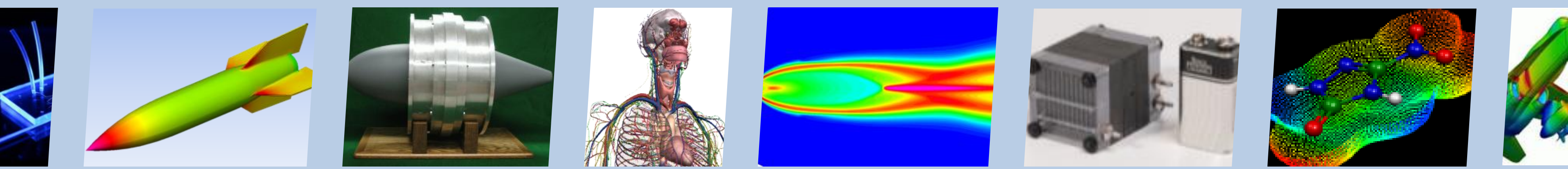
High-Fidelity Modeling and Materials Characterization of Inconel 718 Component Fabrication by Selective Laser Melting Additive Manufacturing



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Company Overview

INNOVATIVE SOLUTIONS

Developing & Transitioning Cutting-edge Technologies into Breakthrough Solutions

Aerospace | Propulsion | Materials | Energy | Life Sciences | Cyber

Supporting Government and Industry since 1987

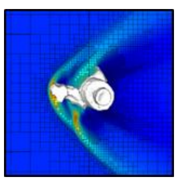
Nationally Recognized Small Business Technology Leader
Multiple Tibbets and SBIR Achievement Awards

NATIONWIDE FOOTPRINT

100 Employees
35 PhD

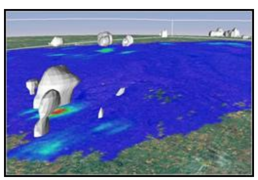
HUDSONALPHA INSTITUTE FOR BIOTECHNOLOGY
ASSOCIATE COMPANY

CORE CAPABILITIES

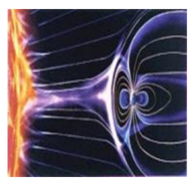


Aeromechanics

Propulsion Systems

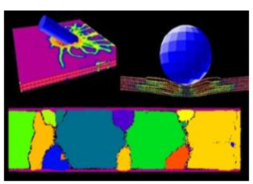


Weather Effects

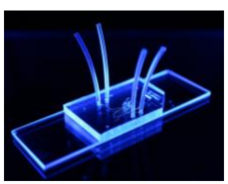


Radiation Effects

Batteries



High-Performance Materials

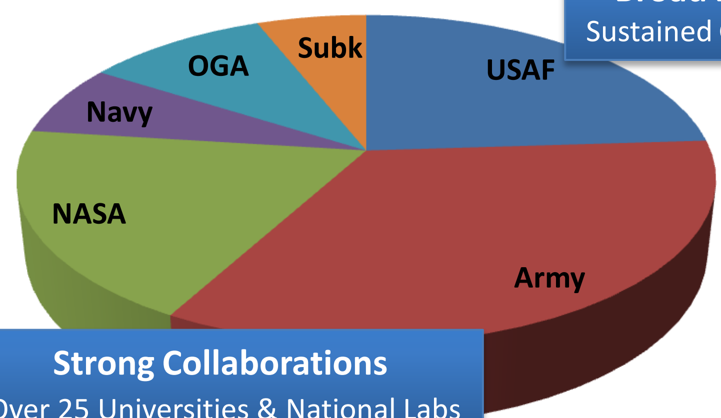


Biological Effects

Human Performance

CUSTOMER BASE

Broad Base
Sustained Growth

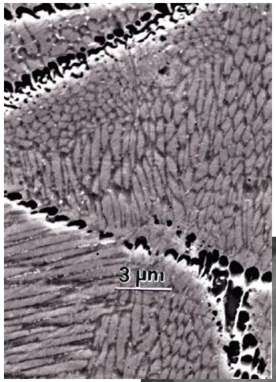


Strong Collaborations
Over 25 Universities & National Labs

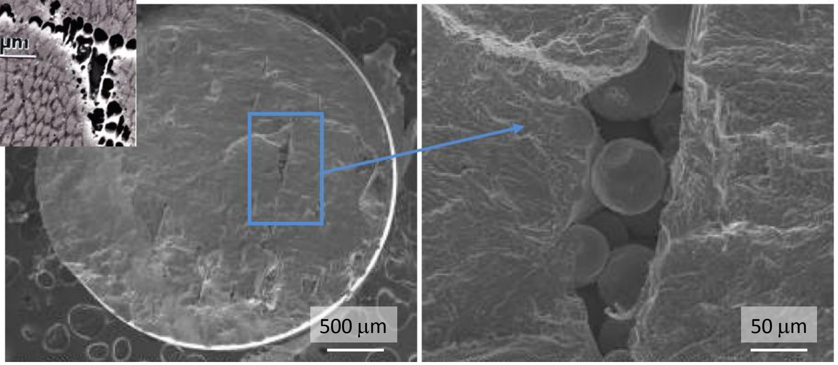
Selective Laser Melting Additive Manufacturing

- Promise:
  - Can fabricate complex parts
  - High ‘buy-to-fly’ for raw materials
  - Rapid prototyping
  - Rapid build of replacement parts and/or repair
  - Design freedom relative to casting and subtractive processes

- Challenges:
  - Shrinkage and geometrical tolerances ⇔ post-processing
  - Material quality and effective properties ⇔ qualification
  - Multiple (20 or more) process variables to ‘optimize’



Weak bonds at scan interfaces



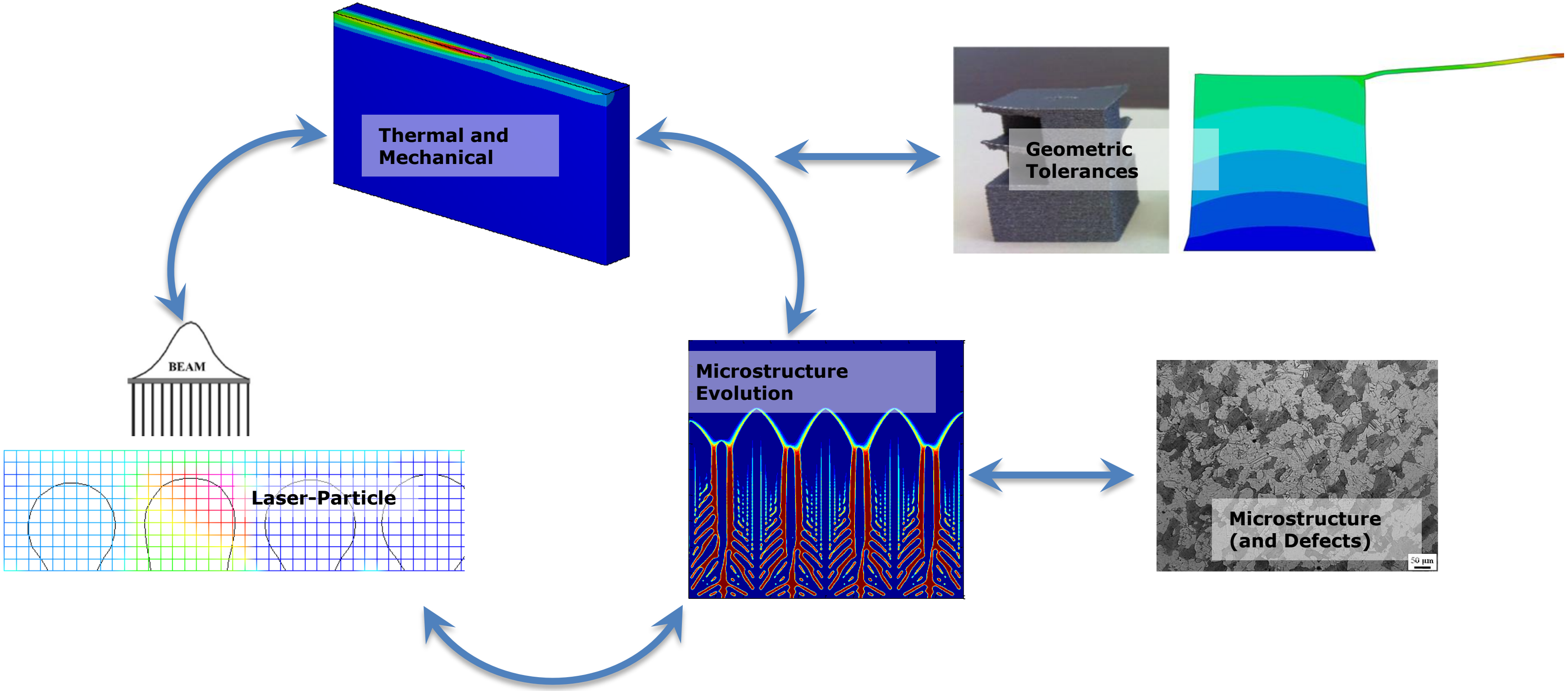
Porosity and ‘balling’

Modeling Motivation and Goals

- Problem and Proposed Solution:
  - Problem: Lack of understanding on the process to property relationships is leading to low yield, unacceptable part-to-part variability, costly post-processing and long qualification times.
  - Solution: Develop state-of-art modeling tools to increase build success – thereby reducing variability, post-processing, and qualification time.

- Modeling tools can give guidance on both component design and build design parameters
  - Will residual stress and materials parameters allow for successful build?
  - What defects are likely to affect material quality?
  - What post-processing is needed?

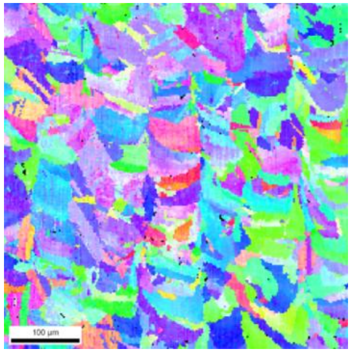
Approach



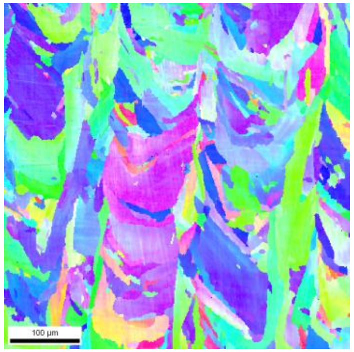
- Approach based on measurement and validation, application-driven code development for useful software and workflow
- Emphasize build analysis: can you make the as-designed part with acceptable residual stress, if so are materials adequate

EBSD Microstructure of As-Fabricated Inconel-718

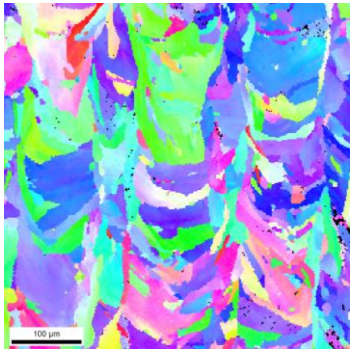
- X plane: Columnar structure, Weld-bead feature, with random texture



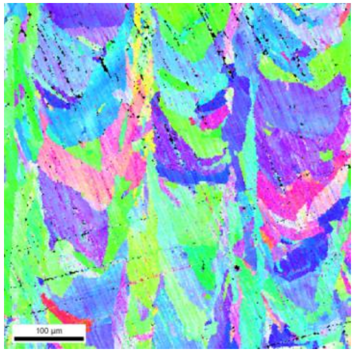
Bottom



Middle Bottom



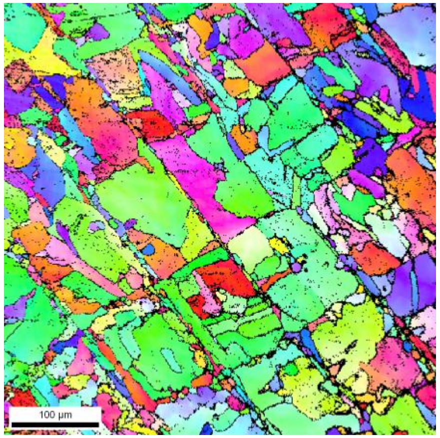
Middle Top

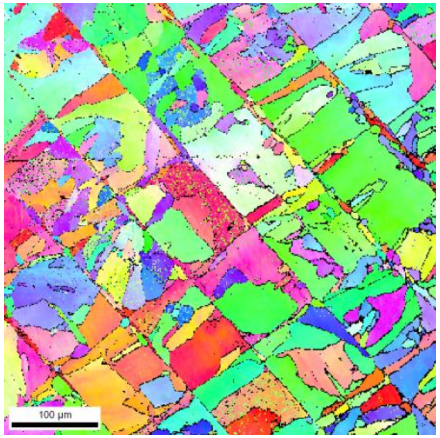


Top

- Z plane: Regular patch pattern, random texture

Bottom





Top

Microstructure Model Formulation

- Governing equations for phase field and solute concentration, Inconel 718 properties:

$$\frac{\partial \emptyset}{\partial t} = -M_{\emptyset}\left[\frac{\partial f}{\partial \emptyset} - \epsilon_{\emptyset}^{2}\nabla^{2}\emptyset\right]$$

$$\frac{\partial c}{\partial t} = \nabla.\left[M_{c}c(1-c)\nabla\left(\frac{\partial f}{\partial c} - \epsilon_{c}^{2}\nabla^{2}c\right)\right]$$

C_0 (wt. %)	5.0
K	0.5
Liquidus slope, m_l (K wt. % -1)	-10.0
Liquidus temperature, T_l (K)	1528
Solidus temperature, T_s (K)	1610
Latent heat, L (J/Kg)	227,000
Specific heat, Cp (J/Kg/K)	600
D_l (m^2s^{-1})	3.0E-9
D_s (m^2s^{-1})	1.0E-12
Anisotropic factor, ε	0.03
Mesh size, dx (μm)	0.2
Interface thickness, λ (μm)	1.77

- Anisotropic, dimensionless form in model:

$$[1+(1-k)U]a_s(\hat{n})^2\frac{\partial \emptyset}{\partial t} = \vec{\nabla}.\left(a_s(\hat{n})^2\vec{\nabla}\emptyset\right) - \frac{\partial}{\partial x}\left[a_s(\hat{n})a_s(\hat{n})'\frac{\partial \emptyset}{\partial y}\right] + \frac{\partial}{\partial y}\left[a_s(\hat{n})a_s(\hat{n})'\frac{\partial \emptyset}{\partial x}\right] + \emptyset - \emptyset^3 - \lambda(1-\emptyset^2)^2(U+\theta)$$

$$\left(\frac{1+k}{2}\right)\frac{\partial U}{\partial t} = \vec{\nabla}.\left(D\frac{1-\emptyset}{2}\vec{\nabla}U + \vec{j}_{at}\right) + \frac{1}{2}\frac{\partial}{\partial t}\{\emptyset[1+(1-k)U]\}$$

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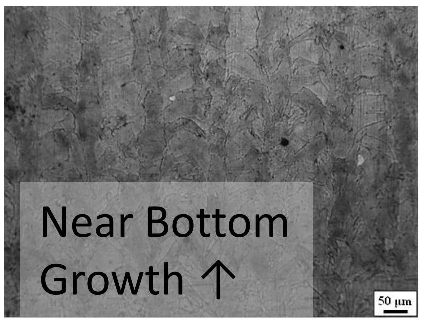
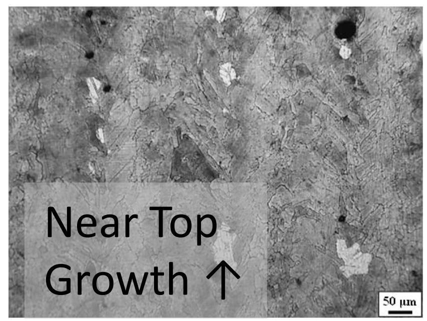
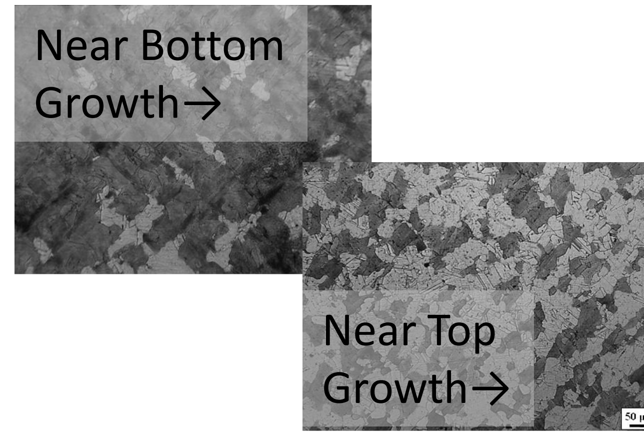
Microstructure Characterization & Modeling

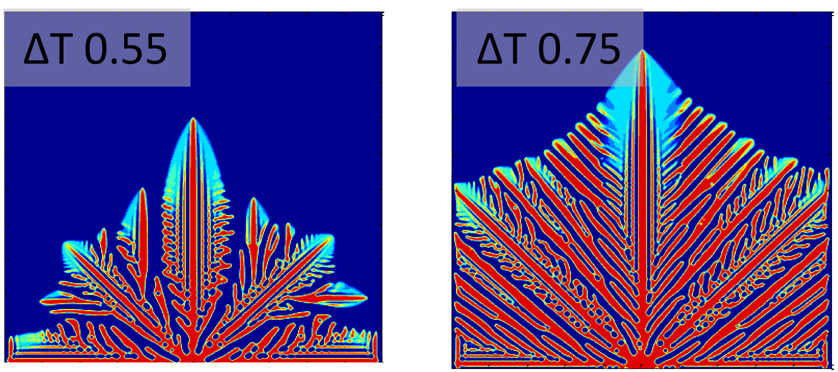
- Micrographs of as-fabricated Inconel 718 consistent with EBSD:
  - Axial 50-100 mm grains in growth direction; equiaxed from above; γ γ'' and Metal Carbide with Laves phase



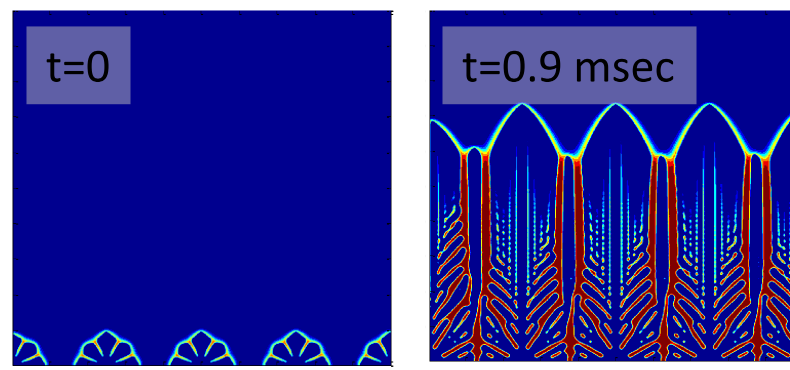




- Phase field models of Inconel 718 solidification:



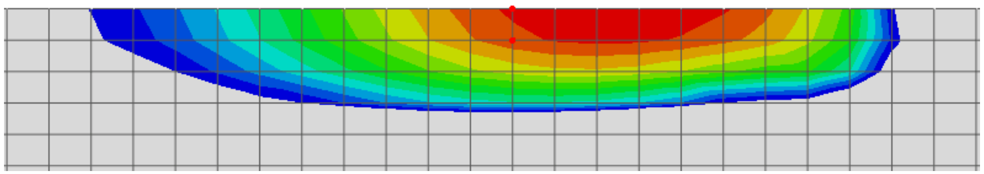
Cooling Rate Effects on Grain Size

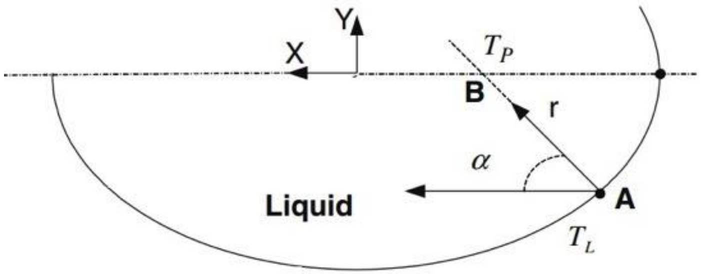


Nuclei Effects on Grain Morphology

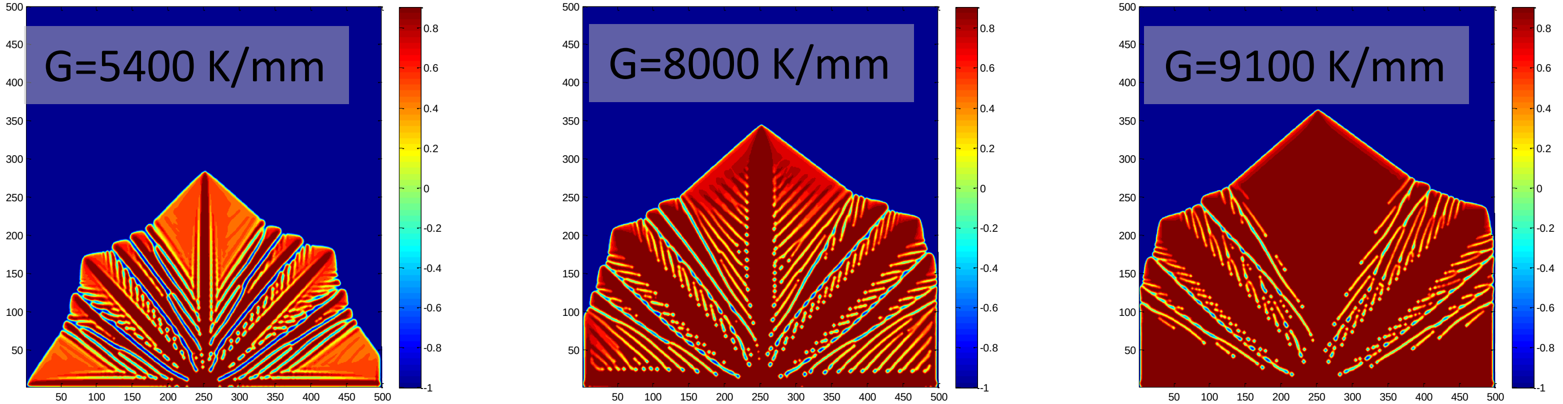
Microstructure Link to Melt Pool

- 2D Cartesian SLM thermal model for dimensionless temperature gradient





- Phase field models of Inconel 718 solidification:
  - Cooling rate range determined from thermal model



Cooling Rate Effects on Grain Size

Mesoscale Model Formulation

- Conservation of Total Mass:

$$\frac{\partial}{\partial t}(\rho)+\nabla\cdot\left(\rho\vec{V}\right)=S$$

- Conservation of Secondary Fluid Mass:

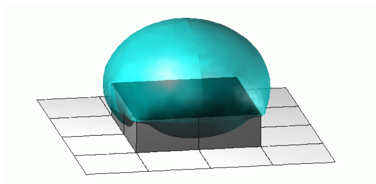
$$\frac{\partial F}{\partial t}+\vec{\nabla}\cdot\left(\vec{V}F\right)=\frac{\dot{m}}{\rho_l}$$

- Conservation of Mass-Averaged Momentum

$$\frac{\partial}{\partial t}\left(\rho\vec{V}\right)+\nabla\cdot\left(\rho\vec{V}\vec{V}-\mu\nabla\vec{V}\right)=\left(-\nabla P+\rho\vec{g}\right)+\vec{B}$$

- Conservation of Mass-Averaged Enthalpy

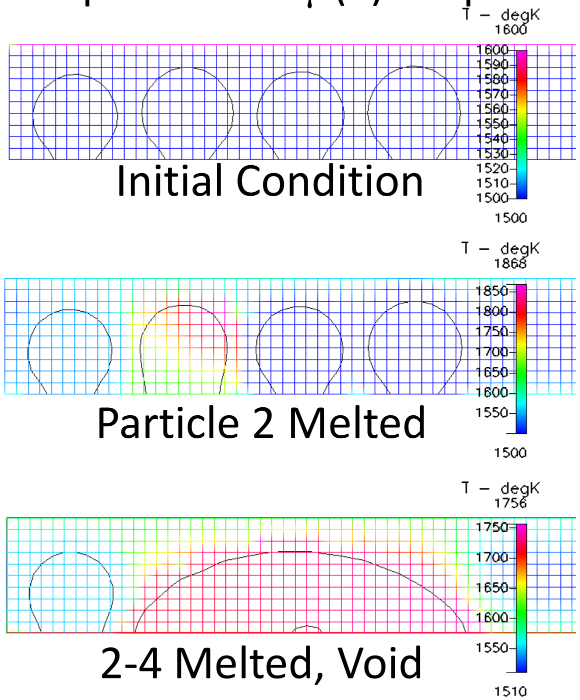
$$\frac{\partial}{\partial t}(\rho h)+\vec{\nabla}\cdot(\rho\vec{V}h)=\vec{\nabla}\cdot\vec{\mathbf{q}}+\tau:\vec{\nabla}\vec{V}+\frac{\mathrm{d}p}{\mathrm{d}t}+\dot{Q}$$



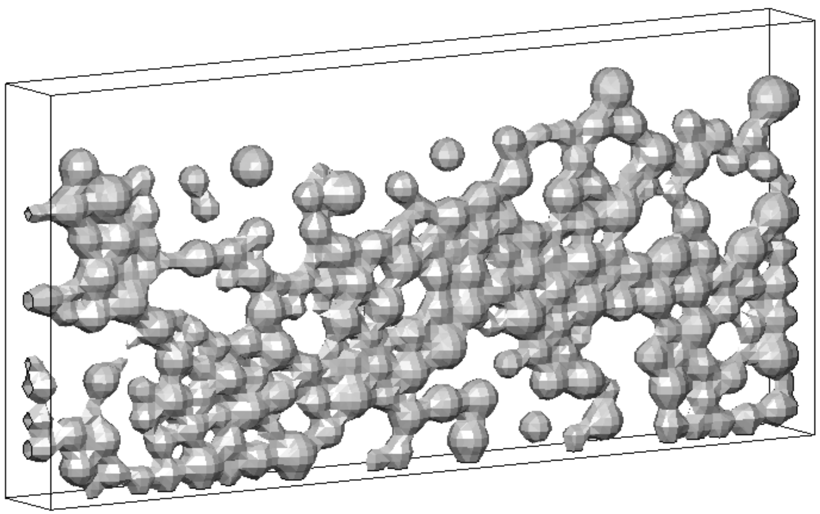
Surface tension as a body force

Mesoscale Laser-Particle Model

- Simulate melting and reflow of metal powder particles to identify conditions causing voids or incomplete melting
  - VOF interface tracking routine coupled with laser source, heat transfer, phase change thermodynamics, fluid dynamics, surface tension
  - Implemented $\mu(T)$ for particles, laser source, phase change thermo



Melting of discrete particles and void formation as laser scans



Static solid Inconel 718 via high-viscosity fluid verified for 3D simulation

Thermal Model Formulation

- Conservation of Energy (Heat equation):

$$\frac{\partial}{\partial t}\left[\rho C_p T\right] = -\nabla \cdot q + \dot{Q}$$

$$\vec{q} = -k\nabla T$$

$$\frac{\partial}{\partial t}\left[\rho C_p T\right] = \nabla \cdot k\nabla T + \dot{Q}$$

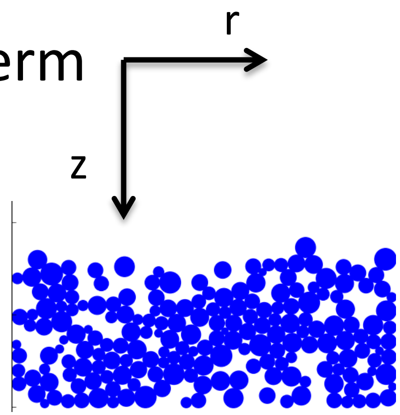
  - The phase change is accounted for by increasing Cp_{eff} between the liquidus and solidus temperatures so that total enthalpy is conserved:

$$h = \int_0^T C_{p,eff}\,dT = \int_0^T C_p\,dT + \Delta H_f\, f$$

with *f* being the solid fraction

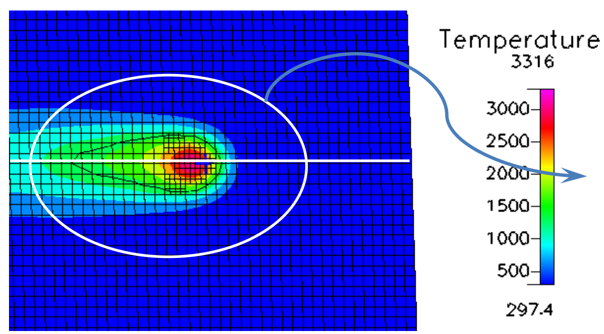
- Moving beam (laser, electron) heating source term
  - Local heating dependent on beam width and penetration depth

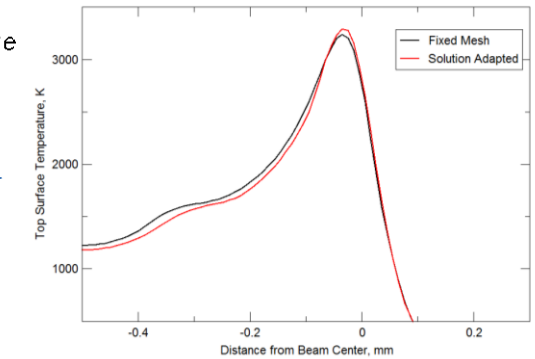
$$\dot{Q} = P_{abs}\, q(r(t))\, f(z)$$

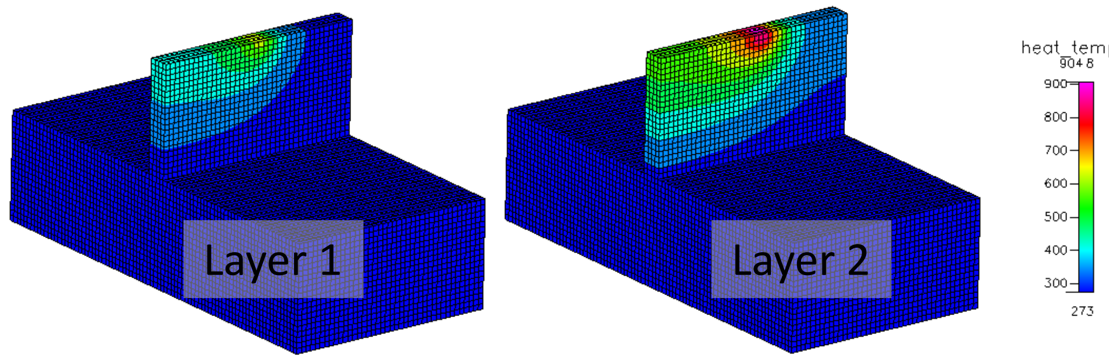


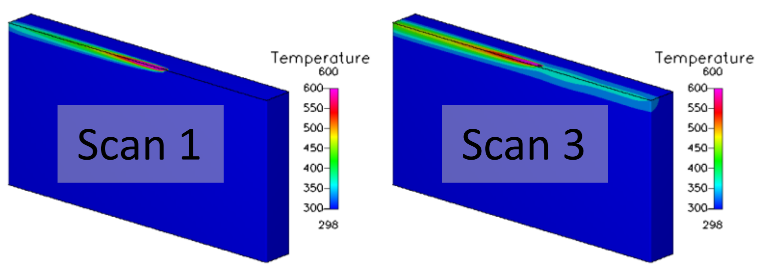
Thermomechanical Model: Demonstrations

- Base Capabilities
  - Mesh Adaptation for speedup - 3x faster than fixed grid
  - Extrusion to address new powder layer
- Demonstrations:
  - Hatch scan for 2 cm line build
  - Thermomechanical Coupling

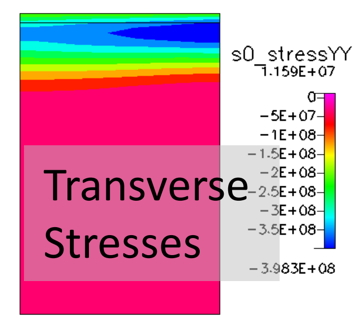






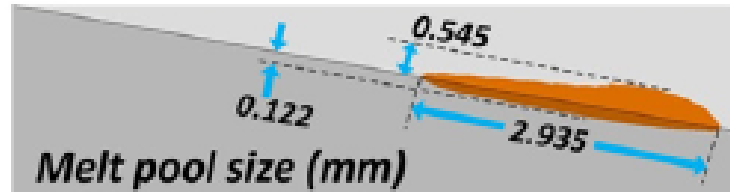


2 cm long x 2mm deep

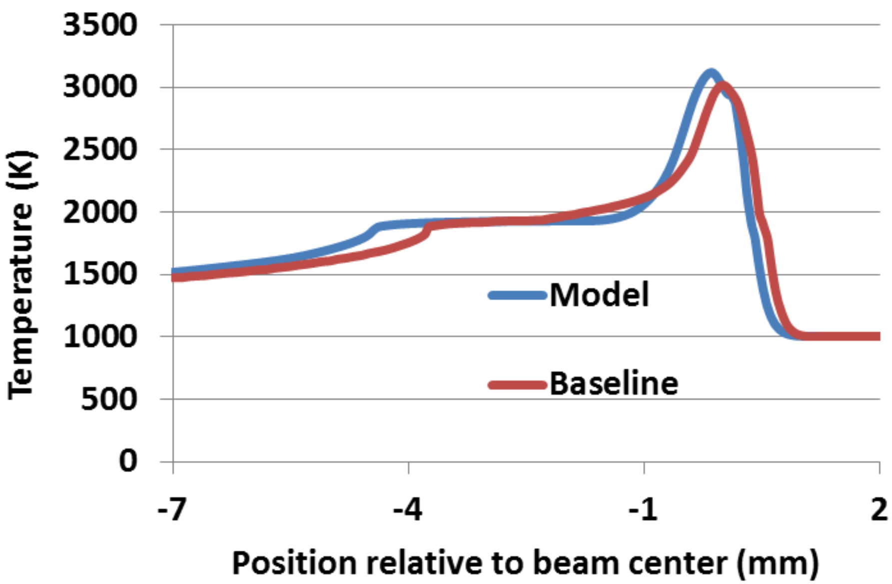


EBAM Temperature and Melt Pool

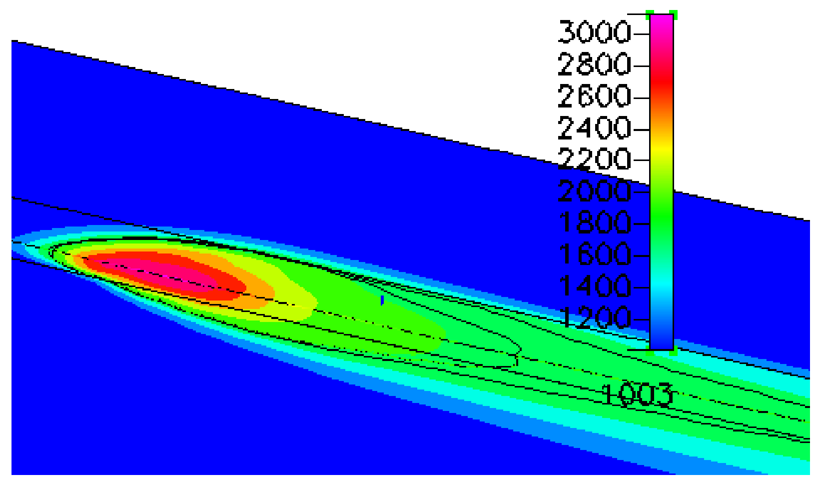
- Good agreement of peak temperature
  - Sensitive to effective conductivity in melt
  - Slightly longer plateau in liquid-solid 2-phase region



Benchmark, agrees with experiment



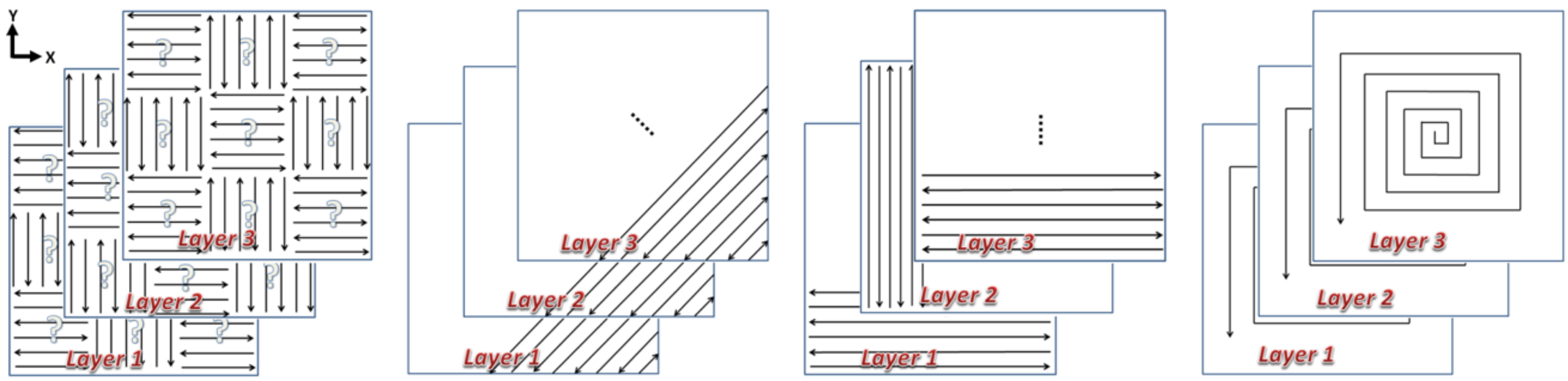
Temperature, K



2.114mm x 0.555mm x 0.140mm

Thermomechanical Application

- Demonstration applications by UA to analyze hatch scan patter effects on T uniformity, stress
  - 6x6 mm scanned region, 8x8 mm base
  - Beam diameter 400 μm, power/area into beam consistent with Concept 3 typical operating conditions



Islands (2x2 mm) | Lines | Rotating Lines | In-Out or Out-In

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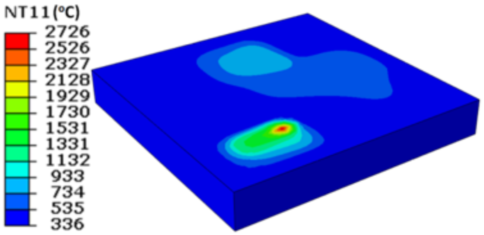
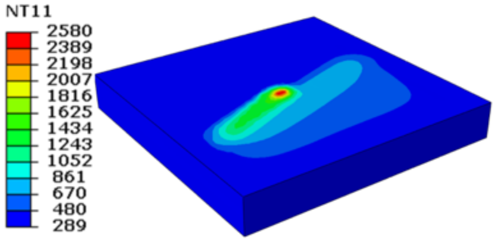
Thermomechanical Application

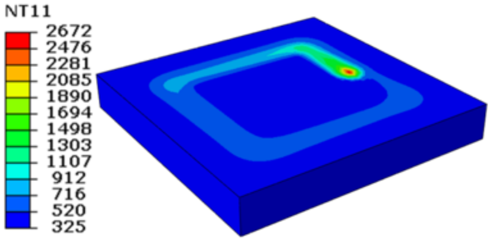
CFDRC



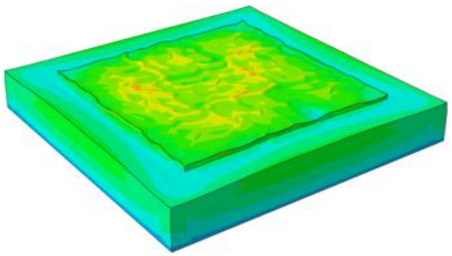
Island T mid-scan



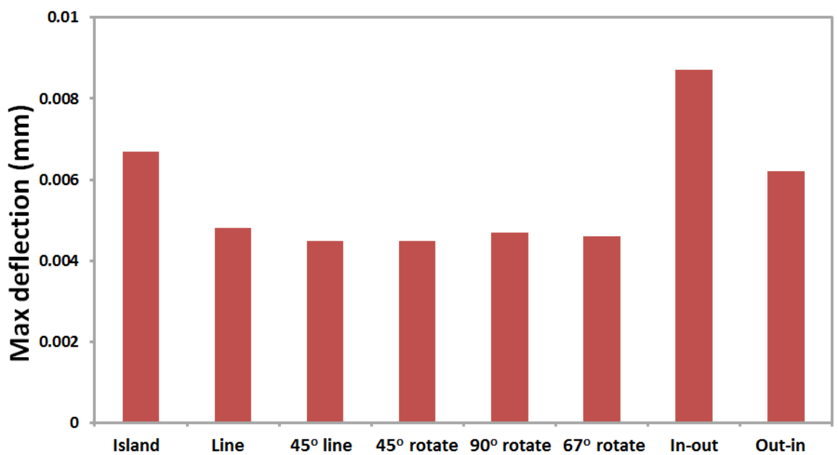
Rotating 67° T mid-scan

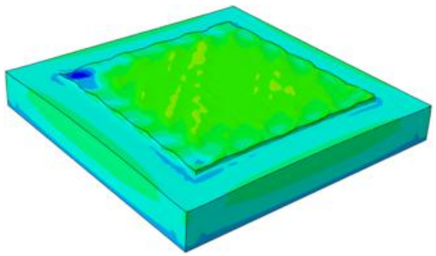


Out-In T mid-scan



Island deflection





Rotating 45° deflection

- Line scan patterns gave lowest max T during scanning due to small part size, long beam line
  - Resulted in lowest distortion for those cases

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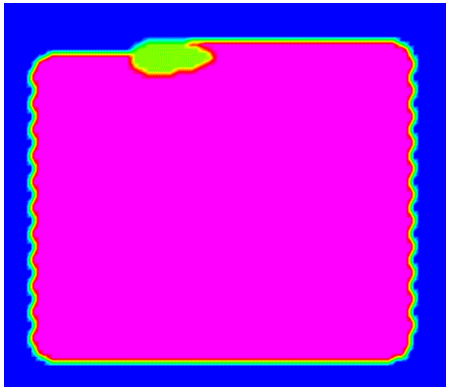
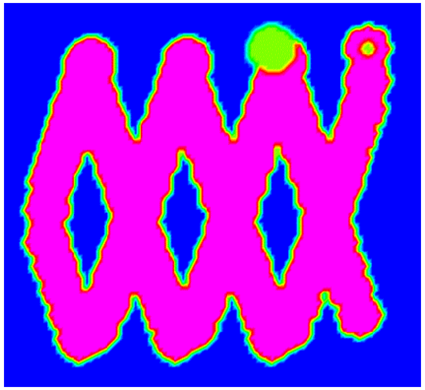
Thermal Model Accuracy/Efficiency

- Resolving the laser spot energy input in position and time imposes a CFL constraint – very small simulation time steps

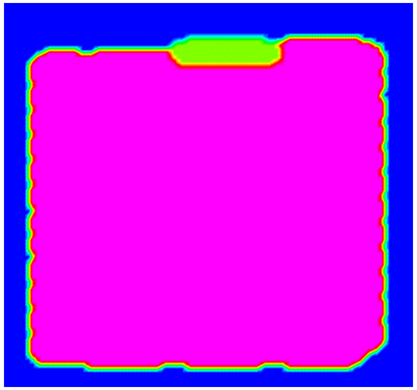


T profile after hatch scan, ‘brute force’



T profile after hatch scan, large Δt

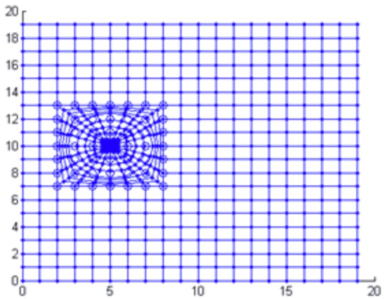
- Alternative: follow beam path and integrate heat input over longer time step



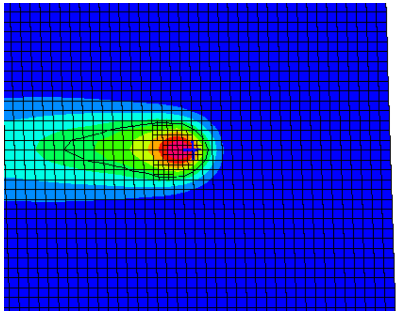
T profile after hatch scan, adaptive quadrature with large Δt

Thermal Model Accuracy/Efficiency

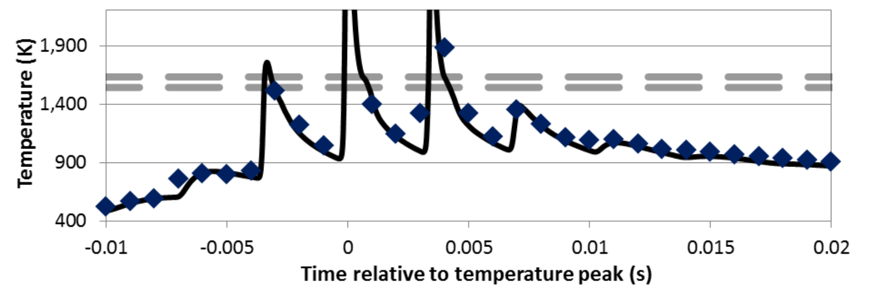
- Current approaches for more practical application:
  - Others: Overset grids, move a high-resolution 'block' with the spot



  - CFDRC: Adaptive meshing, dynamically refine near beam



- CFDRC Adaptive integration:
  - User-specified tolerance for total heat input accuracy
  - Captures T history during cooling and solidification

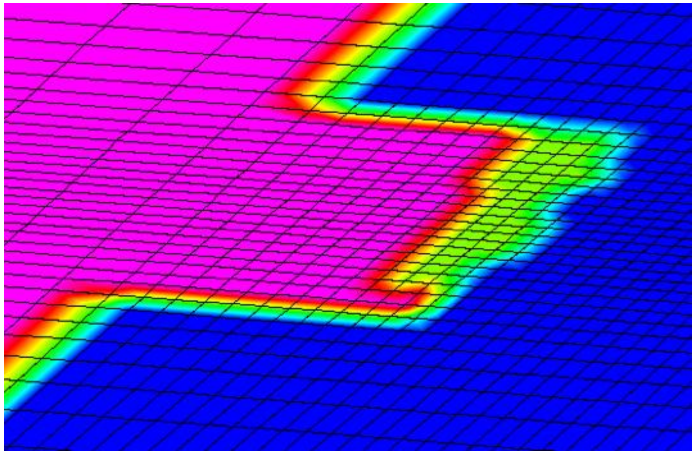


  - Order 5x speedup in clock time

Method	Time step, Δt (s)	CPU / Sim time (s/s)	Relative Speed-up	Accuracy
Point Input	5E-5	9.3E5	--	✓✓
	1E-3	1.1E5	8.90	×
Adaptive Integration	5E-5	1.7E6	0.56	✓✓
	1E-3	1.8E5	**5.25**	✓

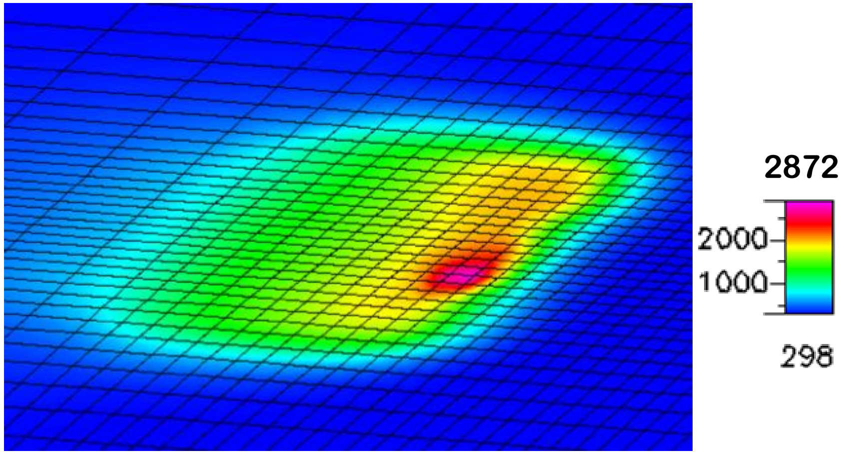
10x speedup possible when combined with adaptive meshing

Overhang First Layer Effects



Phase

(blue=powder, purple=solidified)

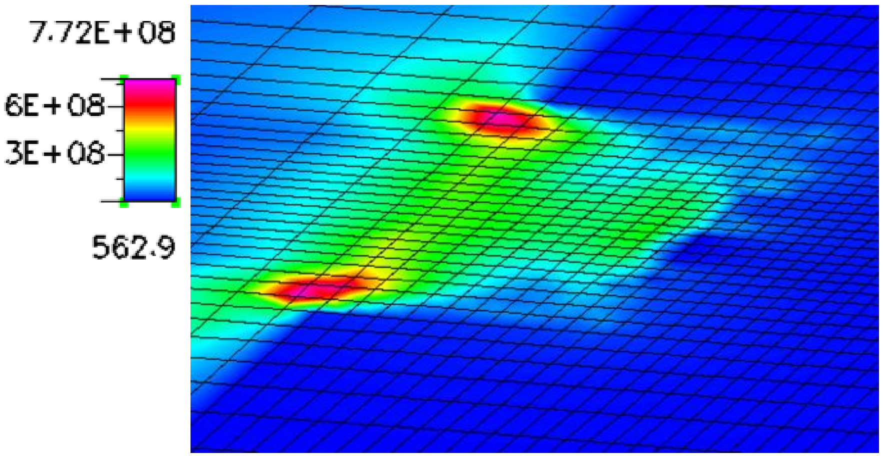


Temperature

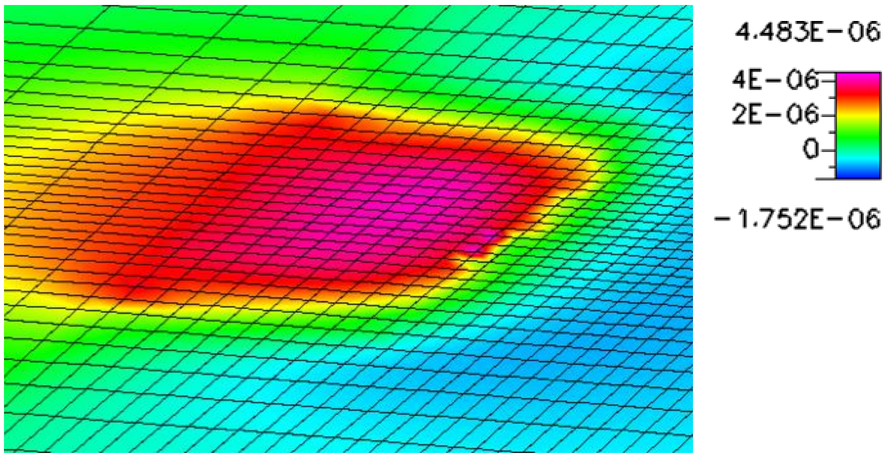
- Manufacturing an overhang adds significant challenges
- Powder does not conduct heat well
  - Increases temperature of melt pool
  - A support may be required to serve as a heat sink

Overhang First Layer Effects

- High stresses in the overhang
  - Limited support from powder
  - High thermal gradients
  - Thermal expansion
- Result in large deflections



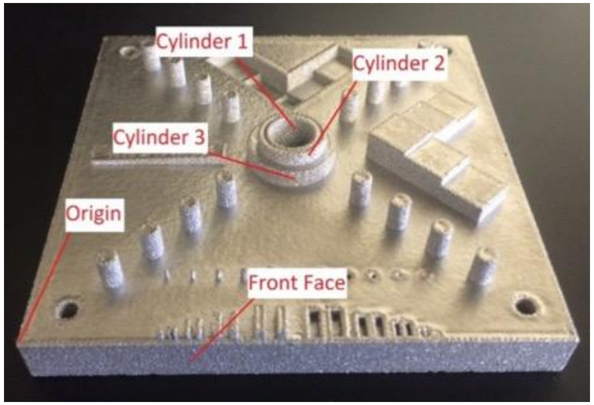
Von Mises Stress

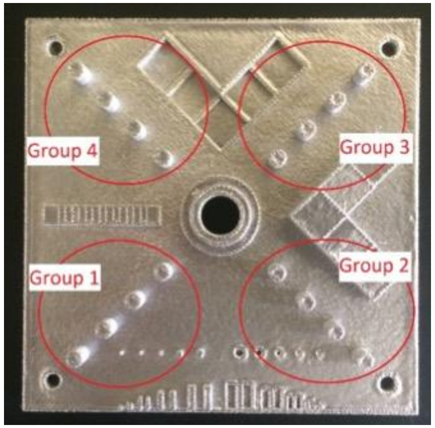


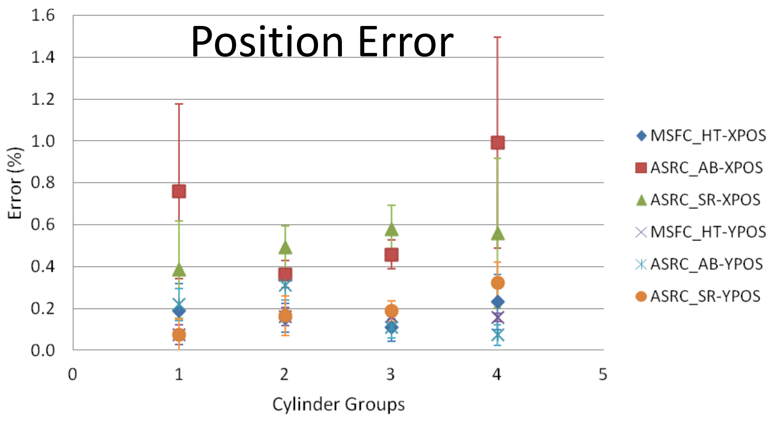
Vertical Deflection

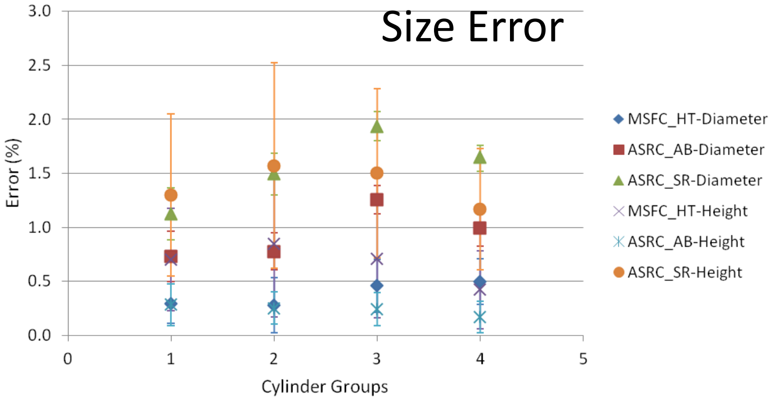
Dimensional Tolerance Characterization – NIST Test Article

- Parts fabricated by ASRC and MSFC
  - ≈1% tolerances after stress relief heat treatment



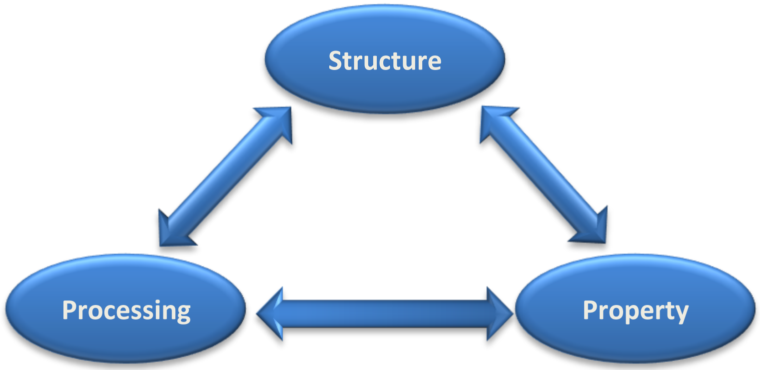




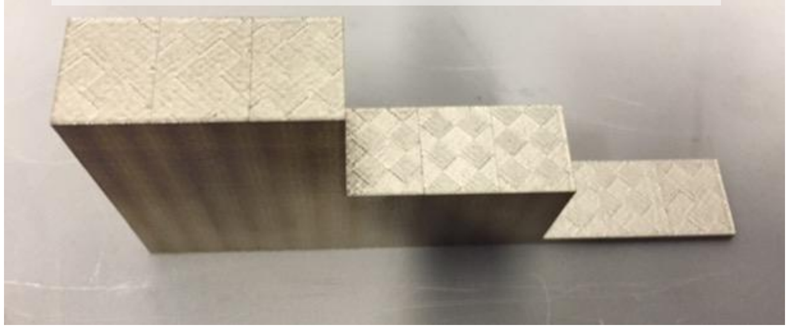


Summary

- The CFDRC-UA team is developing modeling tools to address SLM process performance at each critical level:
  - Microstructure: material properties
  - Mesoscale: material quality
  - Component: manufacturability and dimensional tolerances



Test structure for material characterization vs. build height

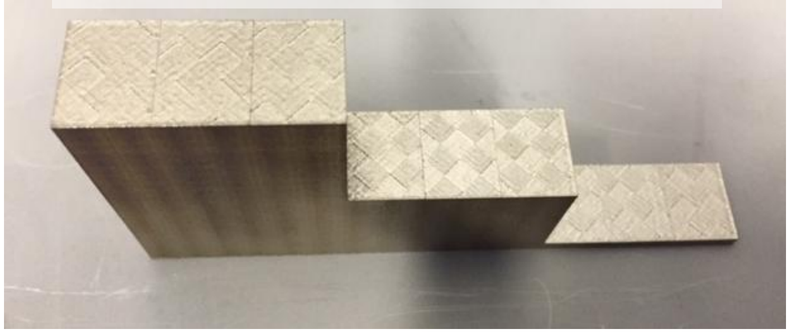


- Companion experimental efforts in process monitoring and material characterization provide learning for material qualification and data for model validation
- Next step is to put the pieces together and apply to test builds
- Outcome will be advanced tools to inform design and process

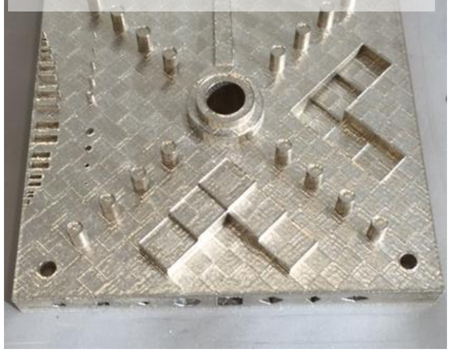
Acknowledgments

- Funded under NASA STTR NNX15CM17c
  - John Vickers (TM), Stacey Bagg, Doug Wells, Brian West, and Ken Cooper for valuable input and feedback
- Arctic Slope Technical Services (ASRC)
  - Sample part builds, process developer's perspective on needs, and Concept Laser SLM tool access

Test structure for material characterization vs. build height



NIST test article for feature tolerances



Questions?

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