on part stress/strain response. **Work has been proposed by ATA to develop capabilities to predict porosity and part fatigue life**

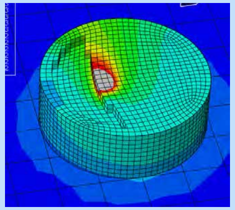
Workflow Cost Analysis

Summary of the labor and computation cost, and computing specs, for each aspect of ATA's workflow for cylinder characterization

Part Design & Process Parameters

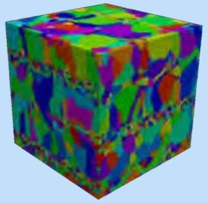
Part Thermal History

Abaqus
Cores: 4
Labor: 16 hr
CPU: 1 week

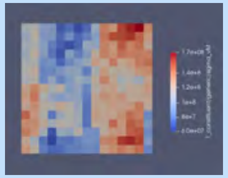


Microstructure & Constitutive Properties

SPPARKS
Cores: 1
Labor: 3 hr/RVE
CPU: 1-2 weeks

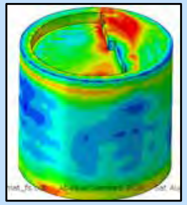


DAMASK
Cores: 2
Labor: 0 (scripted)
CPU: 30 min/RVE



Residual Stress & Net Shape

Abaqus
Cores: 4
Labor: 16 hr
CPU: 2 weeks



As-Built Part Model

Abaqus
Results Mapping
Labor: 0

Total Cost
Labor: ~ 50 hours
CPU: ~ 6 weeks (desktop)

Project Innovations

Several aspects of the workflow developed by ATA improve upon state-of-the-art offerings from major CAE software vendors and AM-focused software vendors

- **Automated translation of data across simulation tools** with Python scripting offers a uniquely capable modular, yet integrated multiscale simulation framework. Underlying tools have been developed by experts and validated for their purpose.
- **An open modeling architecture** with no reliance on proprietary "black box" algorithms or data fitting. Users have access to physics and material models for calibration with empirical data, implementation of alternative approaches, or extensibility to other materials and AM processes
- **Results are embodied in a part Digital Twin FEM** representing the as-built residual stress state, microstructure, and mechanical properties. This Digital Twin model is suitable for simulation of testing or operational loading. Most AM simulation software offers piecemeal analysis results with no way to apply insights any further.

Project Insights

Models developed by ATA incorporate lessons learned from AM process simulations

- Establishment of modeling best practices for part-level and microscale models through mesh sensitivity and other studies
- Validation of 316L metallurgical models through comparison of results to national laboratory simulations with heritage models
- Establishment of microstructure model parameter settings through research and discussion with developers
- Development of workflow cost reduction approaches through implementation of novel multiscale modeling algorithms
- Technical Transfer done at the end of the project through Virtual Workshop open to NSRP community (January 2021)

Capabilities Offered

Outcomes achieved under $150k NSRP panel project funding

- The developed workflow connects parameters to performance by predicting as-built part mechanical response based on part geometry, path definition, and print parameter selection for powder-fed DED/LENS 316L builds
- ATA can support you in applying this framework to your part designs and processes of interest to reduce trial-and-error prototyping and testing efforts to save cost and schedule in achieving designs that meet structural requirements

What's Next?

Expansion of capabilities prioritized based upon needs of funding agencies

- Expanded experimental validation of current capabilities
- Expansion of capabilities to include other materials and AM processes
- Data-driven hybrid models with machine learning (ML) for probabilistic prediction of defects and porosity based on parameter selection, simulated thermal history, and empirical data
- Prediction of fatigue and damage tolerance of as-built AM parts
- Workflow cost reductions through multi-scale physics modeling approaches
- Implementation of ML tools for rapid parameter optimization
  - Thermal simulations with Gaussian Process regression models (1 week → 30 sec)
  - Microstructure simulations with variational autoencoders (1-2 weeks → 30 sec)
- Data fusion and incorporation of empirical data with statistics, including retention of pedigree metadata, into the modeling workflow in support of simulation-augmented part qualification efforts

What’s Next?

ATA’s Ultimate Goal is to Help Reduce Design Costs and Streamline Qualification

- ATA is actively seeking opportunities to continue development of key capabilities for our customers
  - Continued support of the NSRP community
  - DoD OTA contracting available to government customers through the NSTIC consortium out of NSWC-Dahlgren
  - DoD/NASA SBIR/STTR programs
  - America Makes
- ATA seeks to work with expert partners in manufacturing processes and empirical test methods to validate our models and enhance our capabilities with data-driven modeling approaches that enable reduced reliance on thermomechanical testing for part qualification
- ATA eagerly seeks to support development of AM parts across the Navy enterprise, and we will keep our partners apprised of future capabilities enhancements

How Can We Help?

- If you are pursuing additive manufacturing of parts for your systems, we want to help.
  - Contact: Elliot Haag – elliot.haag@ata-e.com

- These simulation tools are adaptable and extensible to customer needs
- We want feedback on your AM priorities, and what capabilities you would need to see before these tools could be applied to your AM initiatives to help us prioritize our development focus
- ATA's business is built around providing solutions to our defense customers' toughest engineering challenges

Thank You!

Acknowledgment of Supporters

- NSRP PTR and Contracts Lead
  - Monika Skowronska and Nick Laney
- Shipyard and NAVSEA partners

GENERAL DYNAMICS
Bath Iron Works

Ingalls Shipbuilding

Newport News Shipbuilding

NAVSEA
NAVAL SEA SYSTEMS COMMAND

- NSRP SDMT and BT panel members for supporting pursuit of this panel project