Ship Design and Material Technologies Virtual Panel Meeting

Simulation Workflow Development for Additive Manufacturing

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

Project Participants

- ATA Engineering
  - David Najera (PM)
  - Dr. Marc Russell, Tommy Board, Eoghan O’Neill, Johnathan Tran, Doug Melville
  - Elliot Haag
- General Dynamics – Bath Iron Works
  - Paul Franklin
- Ingalls Shipbuilding
  - Conlan Hsu
- Newport News Shipbuilding
  - Dan Hebert
- NAVSEA 05T
  - Dr. Justin M Rettaliata
- NSRP Technical Representative: Nick Laney (ATI)
- Program Technical Representative: Monika Skowronska (NASSCO)

Project Benefits

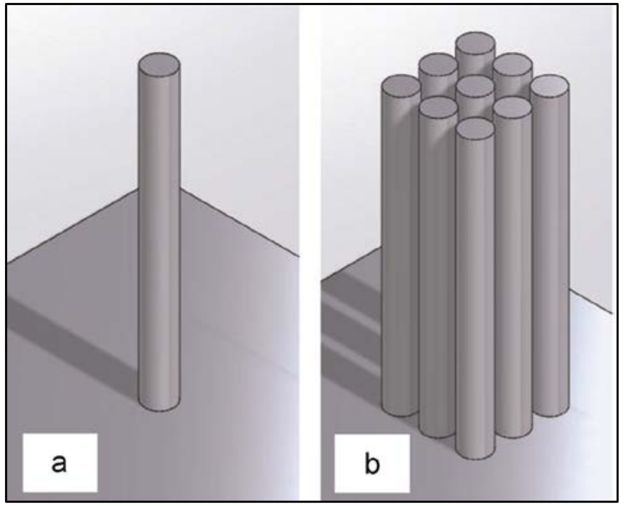
- **Better Design:** Prediction of high-stress or high-deformation regions of AM parts through simulation creates opportunities to improve processes before printing and reduce wasted schedule and cost from current trial-and-error approaches.
- **Better Simulation:** Assignment of varying part mechanical properties based on the AM process and inclusion of the residual stress state will offer more accurate predictions of part response and failure for critical, load-bearing AM parts.
- **Smarter Qualification:** Establishing this physics-based simulation workflow for material, process, and part characterization is a foundational capability. When combined with experimental data in a hybrid modeling approach, a statistical characterization of processes and parts can be created that will enable streamlining of qualification processes.

Project Overview

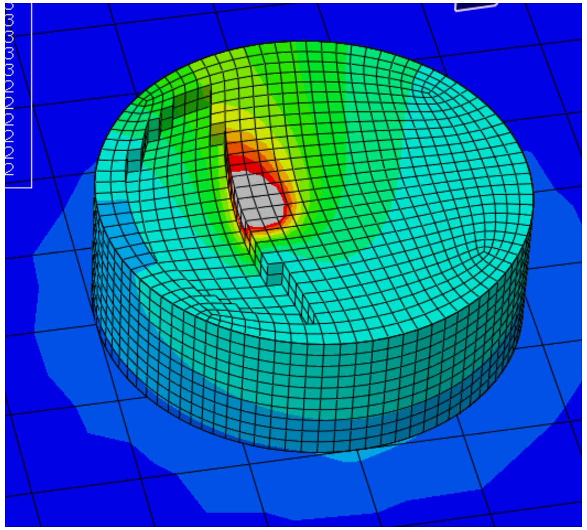
- ATA is building a simulation framework to predict the performance of an additively manufactured (AM) part given its manufacturing process history.
- In this project we will demonstrate the capability to:
  - Simulate the manufacturing process to predict residual stresses and deformations
  - Predict microstructure formation based on the part thermal history experienced during manufacturing
  - Obtain continuum-level nonlinear constitutive models (modulus, Poisson ratio, etc.) based on microstructure features
  - Generate efficient physics-based models that can be used in part-scale simulations
- Project Duration: 1/2020 to 1/2021

Framework Validation & Verification

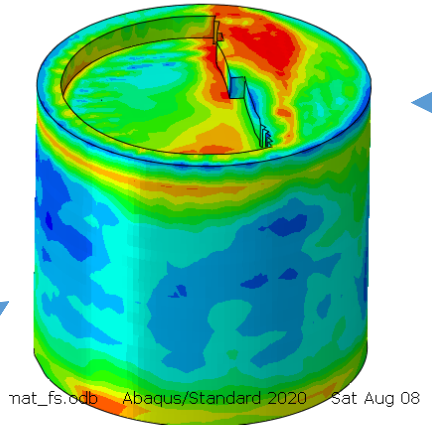
- The modeling & simulation (ModSim) framework will be demonstrated by replicating published test data.
- Part selected from academic work of Yadollahi et al.:
  - "Effects of process time interval and heat treatment on the mechanical and microstructural properties of direct laser deposited 316L stainless steel"
- Summary:
  - Investigated effects of processing time and heat-treatment on part properties
  - Cylindrical specimen geometry
    - Length=75mm, Diameter=8mm
  - Three unique specimen sets:
    - (1) single printed (10s per layer)
    - (2) 3x3 grid of cylinders printed in parallel (90s delay between layers)
    - (3) sub-set of single print cylinders with post print heat treatment
- Attributes:
  - NSRP-relevant material system and process
  - Available experimental data for simulation validation
  - Unique comparison of thermal history variation
  - Availability of data in a public format



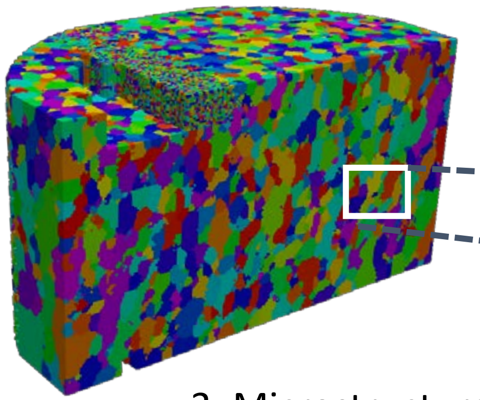
Project Overview: Roadmap for AM Material Characterization



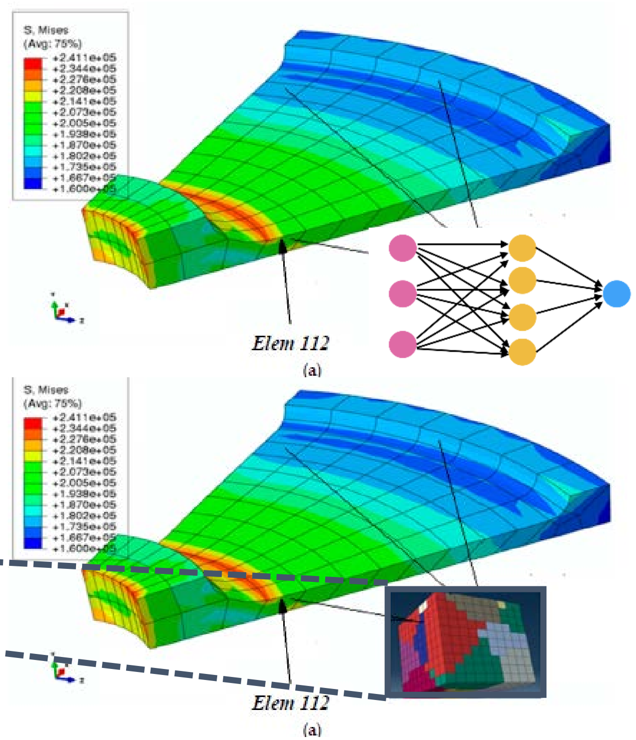
1. Manufacturing Process Simulation



2. Residual Stresses
5. Residual Strains



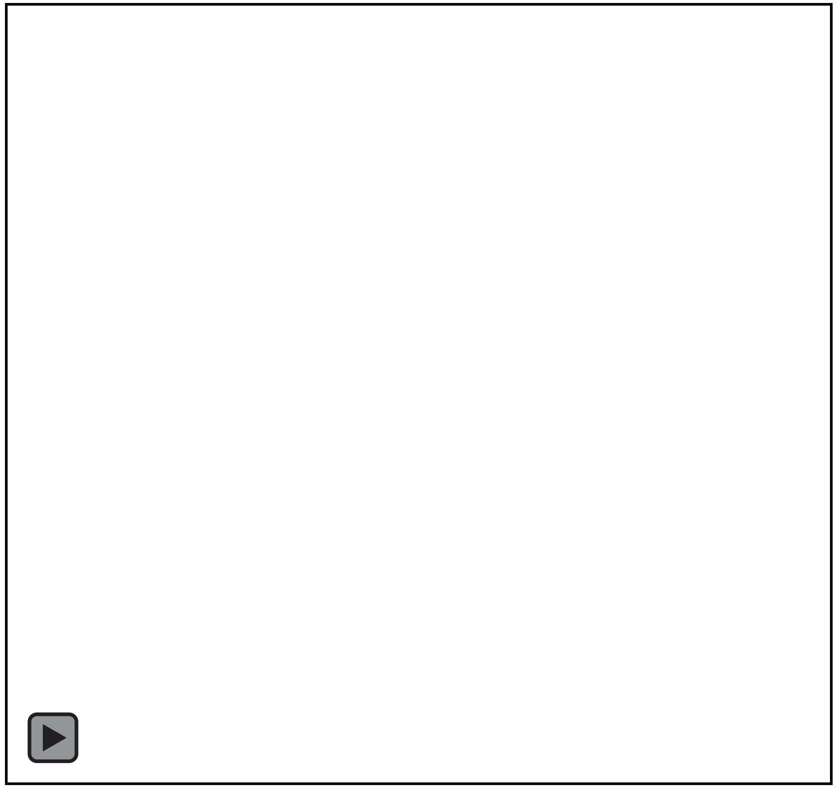
3. Microstructure Prediction



4. Mechanical Property Assignment

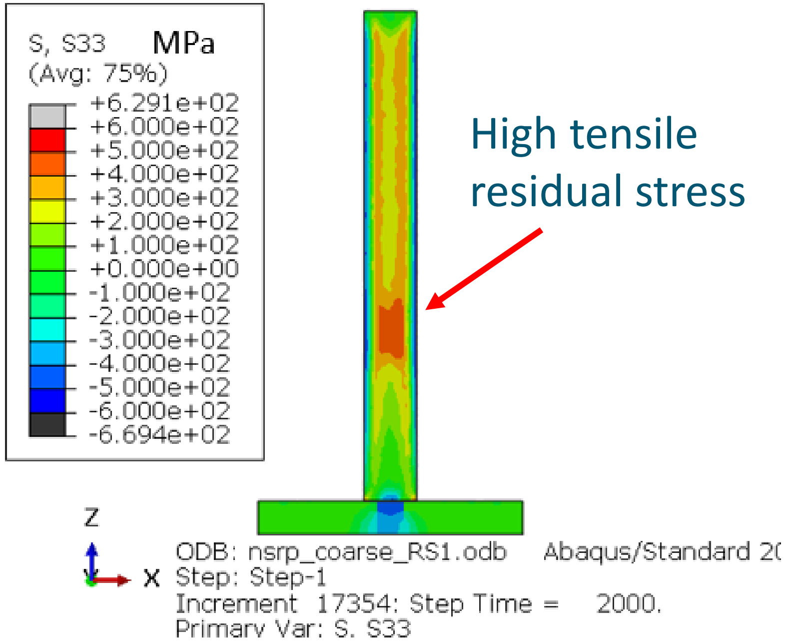
1. Simulation of Additive Manufacturing Process

Thermal Simulation

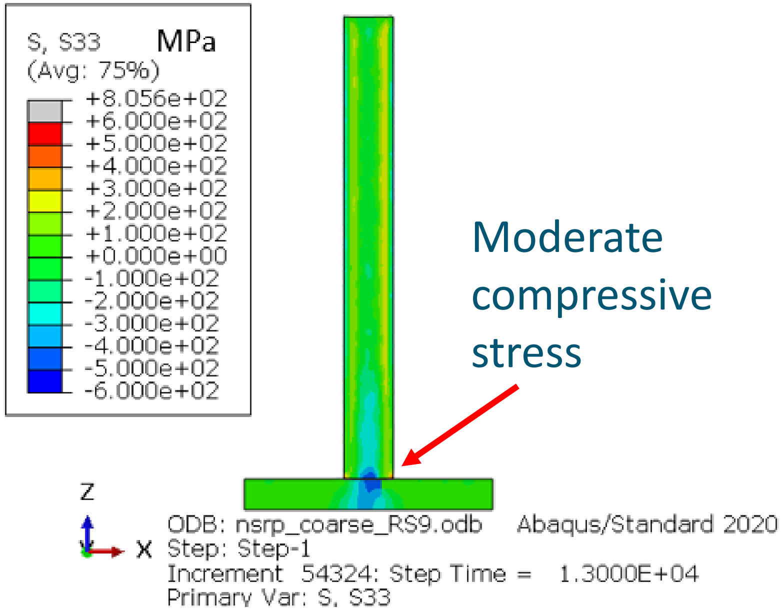


Structural Simulation: Final Residual Stresses

Single Cylinder Printing



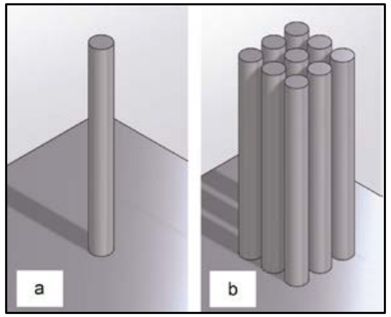
Nine Cylinder Printing



The manufacturing process thermal history and resulting residual stresses are computed with Abaqus

2. Microstructure Prediction

- Microstructure prediction performed with SPPARKS
- SPPARKS: Open-source code developed by Sandia for simulating microstructure evolution
- Kinetic Monte Carlo based algorithm which uses thermal history and material parameters to simulate grain growth



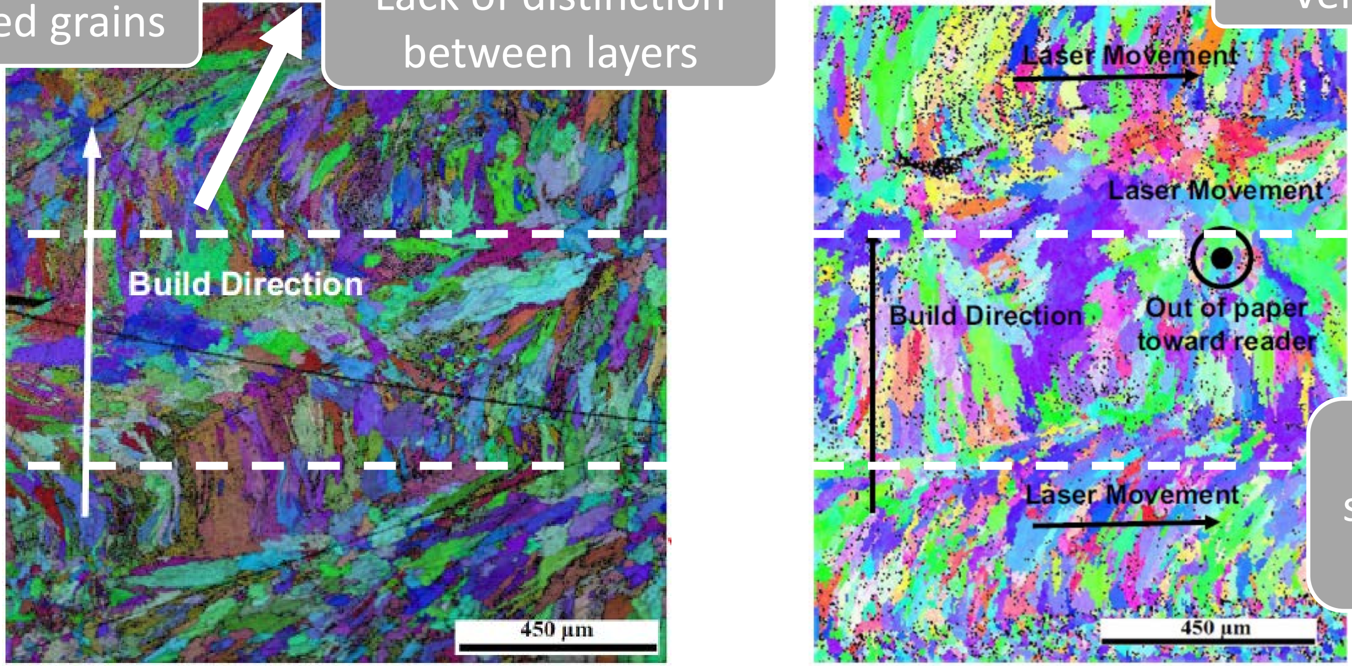
A. Single cylinder

B. Nine cylinder

Angled grains

Lack of distinction between layers

Very distinct layers



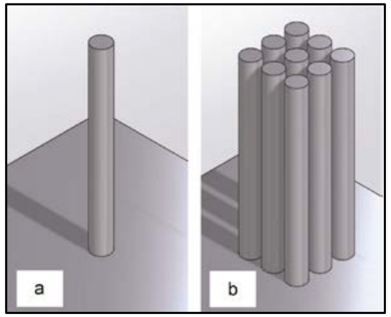
Transition from smaller to larger grains

Electron Backscatter Diffraction Scans

Microstructure is predicted based on the computed thermal history from the manufacturing simulation.

2. Microstructure Prediction

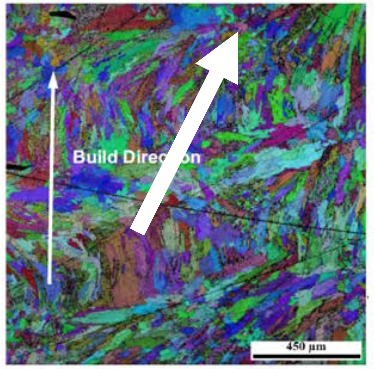
- Microstructure prediction performed with SPPARKS
- SPPARKS: Open-source code developed by Sandia for simulating microstructure evolution
- Kinetic Monte Carlo based algorithm which uses thermal history and material parameters to simulate grain growth

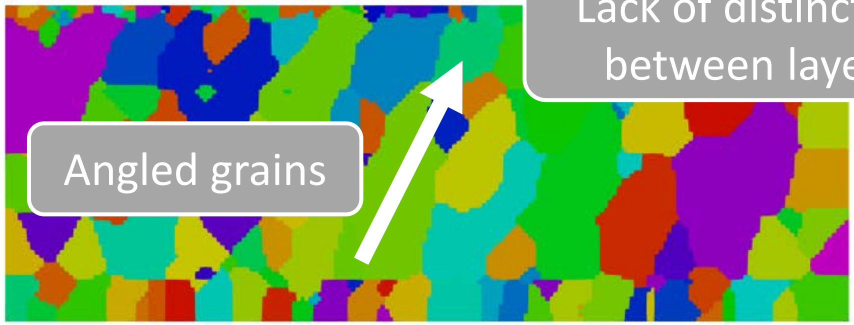


Test Inspection

Numerical Predictions

A. Single cylinder

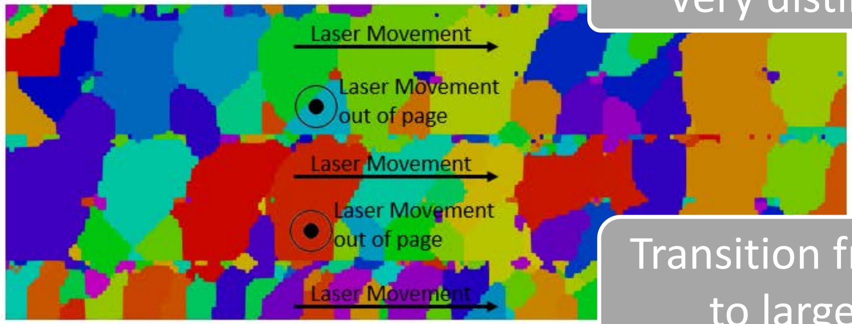




Lack of distinction between layers

Angled grains

B. Nine cylinder



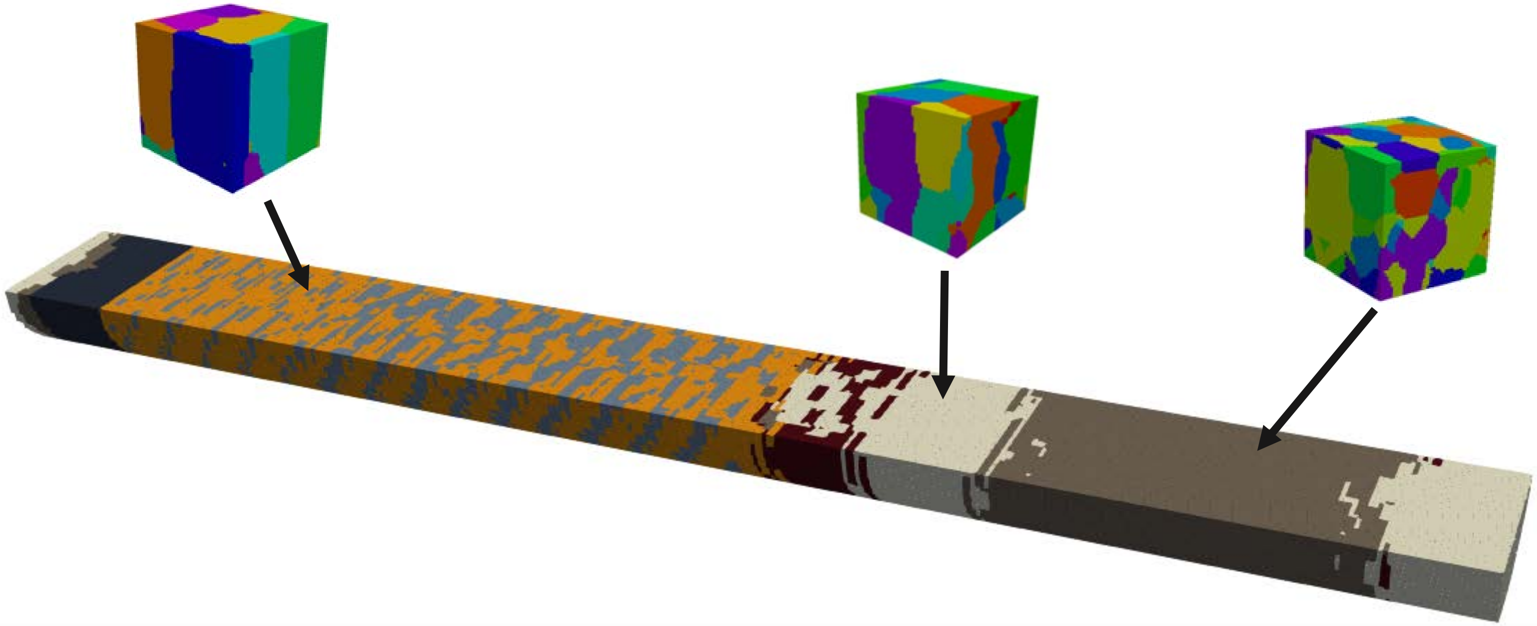
Very distinct layers

Transition from smaller to larger grains

Microstructure is predicted based on the computed thermal history from the manufacturing simulation.

2. Microstructure Prediction - Clustering

- The cylinders are partitioned into six distinct clusters based on the thermal history at each element. Each cluster represents a grouping of material with similar microstructure.

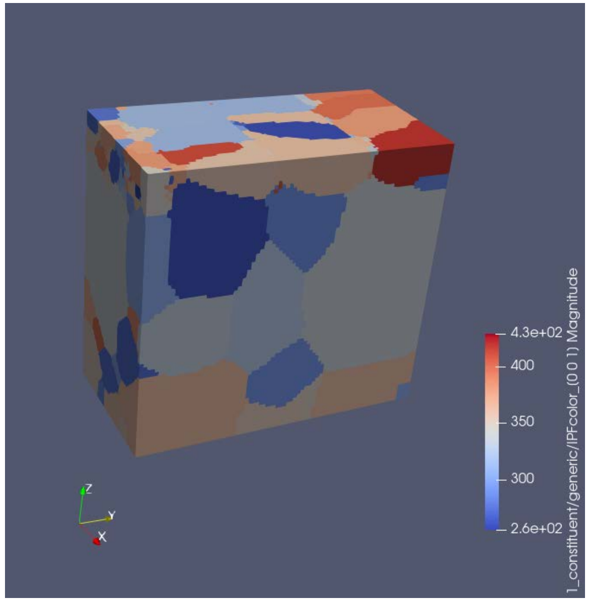


*Only cylinder (A) is shown

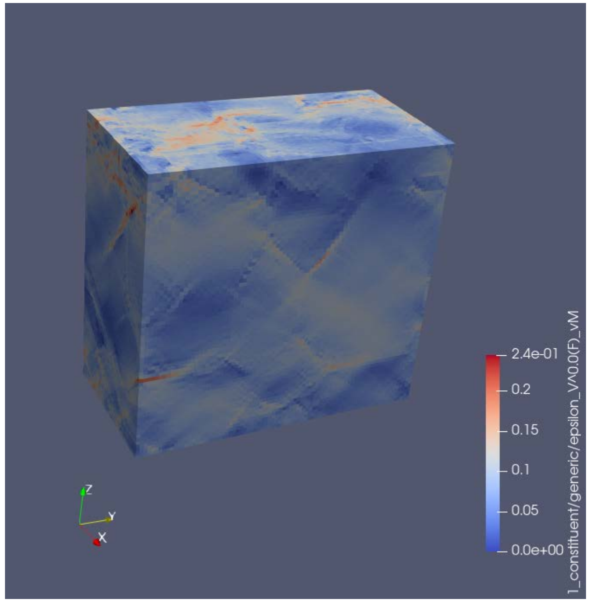
Clustering reduces the dimensionality of the data and enables rapid mechanical property assignment based on the microstructure constitutive response.

3. Constitutive Modeling

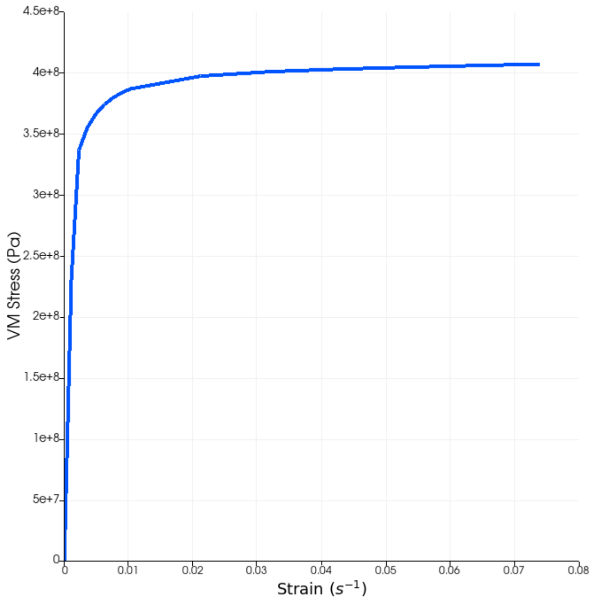
Microstructure representative volume element



Stress distributions



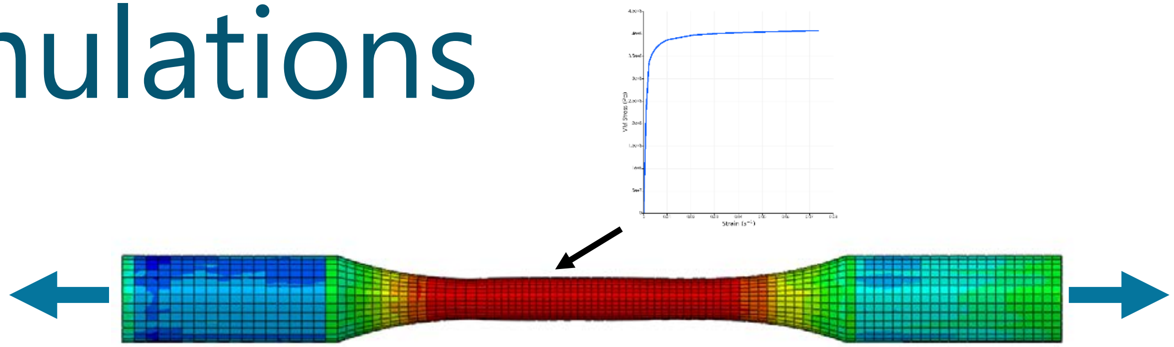
Stress-strain response



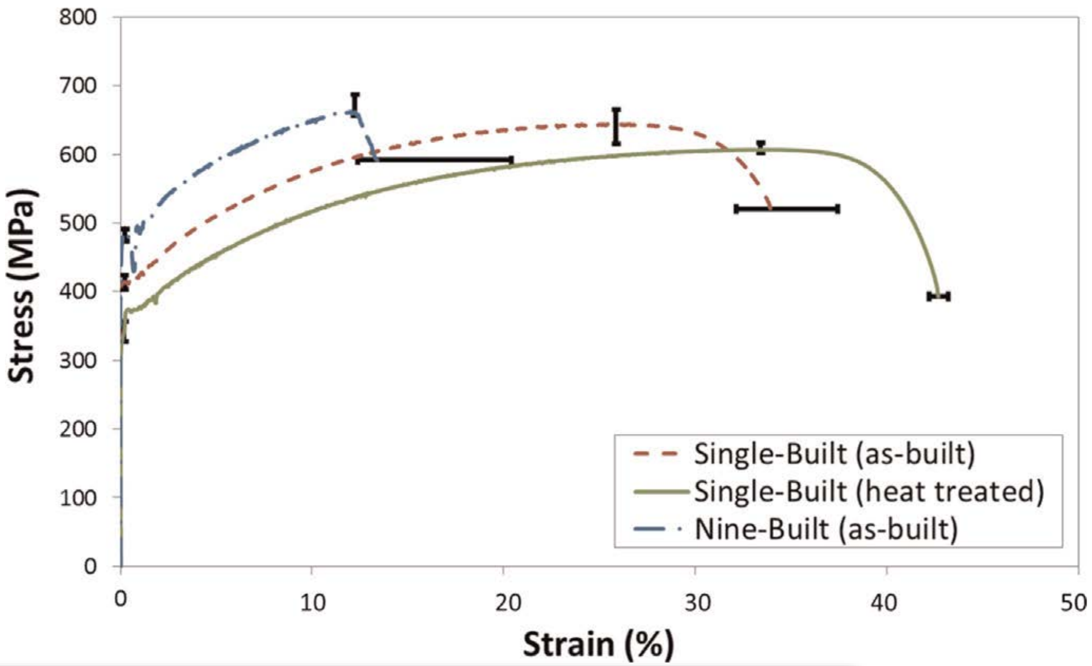
Constitutive response is computed based on the spatially varying microstructure topology.

4. Tensile Strength Simulations

- Spatially varying properties and residual stresses will be assigned to the coupon FEM according to the microstructural distribution.
- The pre-stressed coupon will be subjected to tensile loads for simulation-based testing and comparison to published results.



Test tensile response

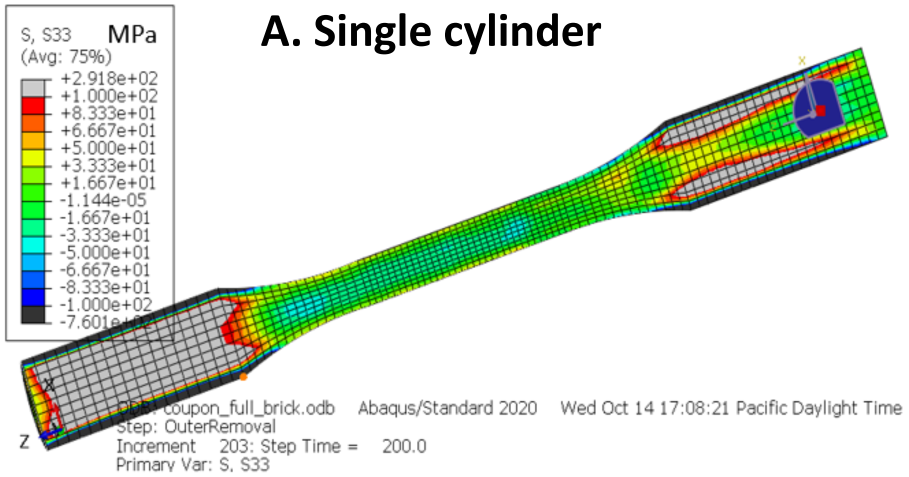


Coupon tensile strength is computed by assigning spatially varying properties based on constitutive response.

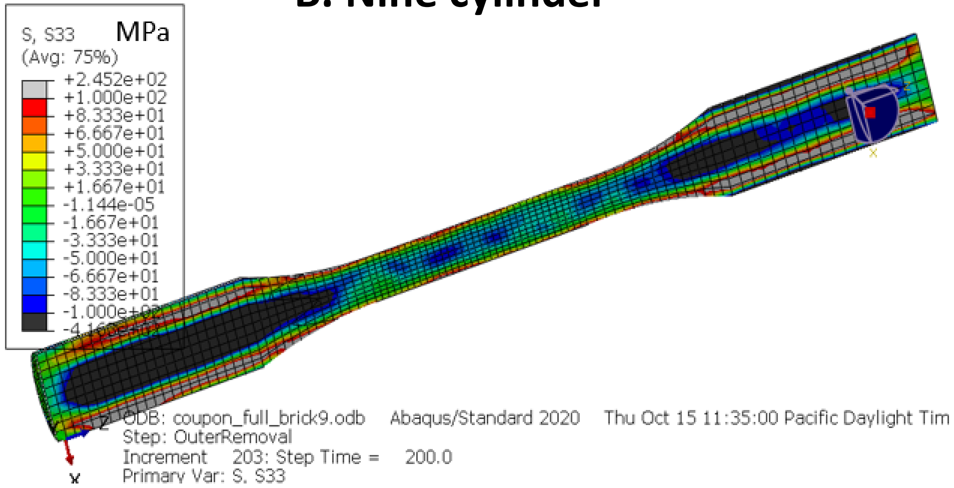
4. Tensile Strength Simulations – Preliminary Results

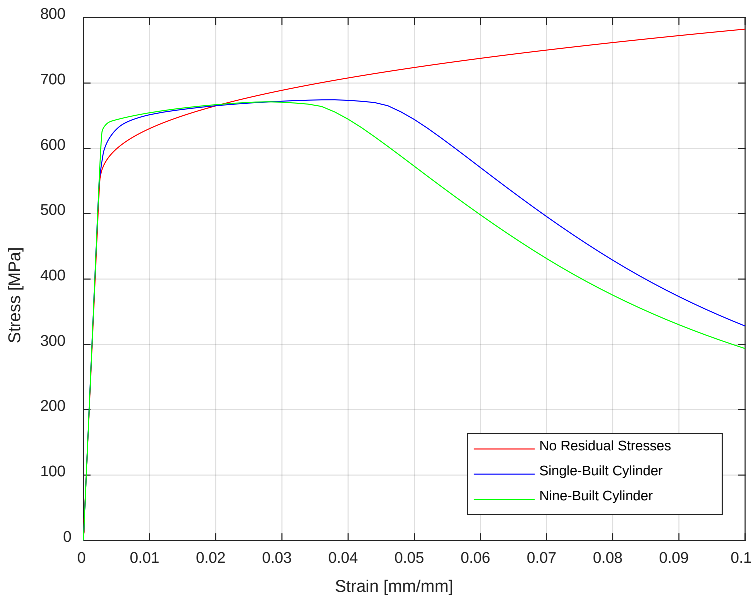
RESIDUAL STRESSES

A. Single cylinder



B. Nine cylinder





Tensile results not apples-to-apples with published data. Mechanical properties will be assigned in Q4.

Takeaways from preliminary results:

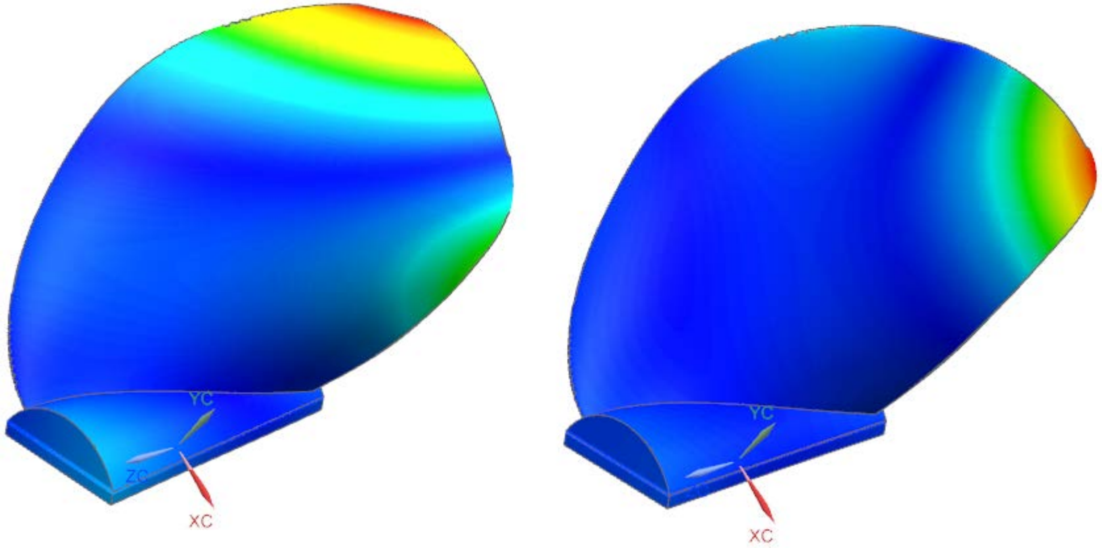
- Residual stresses have a significant effect on part ductility
- (A) had a lower yield strength due to tensile stresses forming in the coupon’s gauge area, while (B) had mostly compressive stresses
- (A) had a higher ductility than (B)
- These trends are consistent with the test data

Project Demonstration

- The framework will be demonstrated by applying the workflow to a notional propeller blade part
  - Blade geometry: Wageningen B-Series
  - Assumed the blade would be printed on a cylindrical shaft
- The part will be linearized about its pre-stressed state to demonstrate how to perform dynamic simulations (e.g., shock, random vibration)

Geometry scaled to be 5cm in height for computational efficiency, thermal build simulation takes ~75 hours for a ~3mm melt pool process

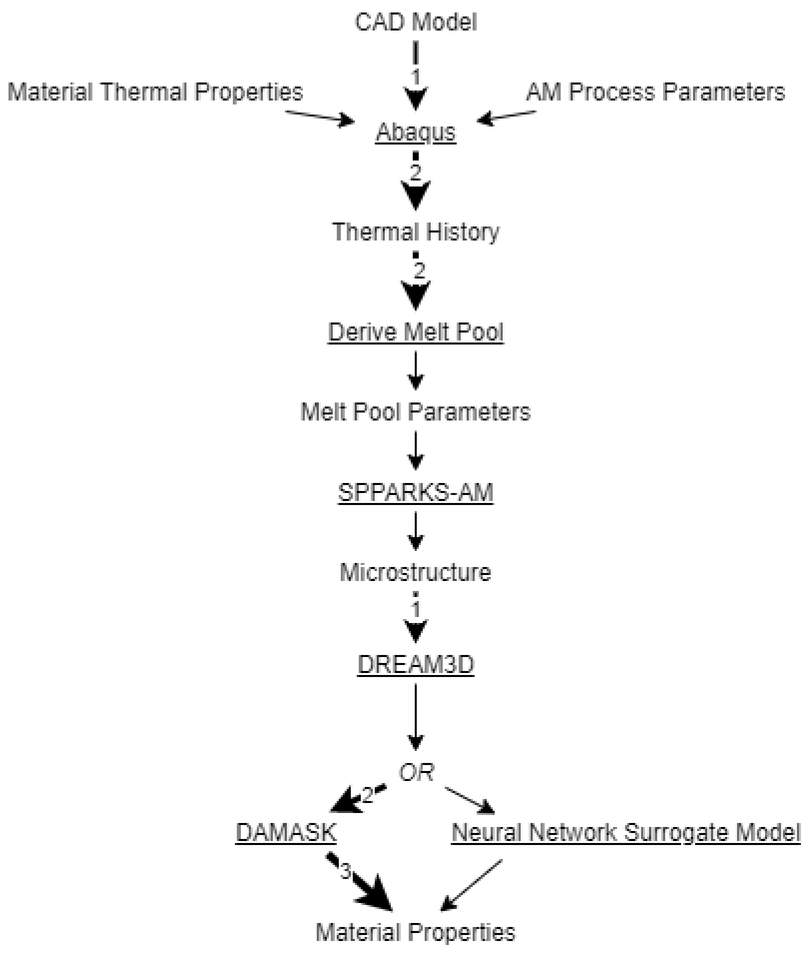
Demonstration Propeller Blade Part



Propeller blade representative mode shapes

ModSim Code Workflow

- The ModSim workflow incorporates disparate software packages across multiple platforms. ATA seeks to streamline the workflow and facilitate its adoption through a series of scripts.
- ATA will demonstrate its use at the end of the project and transfer the scripts to participating shipyards and NAVSEA.



Future Work

- These physics-based simulations offer predictive capabilities that connect process parameters to end part performance. ATA is presenting IRAD work in November showing how surrogate modeling with machine learning can leverage simulation training data to ***rapidly*** sample the design space and optimize AM process parameter selection.
  - ASTM ICAM Presentation: Surrogate modeling of temperature simulations
  - ASME IMECE Presentation: Surrogate modeling of microstructure simulations
- Because many aspects of the AM process carry statistical variation, these simulations must be combined with experimental data to form a ***statistical*** characterization of AM part performance in a hybrid modeling approach
  - ATA has successfully demonstrated to the government that this hybrid approach can provide significant program savings and reduce thermomechanical testing needed to characterize advanced composite materials
- Demonstration of this statistical characterization approach against current qualification methods is likely required to help evolve requirements
- ATA is actively seeking funded development opportunities, and partners for sharing of AM data, to develop these hybrid modeling capabilities, with contracting mechanisms available to government customers.

Questions?

Contact: david.najera@ata-e.com
elliot.haag@ata-e.com