AM Part Qualification by ICME Analysis and Real Time NDE Monitoring (*Additive Manufacturing Science*)

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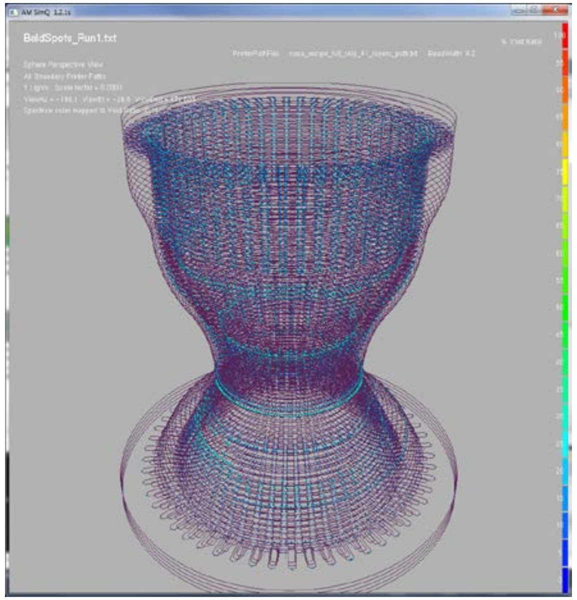
Technical Agenda

1. **Motivation / Problem**
2. **Micro Structure Material Modeling**
   - **Gain Modeling (Diffusional Creep):** Defects, Cracks, Oxidation, Surface Roughness
   - **Mechanical Properties Prediction:** Stress-Strain Curve, Effect of Voids
   - **Fracture –Fatigue Properties Prediction:** Toughness, Fatigue Crack Growth
3. **Process Model**
   - **Path Coverage**: Defects
   - Residual Stress, Net Shape, shrinkage
   - Topology Optimization/DOE
4. **Thermal Management:**
   - **Thermal State:** Heat Affected Zone, Melt, Super melt, Super heated Cool, Sintering/Consolidation, Cooling
   - **Material state:** (density, void), and
   - Process Map (Power, Velocity, Temperature)
5. **Qualification & Quality Assurance:**
   a) **AM Properties:** Scatter uncertainties
   b) **Service Loading:** Static, Fracture control Plan, Fatigue, Life
6. **Emerging Technology:** In-Situ Monitoring
7. **Conclusion**

Void Detection

Chamber Nozzle (Inconel-718)



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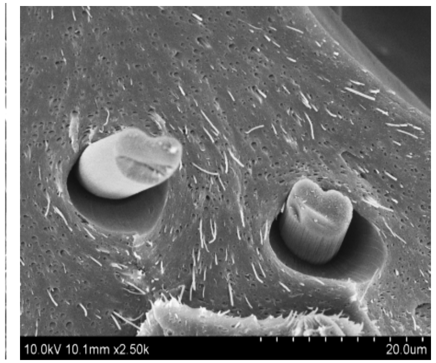
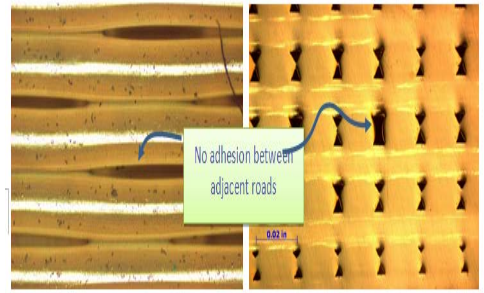
Key Challenges: to Polymer Additive/Reactive Manufacturing

A large number of variables can influence the number and locations of defects in the additively manufactured part.

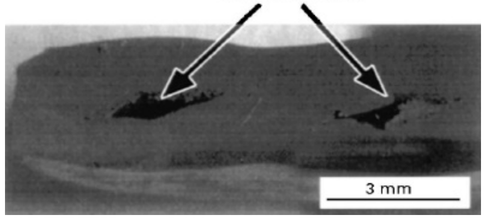


Weak Fiber-Matrix Interphase



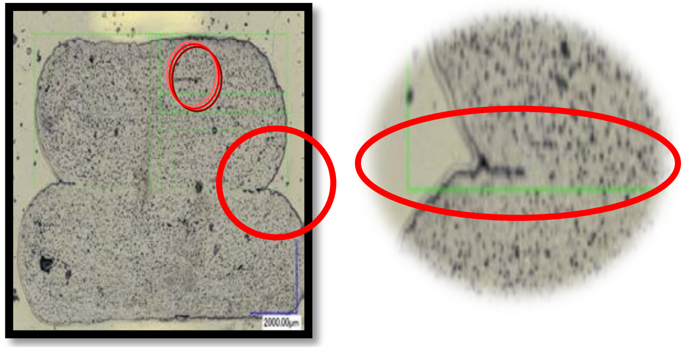
Delamination & Porosity

Cross-section of bloated specimen



Reactive: Bloating & Acid Formation

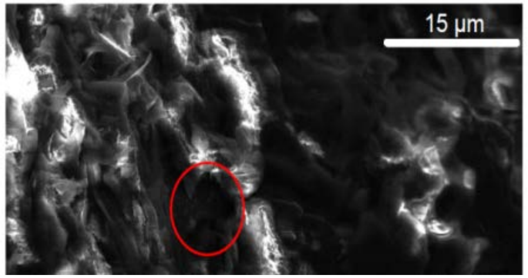
- Shrinkage and Warpage
- Cracks and Delamination
- High Porosity
- Interfacial Bonding
- Residual stress
- Wrinkles
- Fiber Waviness and Agglomeration
- Others



Cracks within/between Beads

These challenges can be addressed using ICME material modeling and print error management tool sets

Delamination



Wrinkle in Thermoset: due to residual stress, interphase, surface functionalization

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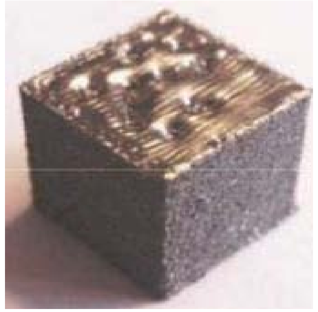
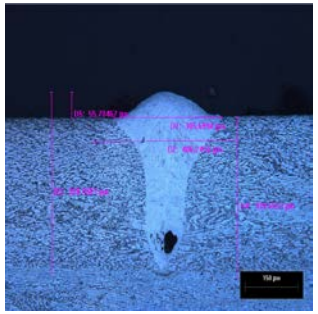
Challenges in Metal AM

Defects Resulting From AM Process Related to Thermal Behavior

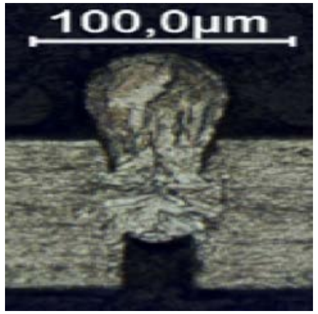
Swelling



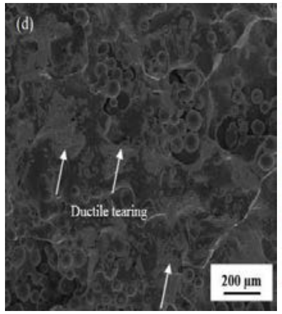
Keyhole



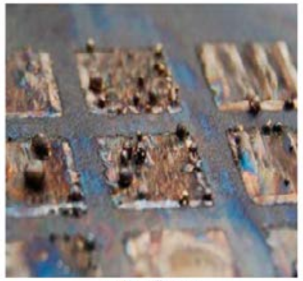
Humping



Unfused

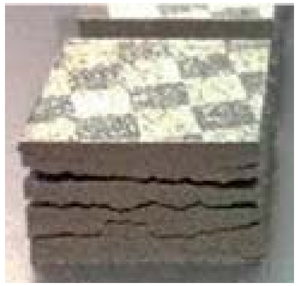


Balling



Balling effect [1]

Delamination



When It Happens?

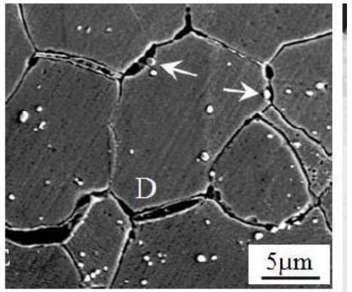
- High Residual Stresses
- Surface Roughness
- Voids and Cracks
- Oxidation
- Inconsistent Density
- Anisotropic Microstructure
- Mechanical Behavior

Consequences?

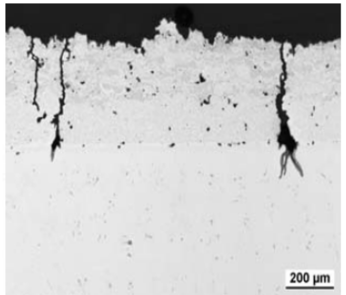
Why It Happens?

- Speed and Power Range (All Phenomena)
- Unfused Powder: Insufficient Melting
- Humping: Meltpool Length and Duration
  Humping: Meltpool Pile-up
- Gas Pores/Keyhole: Trapped Gas in Particles
  Swelling & Balling: Surface Tension Effects

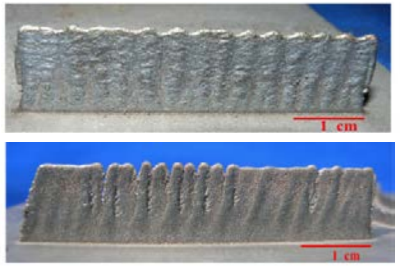
Intergranular Crack



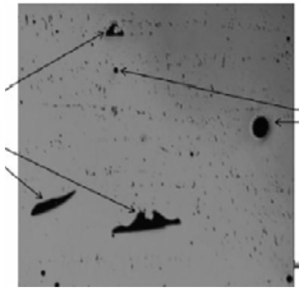
Surface Crack



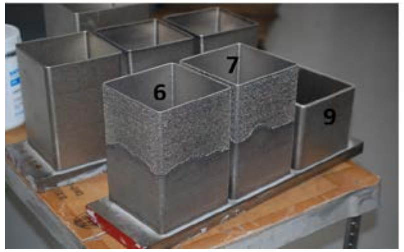
Surface Roughness



Gas pores



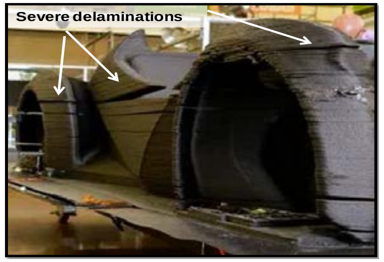
Roughness, Netshape, Shrinkage



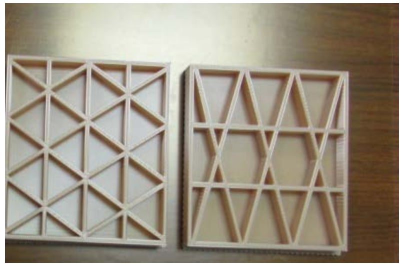
GENOA3DP – Addresses Metals, Polymers, and Ceramics

Composite

3D Printed Shelby Car
Minimize Delamination



Multi Material (ULTEM-Silver)
Diffusion/Inclusion



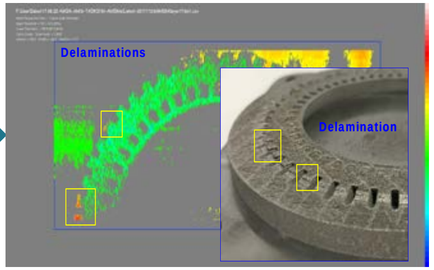
Wing (Thermoplastic-PPS)
Delamination/CTE

Ceramic Part (Binder Jet)
PIP & Voids

Metal

UAV Wing (Titanium)
Design Stress Free Support Structure

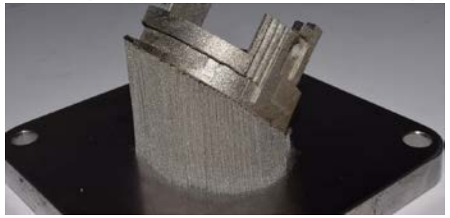
Heated Chamber Nozzle (Inconel)
In-Situ Roughness



Box (Inconel)
Roughness & Net Shape

Conformal HeX (steel)
Weight Minimization, Thickness & Leakage

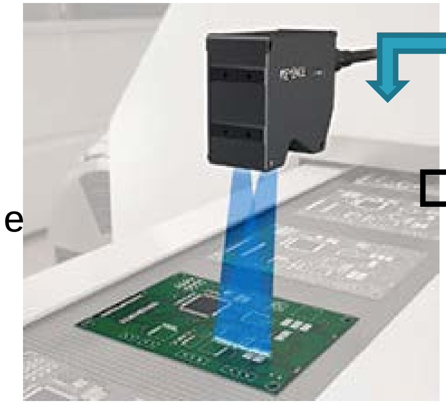
Mount Ring (Inconel 718)
Roughness, Warpage, Base Plate & Support Design



In-Situ Monitoring

Benefit of Big Data Processing / Discovery: Monitor Defects in Real Time

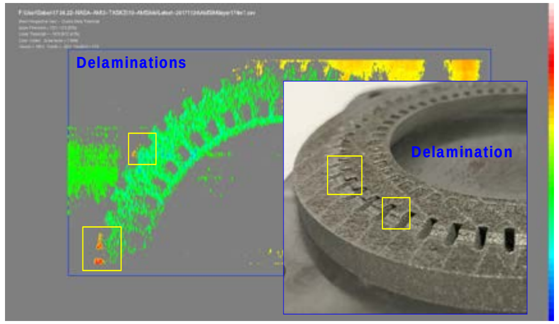
- Big Data Monitoring, Real-time Process
- **Visualization**
  - Surface Roughness by Profilometer
  - Heat Affected Zone form IR Thermal Came
  - Photo-Diodes: Meltpool, Plasma duration
- **Calculation**
  - Real-Time Calculation
    - Heating, Meltpool, Solidification, Cooling
  - Absorption of Laser Energy in Powder
  - Microstructure and Voids



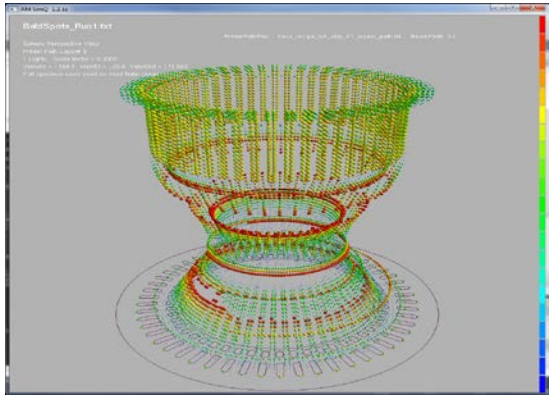
Profilometer/IR Camera

IN718 Chamber Liner

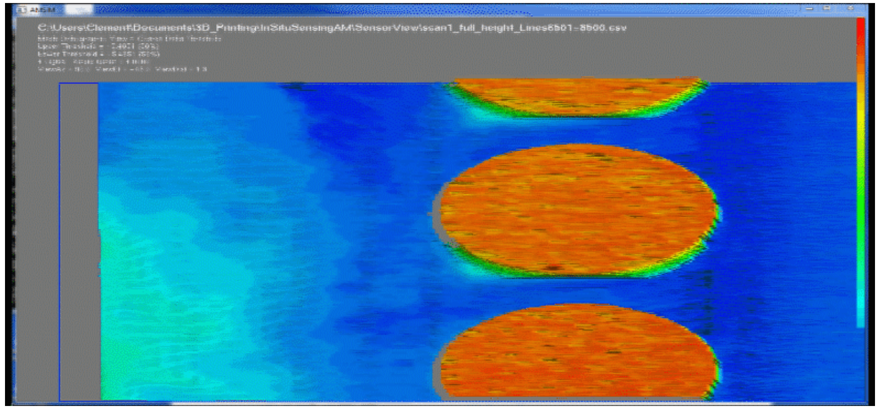
Roughness/Delamination



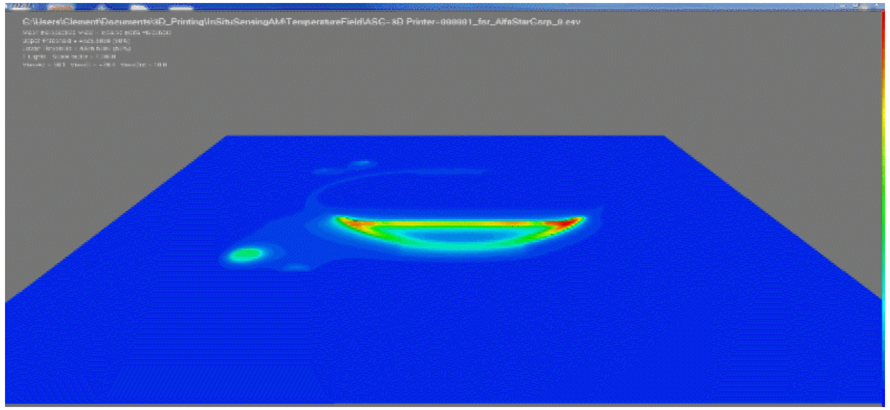
3D Visualization Anomaly Size/Intensity



Surface Roughness from Laser Profilometer



Heat Affected Zone Processing (IR)



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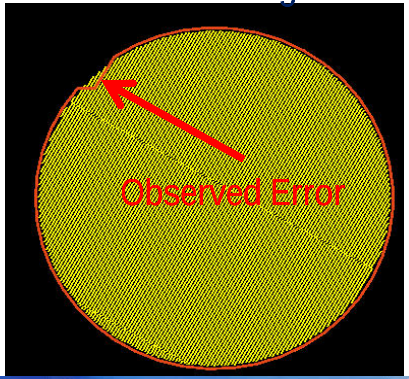
In-Situ Monitoring: Surface Roughness and Thermal Map

Real-Time Big Data Processing: Printing Error, Thermal Map, Roughness Visualization / Processing (Profilometer & Thermal Data)

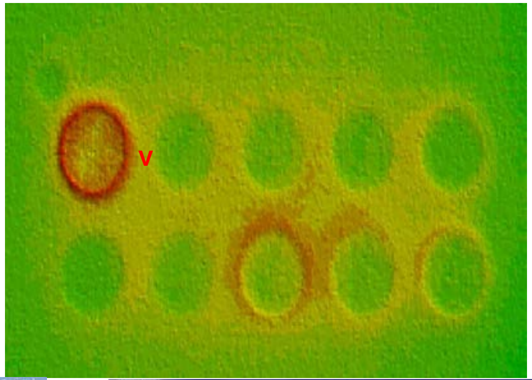
Material: Inconel-718

10 Inconel-718 Coins Printed Different Power & Speed

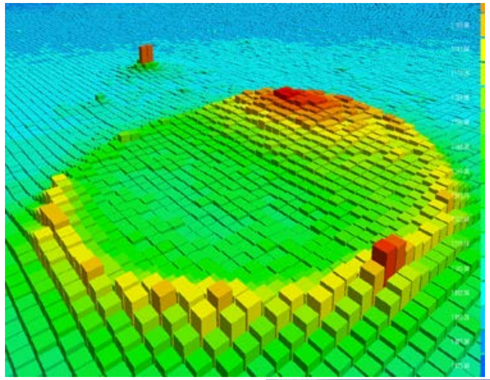
Detected Printing Errors by PathCoverage



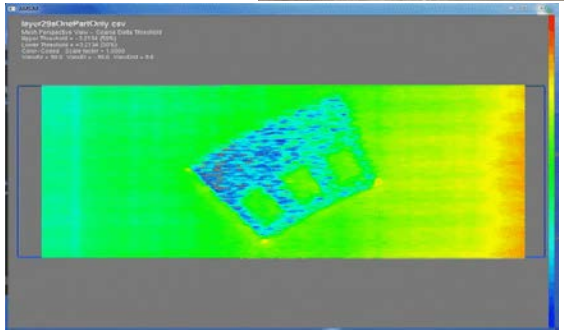
Single Layer Thermal



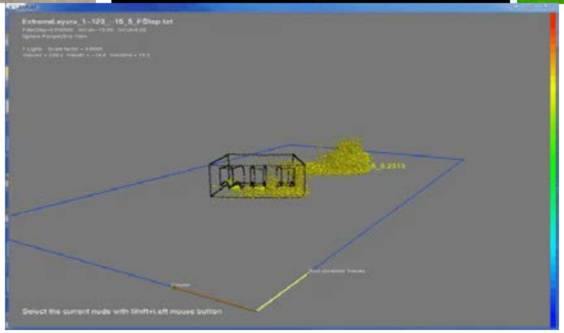
Observed Splatter



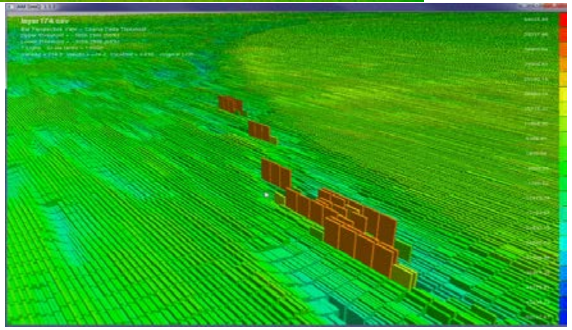
Single Layer



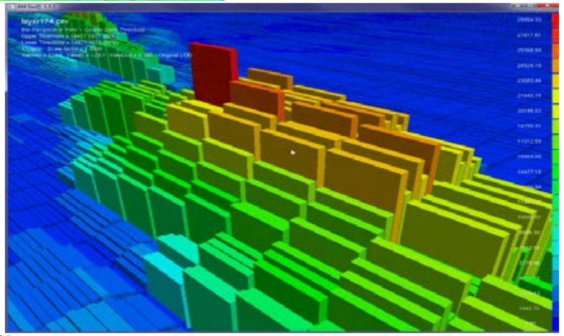
Multi Layer



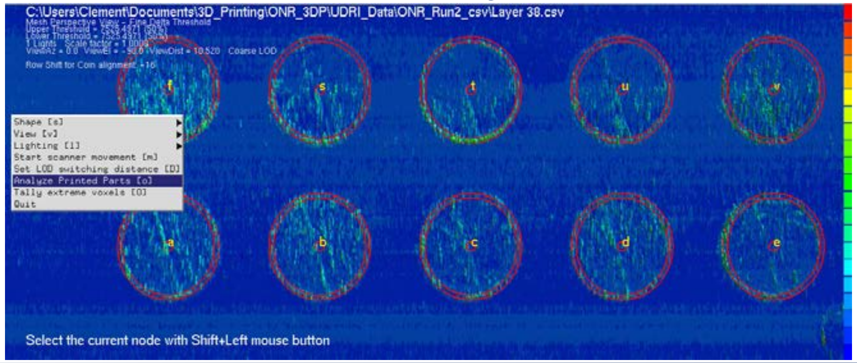
Super Elevation



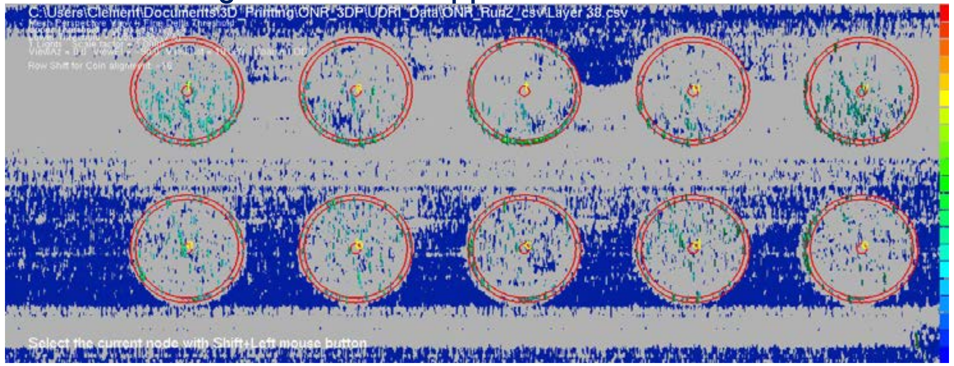
Roughness



Unfiltered voxels for Roughness Calculation



Roughness Filters applied for Voxel Tallies



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Part Qualification Account for Defects

GENOA 3DP PathCoverage: Anomalies Visualization, Material Degradation

PathCoverage: Tracks Void (shape, size, distribution), Predicts Stiffness/strength Degradation

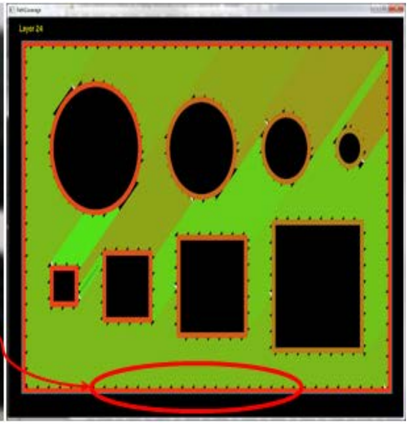
Methodology: Inputs: bead width, gcode, FE mesh

— Superimpose G-code to FE mesh calculating material properties (strength/stiffness) degradation per element

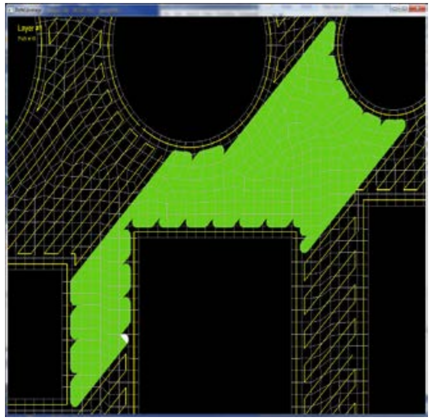
Polymer

As-Built Part

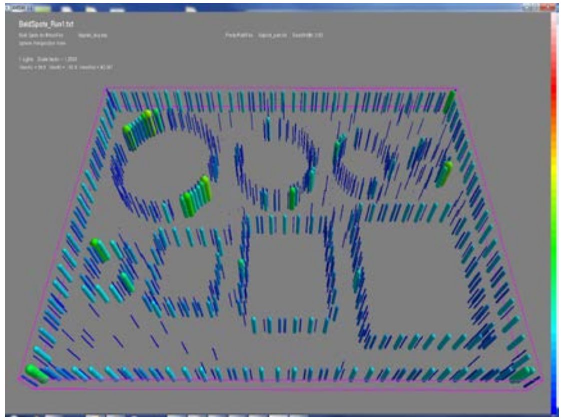
G-code/FE Mesh



Around hole



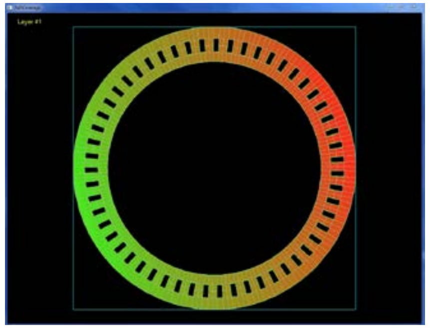
Anomalies Inside Visualization



Metal Powder

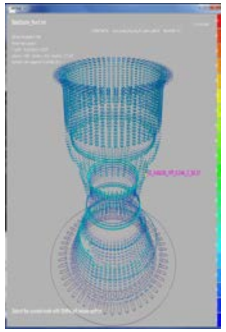
As-Built Part

Video-G-code/FE Mesh

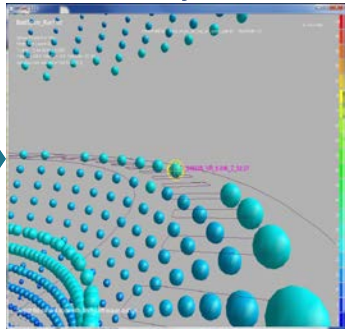


Around hole

Anomaly Location



Anomaly Size



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GENOA 3DP Thermal Management (TMg) -Micro Scale

A. Extremely fast calculation and high accuracy

B. Predicts Thermal History (6 regions)

i) Heating, ii) Melting, iii) Melt-superheated iv) Superheat-cooling v) Solidification/Sintering & vi) Cooling

C. Calculates Meltpool size / shape

Length, Width, & Depth

D. Calculates transient material states Density, Volume of Solid (VOS), void ratios

E. Predicts 3D dynamic process map (power, speed, vs. temperature)

safe/unsafe regions & optimum printing parameters to avoid defects due to Thermal behavior

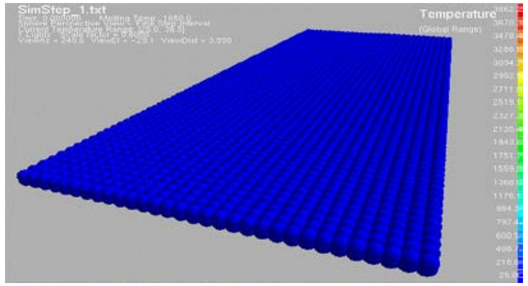
F. Grain-boundary engineering (Beta-Release)
Phase-Diagram, Crystallization, Temperature Time Transformation (TTT) Diagram, Continuous Cooling Transformation (CCT), Fine/Coarse Grains

Data Base:

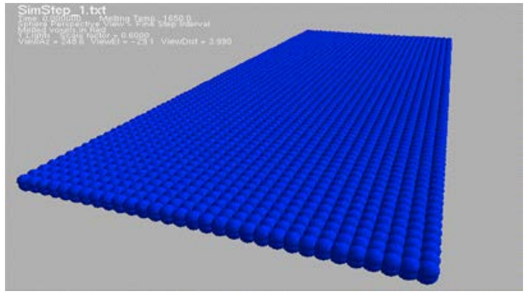
Metal: Titanium, Steel(SS 316L), Inconel 718, AlSi10Mg

Polymer: PA11, PA12, ABS (CF), ULTEM (9085, 1010), PLA

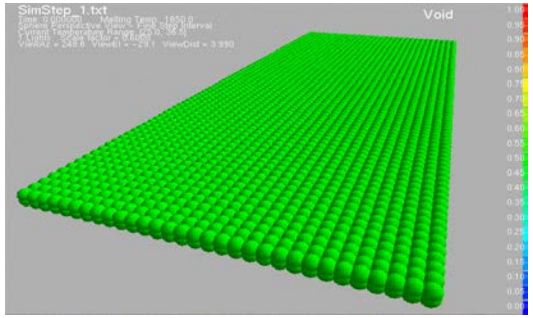
B. Thermal History (HAZ)



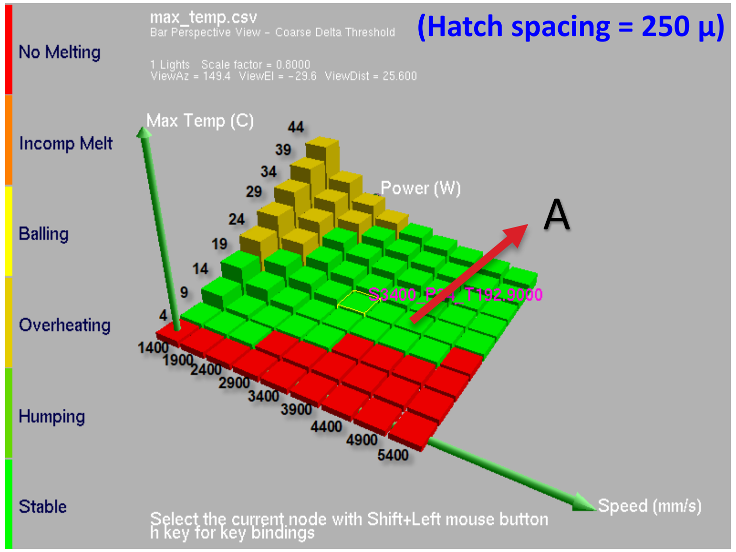
C. Dynamic Meltpool

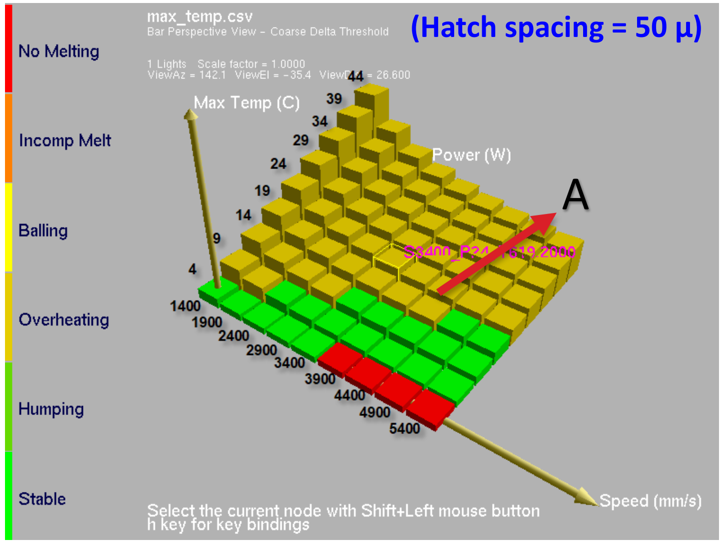


D. Transient Void Volume Ratios



E. Process map





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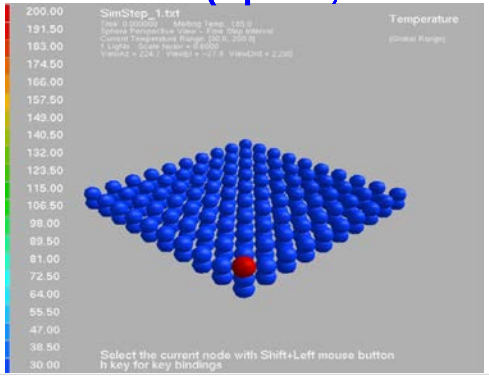
Microscale Thermal Management (TMg): FDM Vs. SLS

Prediction/Comparison of Meltpool, Density, Voids & VOS in FDM and SLS

FDM 3D Print (Speed, Init Temp)

Video

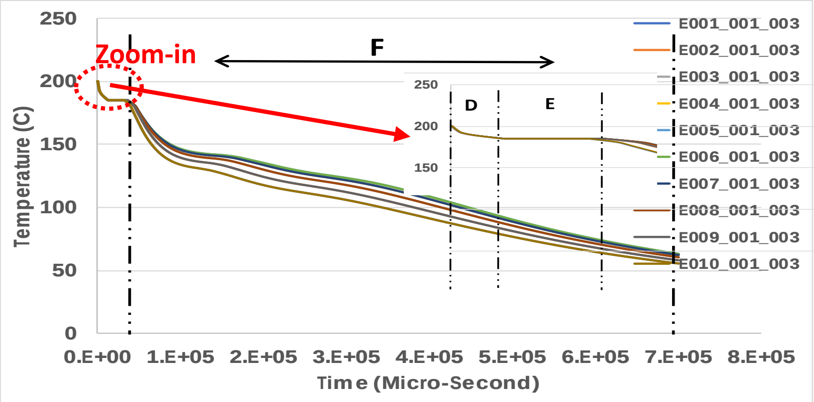


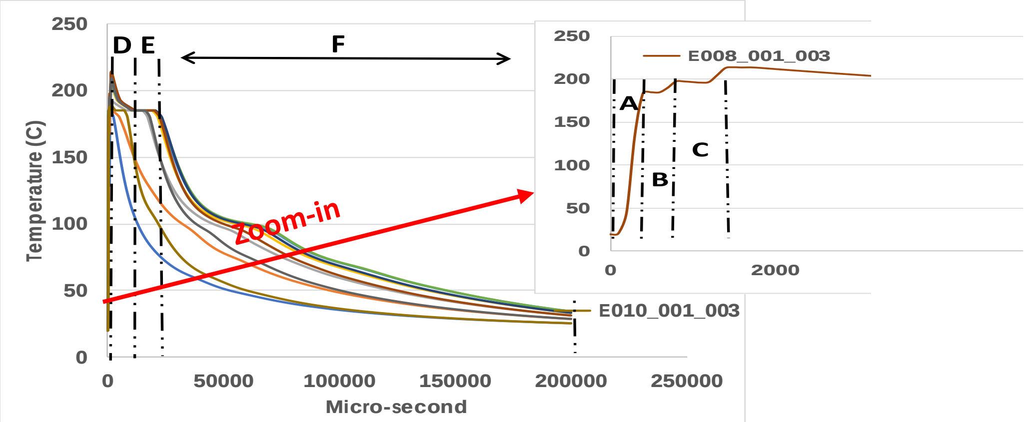
SLS 3D Print (Power, Speed)

Video

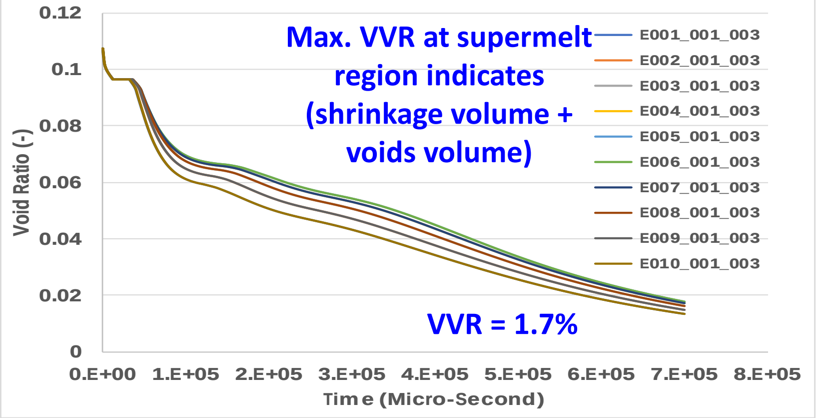
A: Heating
B: Melting
C: Melt-Supermelt
D: Superheat-Cooling
E: Solidification
F:Cooling

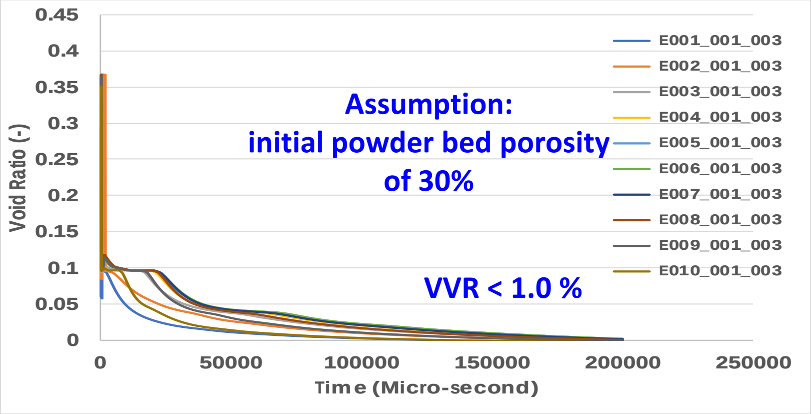
Temperature (°C) vs. Time (μs)





Void (-) vs. Time (μs)





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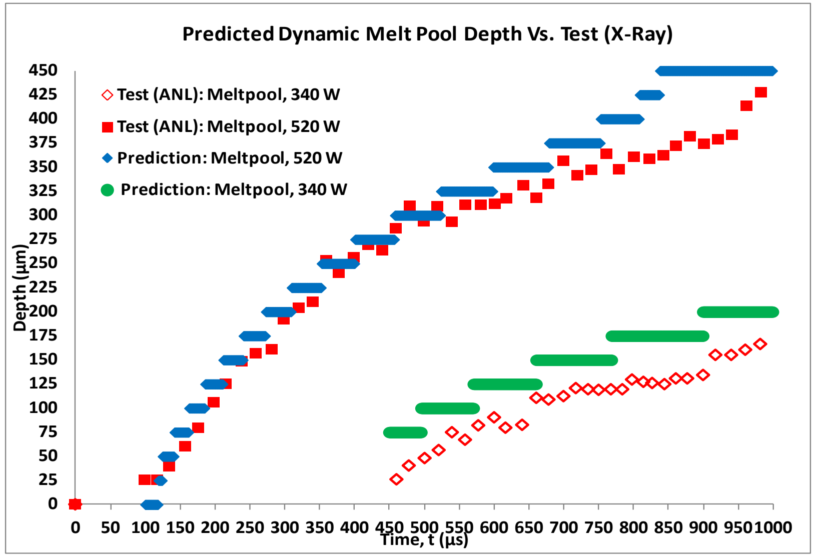
Case Study: Validated Dynamic Meltpool Evolution

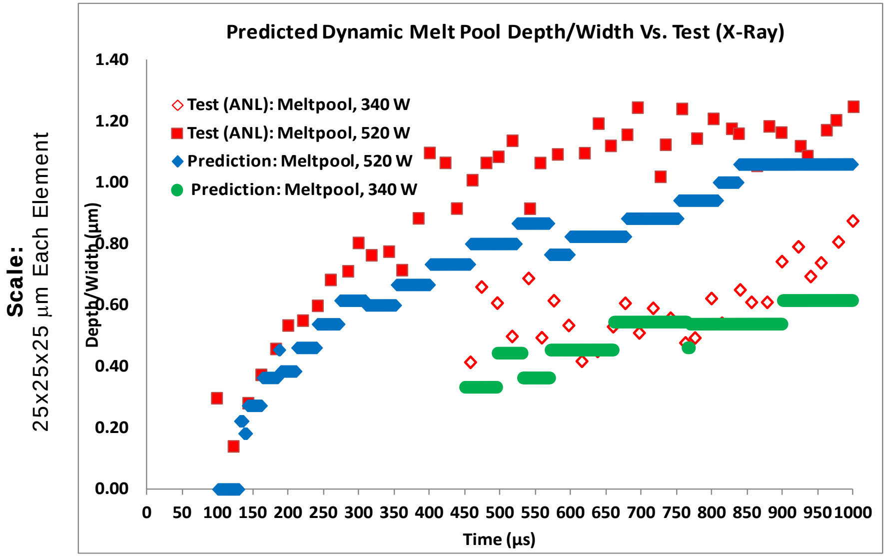
Validated Dynamic Meltpool Depth & Width (Micro-scale): TMg vs. X-ray Image

Material: Ti-6Al-4V

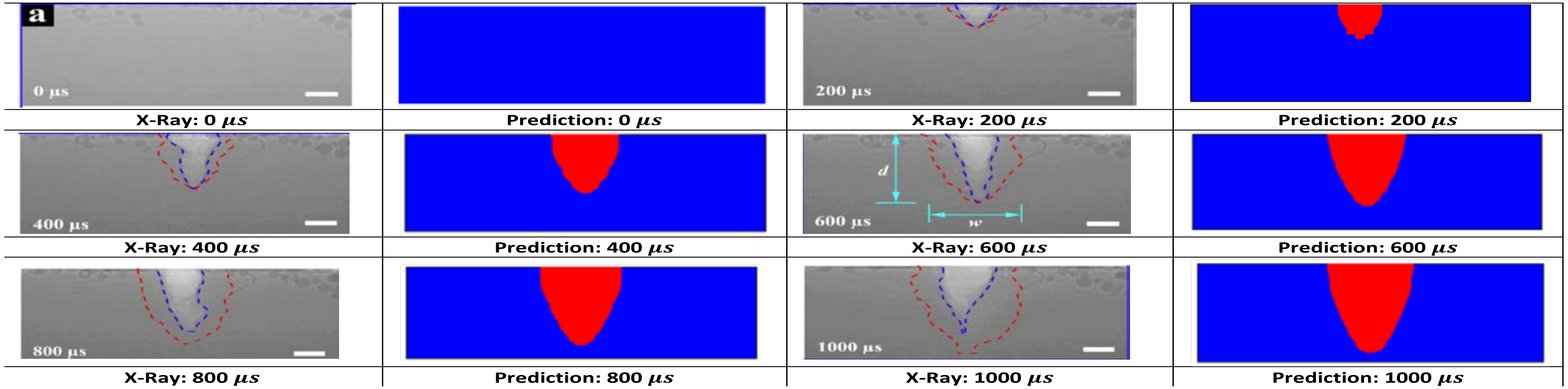
Meltpool Depth vs. Time: 3DP TMg VS. X-Ray



Meltpool Depth/Width vs. Time: 3DP TMg VS. X-Ray



Validated Dynamic Meltpool Evolution, Power = 520 W, 3DP TMg VS. X-ray Image, Laser Powder Bed Fusion (LPBF)



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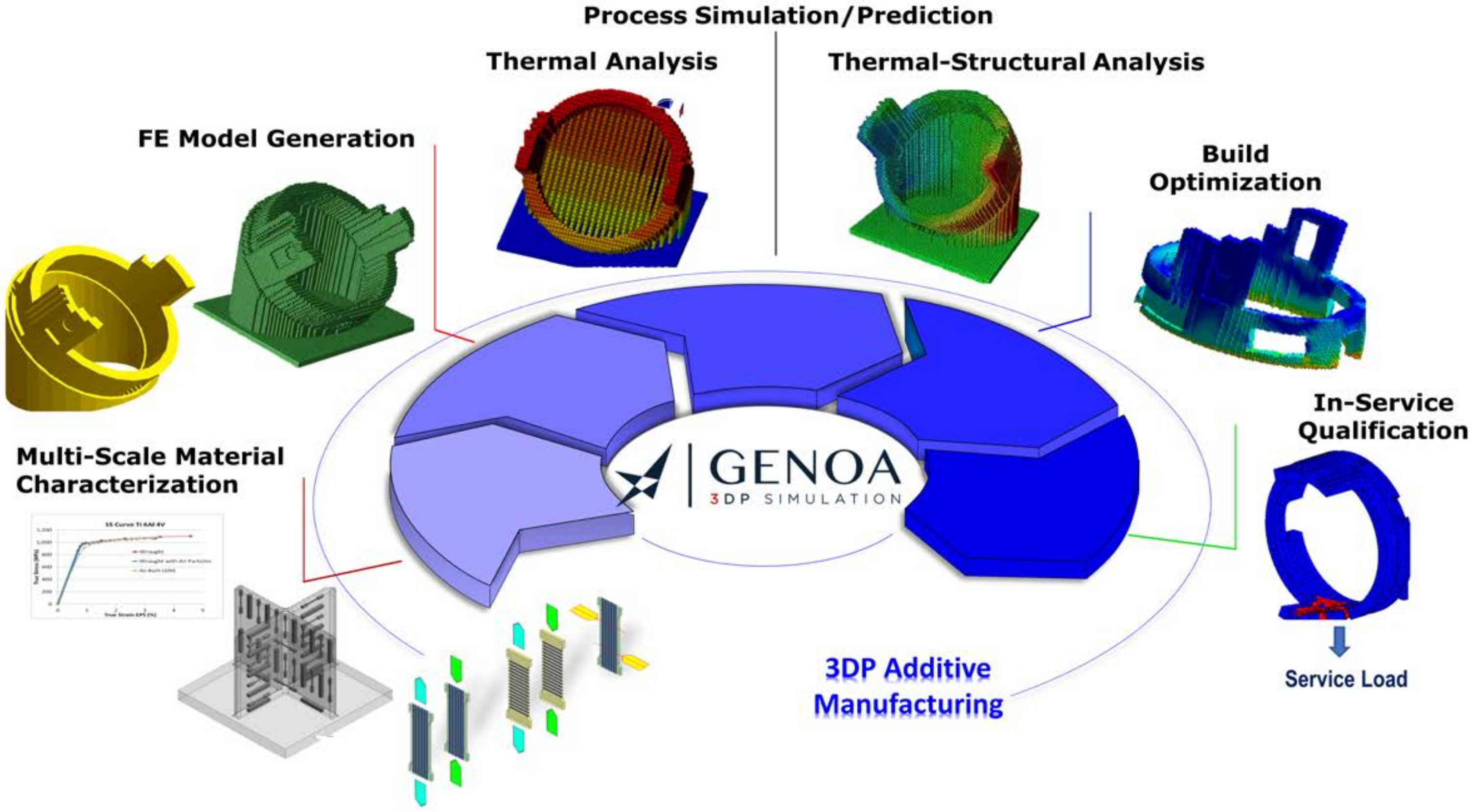
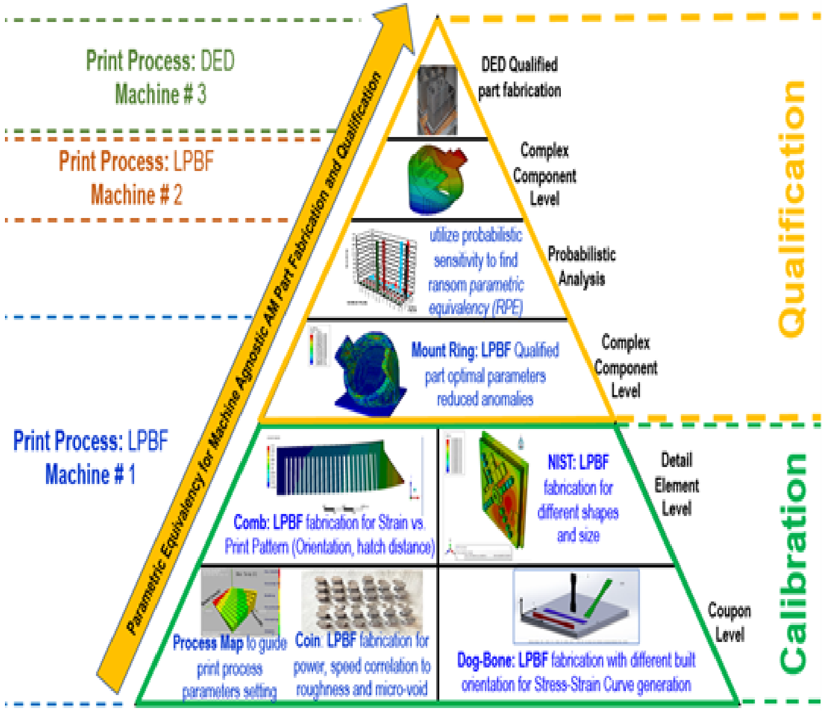
ICME Workflow for Metal AM

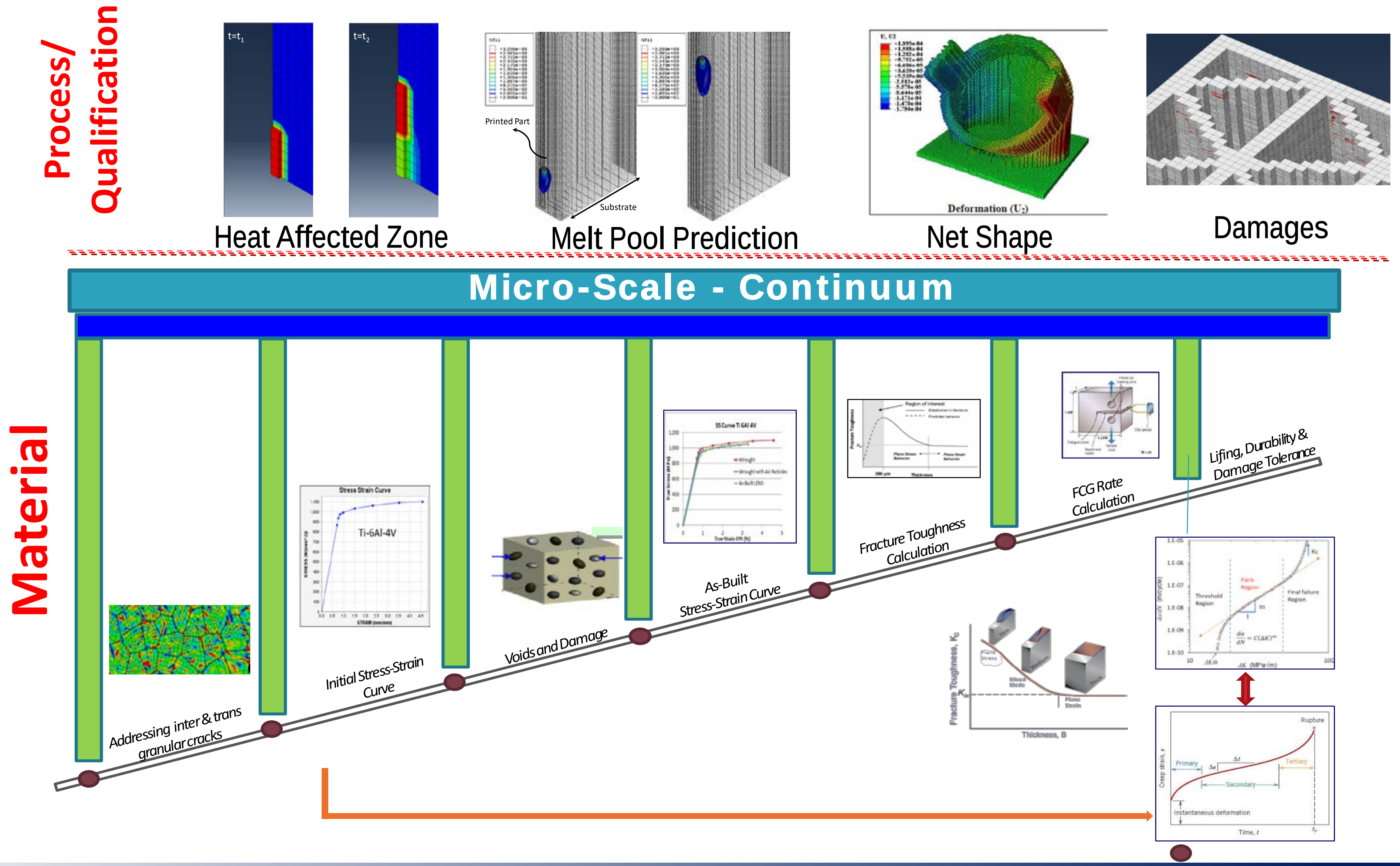


Building Block Validation



AlphaSTAR Metal ICME Tool

Multi-Scale Modeling: Material, Process, Qualification



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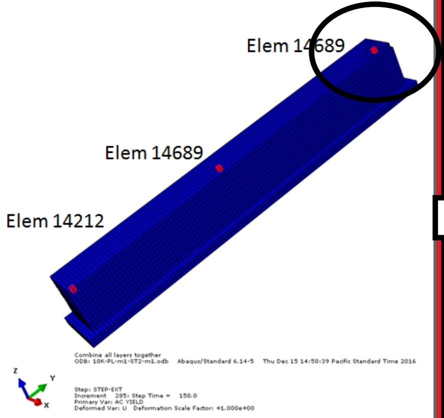
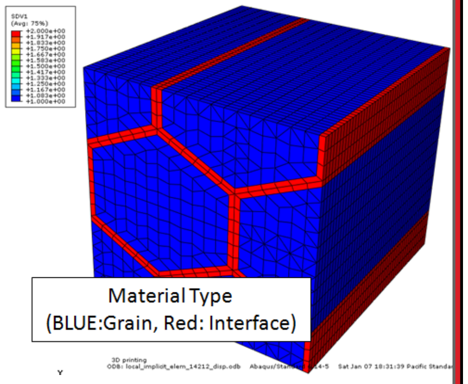
Global Local Modeling

Diffusional Creep: Predict Void, Oxidation, Residual Stress in local model

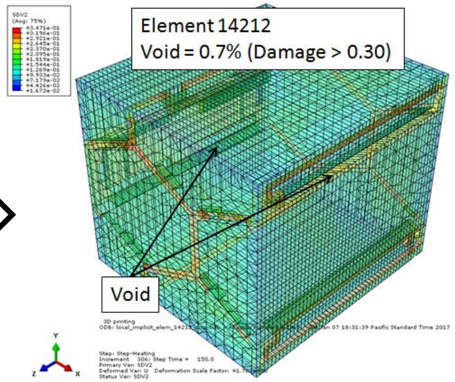
Global Model



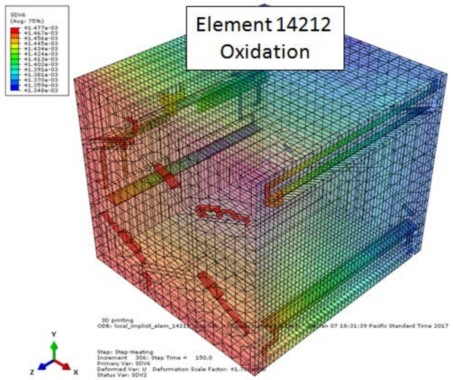
3D Local Model



Void



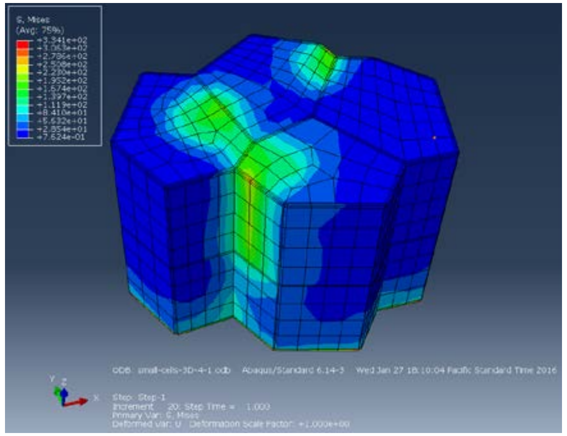
Oxidation

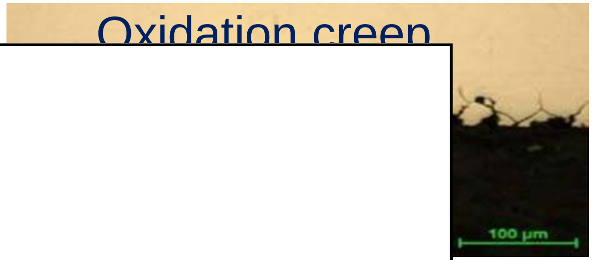


Oxidation/Diffusional Creep

Video

Residual Stress





130 MPa Von Mises stresses

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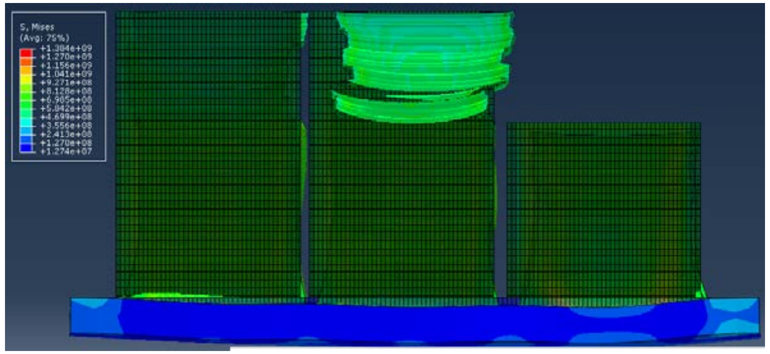
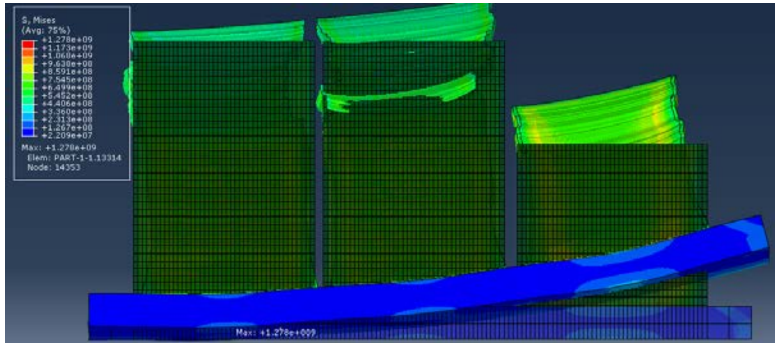
Part Qualification

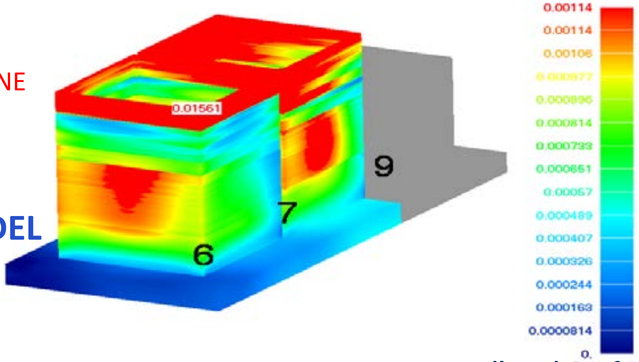
Net Shape: Sensitivity to Bolt (Fixed Corner) Removal

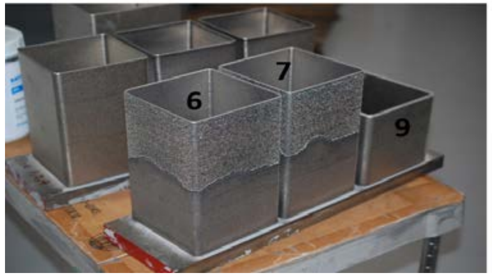
Redistribution of Residual Stress While Removing Clamps





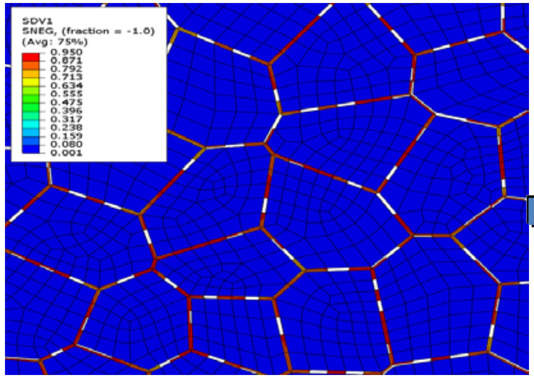
RED = SURFACE ROUGHNESS ZONE



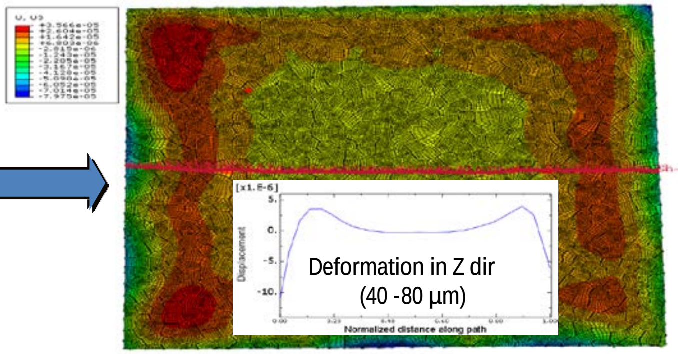


GLOBAL-LOCAL MODEL

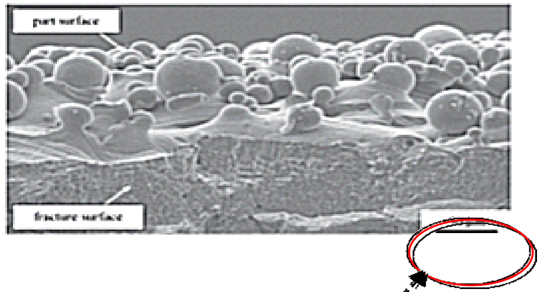
Local Model



Predicted Surface Roughness



Measured Surface Roughness



50 Micron

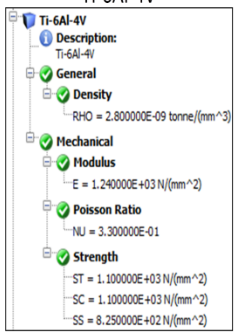
AlphaSTAR

3D Printing SS Curve Prediction vs. Test

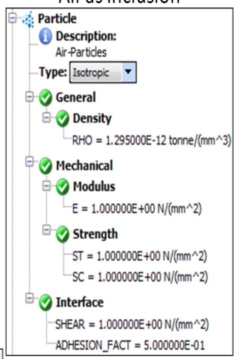
DMLS Material Model, Nano Based Inclusion / Defects Algorithm

Input Properties for Ti-6Al-4V and Inclusion

Ti-6Al-4V

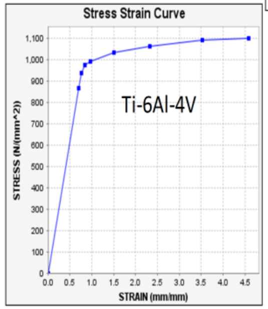


Air as Inclusion



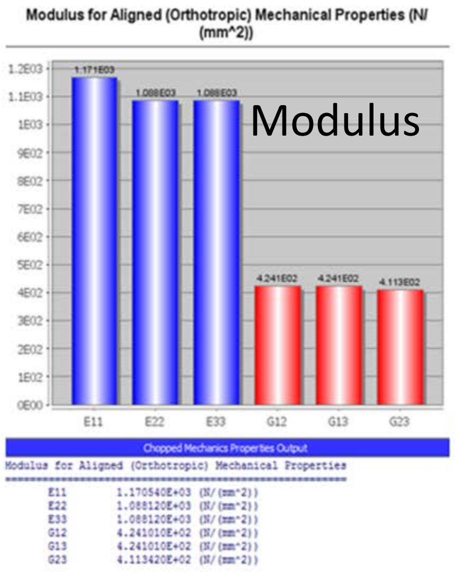
Inclusion Parameters

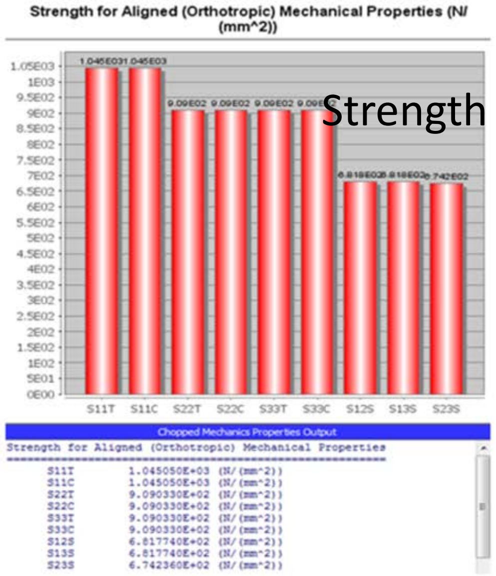
Property	Value
Shape	FIBER
Enable Void As Inclusion	false
Type	STRAIGHT
Void Volume (Fraction)	0.000000E+00
Weight (Fraction)	2.434151E-05
Volume (Fraction)	5.000000E-02
Length (mm)	5.000000E-04
Width (mm)	1.000000E-04
Height (mm)	1.000000E-04
Enable Interphase	No
Dispersion	UNIFORM

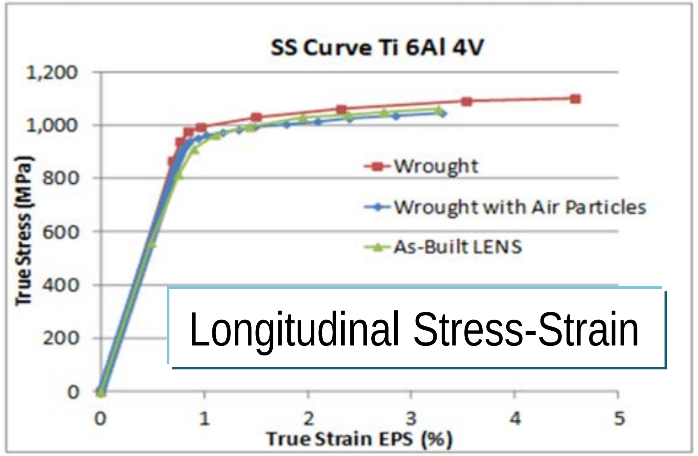


Void Volume Fraction 5%
Void : Cylindrical with AR=5
Voids are all aligned in 0 direction

Output: Modulus, Strength, Longitudinal Stress-Strain



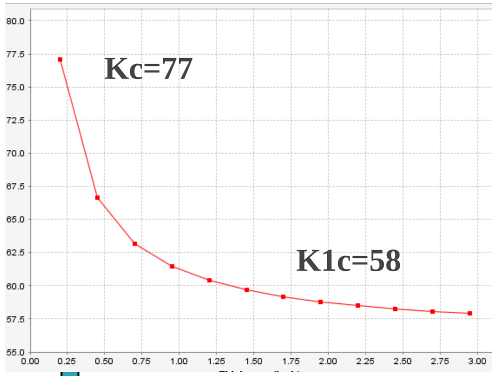




3D Printing Fatigue Prediction vs. Test

Validation of Ti 6Al 4V – DMLS at Room Temp

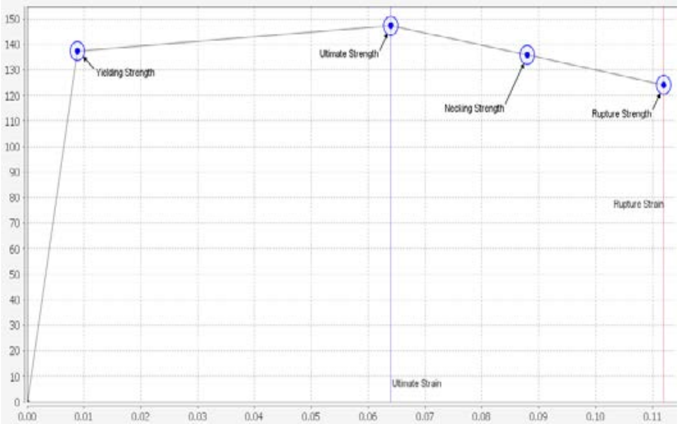
Toughness Vs. Thickness



Material Properties
- Yielding Strength = 1.375000E+02 ksi
- Ultimate Strength = 1.475000E+02 ksi
- Rupture Strength = 1.240000E+02 ksi
- Apply Stress = 1.350000E+02 ksi
- Normal Modulus = 1.550000E+04 ksi
- Poisson Ratio = 3.300000E-01
- Ultimate Strain = 6.400000E-02 in/in
- Rupture Strain = 1.120000E-01 in/in
- h Constants = 5.570000E-04
- Alpha Constants = 2.860000E+00

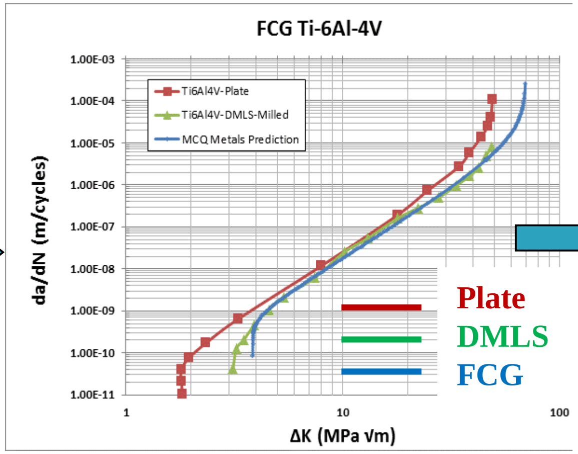
Geometry
- Specimen Thickness = 2.500000E-01 in
- Gauge Length = 2.000000E+00 in
- Initial Half Crack Length = 0.000000E+00 in
- Panel Width = 3.000000E+01 in
- Panel Thickness = 2.000000E-01 in

Full Stress-Strain Curve

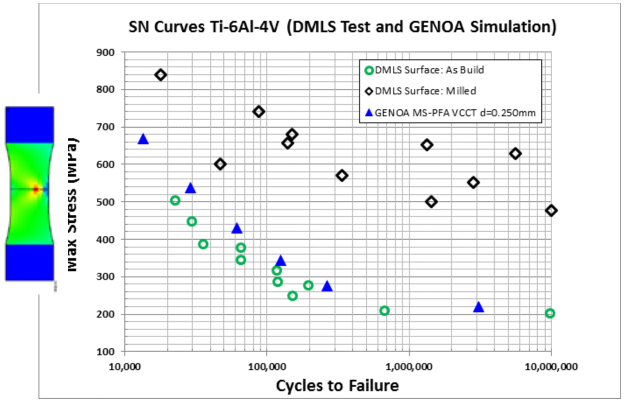


FCG Materials (1)
- **Ti-6Al-4V-DMLS**
  - **Description:** None
  - **Material Properties**
    - P Constant = 2.500000E-01
    - Q Constant = 7.500000E-01
    - Kc = 7.100000E+01 ksi*sqrt(in)
    - Klc = 4.100000E+01 ksi*sqrt(in)
    - Stress Ratio = 1.000000E-01
    - Plate Width = 5.000000E+00 in
    - Maximum Stress = 1.500000E+01 ksi
    - Alpha Constant = 2.500000E+00
    - Young's Modulus = 1.690000E+04 ksi
    - Yielding Stress = 1.400000E+02 ksi
    - alpha1 = 1.125000E+00
    - alpha2 = 9.300000E-01
    - beta1 = 1.000000E-07
    - beta2 = 5.000000E-03
    - Kth Ratio = 1.200000E+01
    - Plate Thickness = 9.000000E-01 in

FCG: Output

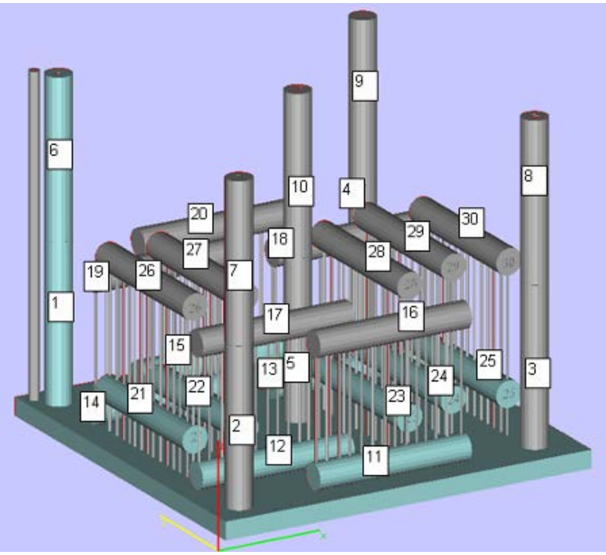


S_N Prediction/Validation R=0.1



Allowable Generation: EBM Ti-6Al-4V

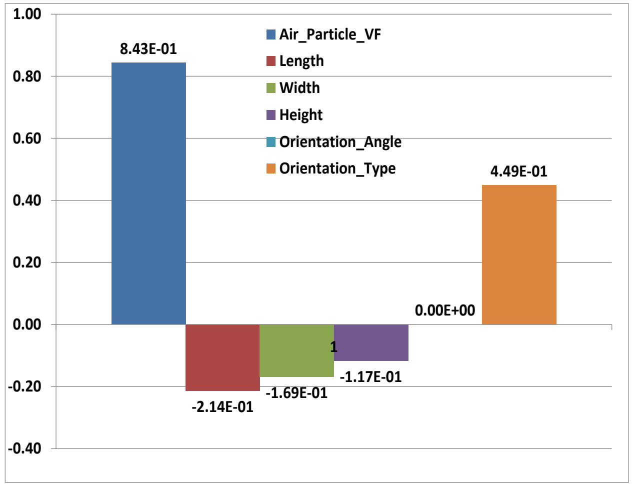
AM Test Data Scatter Predicted (Yield, Ultimate and Strain) at Room and 700F



Oxygen Level, % 0.224 %

- **Print Direction** will affect stiffness and strength properties
- **Void Shapes and Sizes** are key in determining properties
- **Scatter (COV) Prediction** was performed with acceptable results for Room and High Temperature

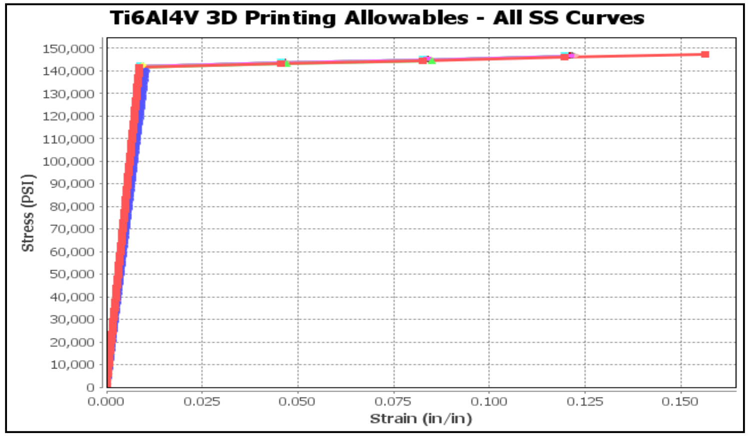
Yield Sensitivities for Test Guidance



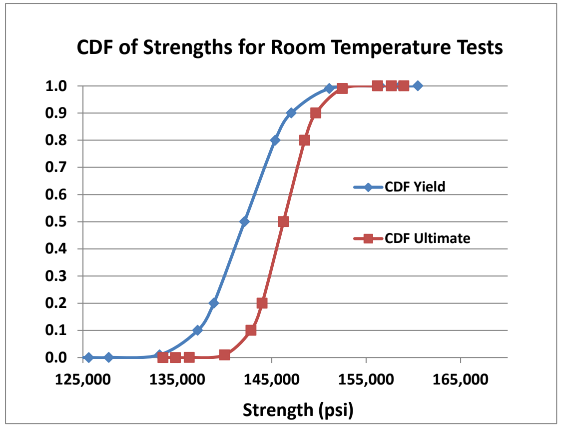
Prediction Vs. Test at RT Yield, Ultimate, Elongation

RT	YS, ksi	MCQ	%Diff	UTS, Ksi	MCQ	%Diff	El, %	MCQ	%Diff
Mean	141.1	142.1	-0.7	146.1	146.2	-0.1	13.9	12.6	9.4
SD	3.96	3.86	2.4	2.81	2.68	4.5	1.22	1.25	-2.6
COV (%)	2.81	2.72	3.1	1.92	1.83	4.6	8.78	9.76	-11.1
HT	**YS, ksi**	**MCQ**	**%Diff**	**UTS, Ksi**	**MCQ**	**%Diff**	**El, %**	**MCQ**	**%Diff**
Mean	78.1	75.3	3.5	96.0	87.7	8.6	19.1	18.2	4.9
SD	2.83	2.79	1.4	2.46	2.55	-3.8	0.84	0.91	-7.4
COV (%)	3.63	3.71	-2.2	2.56	2.91	-13.6	4.42	4.98	-12.9

SS Curves from MCQ Predictions



CDFs for Reliability



Part Qualification & Requirement

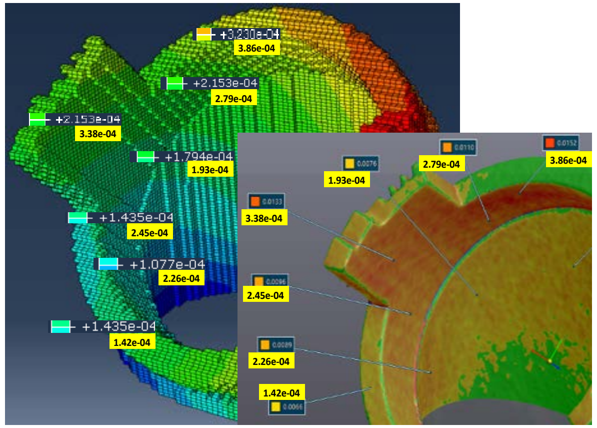
Qualification Categories

Qualification Category	Description
1-Micro defects	Micro voids/Density during thermal history, super melting sintering and solidification
2-Macro defects	Macro porosity: Printing error around hole and boundary
3-Surface roughness	Diffusional creep, Triaxial stress
4-Intergranular cracks	Diffusional creep, Biaxial stress
5-Scatter in material properties	Stress-strain relation (yield stress, ultimate/plastic strain) due to voids (micro/macro) and cracks
6-Fracture control plan	Characterization of fracture properties, fatigue crack growth, stress intensity curve
7-Warpage	Evaluation of support, Residual stress
8-Net shape	Residual stress, Baseplate removal
9-As-built performance	In-service loading
10-Post heat treatment	Grain growth, lower strain; thermal analysis

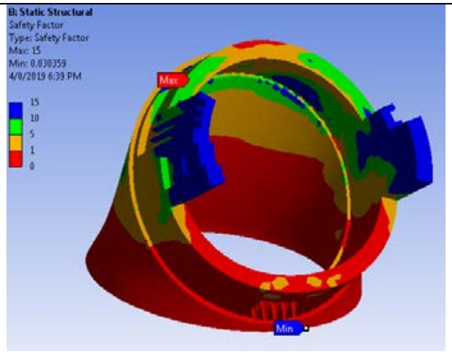
Primary Machine Parameters

Item	Parameter	Description	Controled or Predefined
1	Average Power, P	Total Energy Output of Laser	Controlled
2	Scan Velocity, v	Velocity of laser across surface	Controlled
3	Scan Spacing, Ss	Distance between neighboring passes	Controlled
4	Scan Strategy	Pattern of laser scanning (spirals, zig-zag)	Controlled
5	Deposition System Parameters	Recoater vel, pressure, recoater type, closing	Controlled
6	Layer thickness, L	Height of single powder layer	Controlled
7	Powder bed temperature, Tp	Build temperature of powder bed	Controlled
8	Oxygen level, %O2	Likely most important environment parameter	Controlled
9	Gas flow velocity, vg	Influences convective cooling	Controlled
10	Ambient Temeprature, Tinf	Affecting cooling,reheat, and residual stress	Controlled

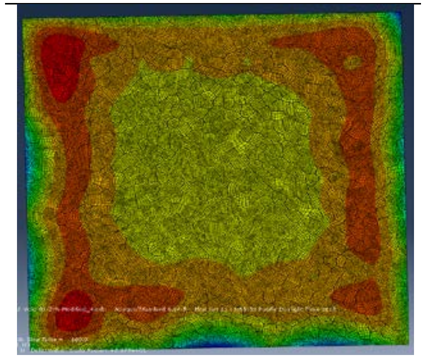
Netshape



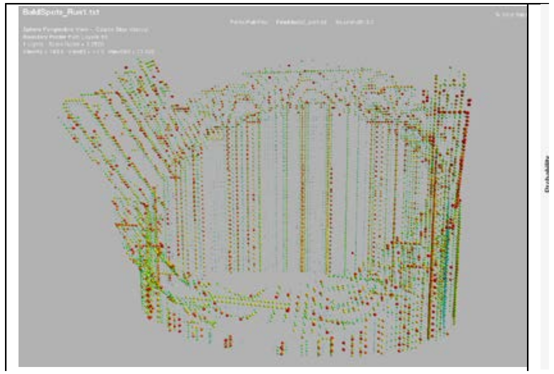
Safety Margin



Roughness



Porosity



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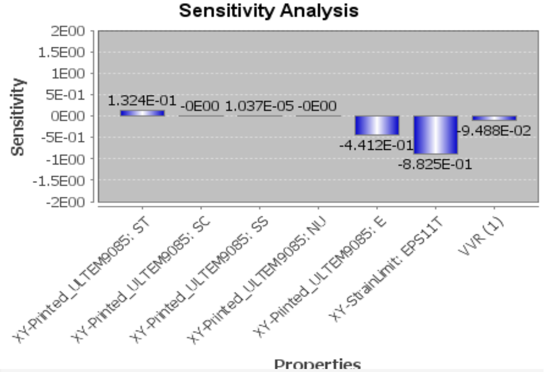
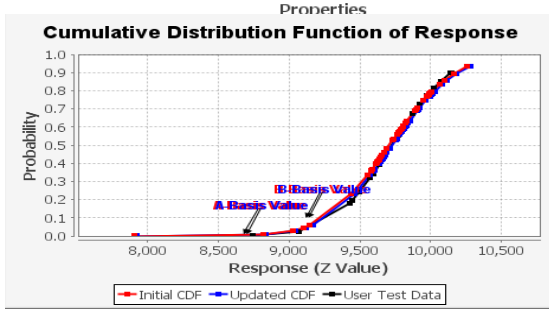
Part Distortion: ULTEM 9085

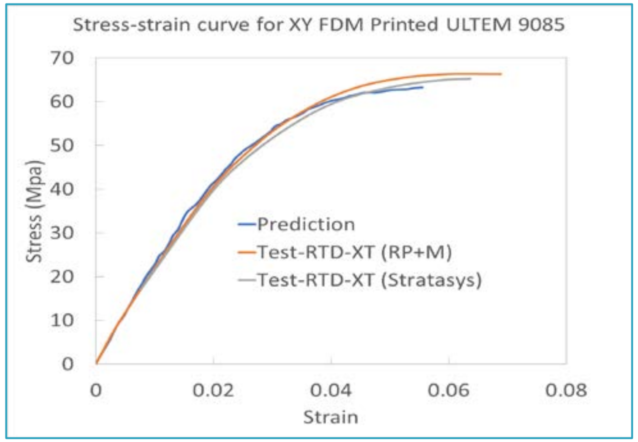
Allowable-Sensitivity



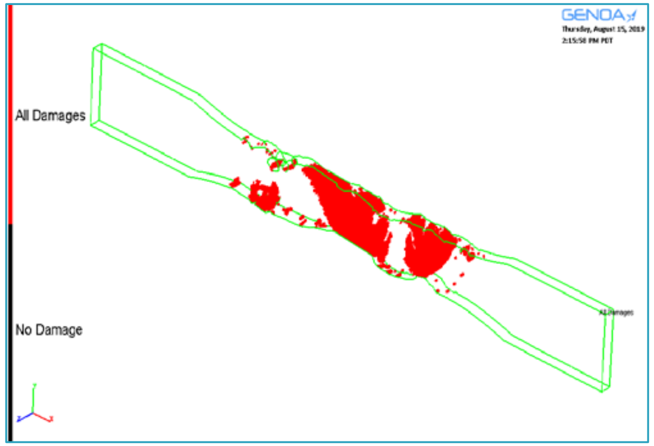


Material

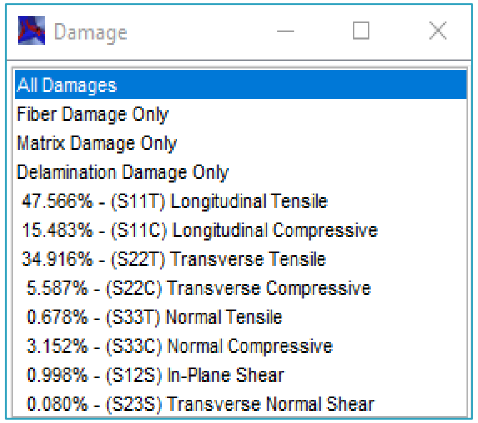
Stress-Strain Vs test



Damage Location



Damage Index



Assumed Print Input Parameters

- Printing Speed: 60mm/s
- Layer Thickness : 0.253mm
- Bead width : 0.33mm
- Chamber or ambient Temperature : 100 °C
- Bottom Plate Temperature : 160 °C
- Bottom Plate Thickness : 1.524 mm
- Bottom Plate Material : Stainless Steel
- Nozzle Temperature : 350 °C

Input

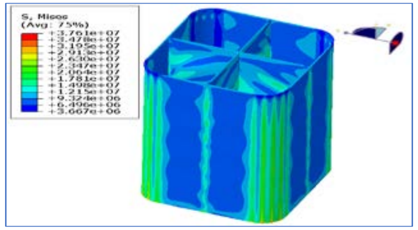
- Temperature dependent Non-linear material properties in ABQUS GENOA UMAT
- External Mesh with 510507 elements and 793560 nodes

Assumption

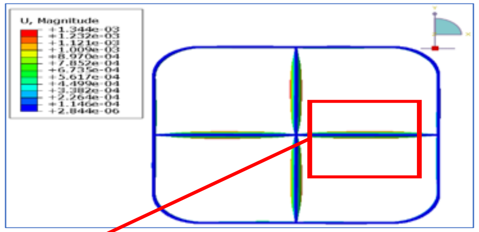
- Layer-by-layer printing
- 1 % spherical shape micro void is implemented which was predicted by TMg

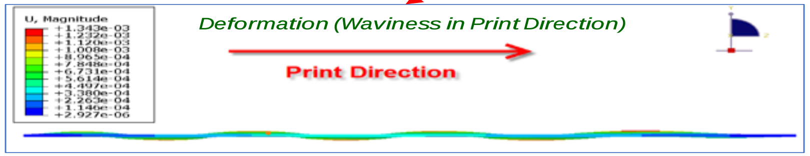
Results & Conclusion

Residual Stresses after Bed Removal



Deformation





Added Value: Prediction of waviness in XY plane and also in Print Direction (Z)

PART

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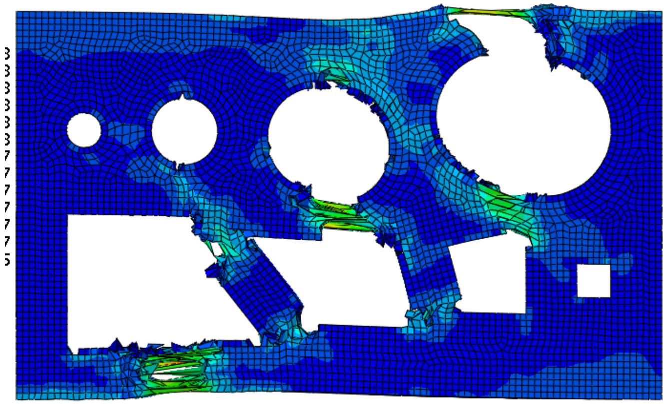
Service Loading Qualification & Damage Evolution

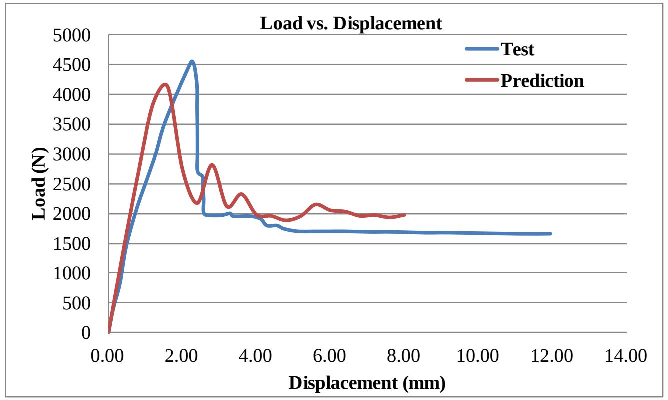
Multi-Scale Progressive Failure Analysis

Open-Hole Plate Part – Test

Open-Hole Plate Prediction

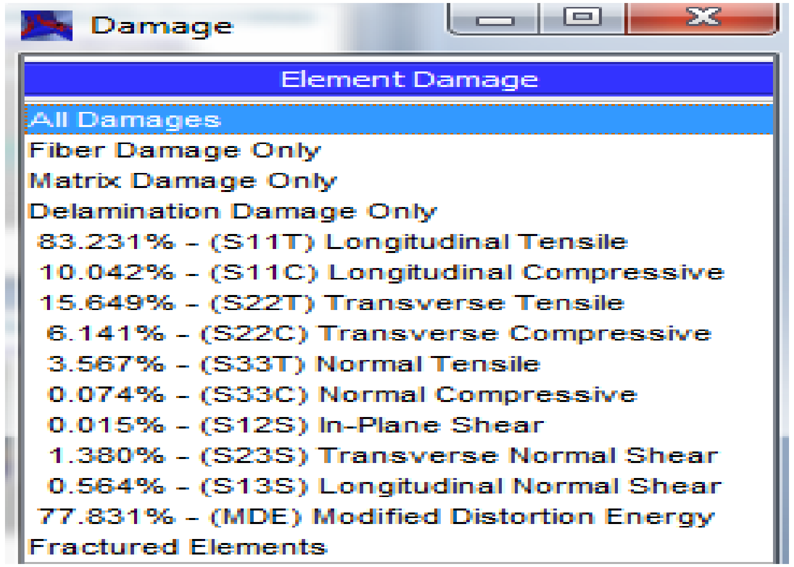


Load Displacement



All Damages

Damages Type



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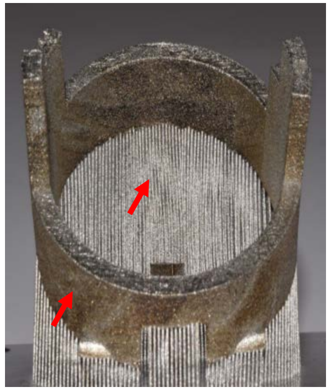
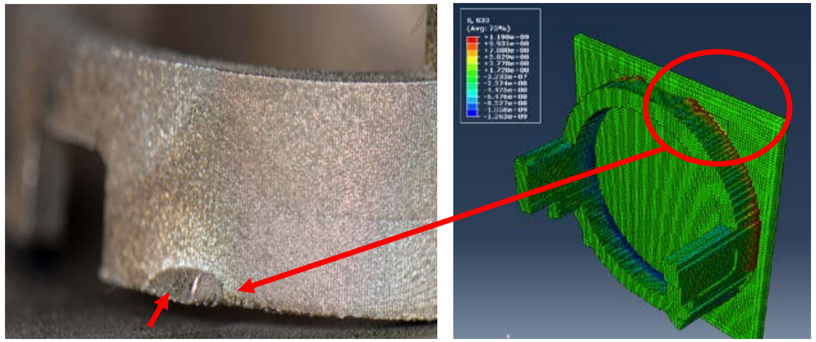
Case Study: Warpage & Residual Stress Prediction

Stress buildup leads to Bracket and Support Warpage – Reduce Trial-Error, Scrap Rate Problems

Ring Bracket Built Using Inconel 718 Powder

1st Build – Bad Part





Warping/residual stresses predicted in simulation

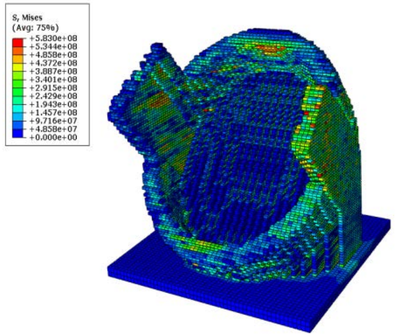
Warping eliminated through simulation DOE: improved support design and optimized build parameters to reduce residual stresses

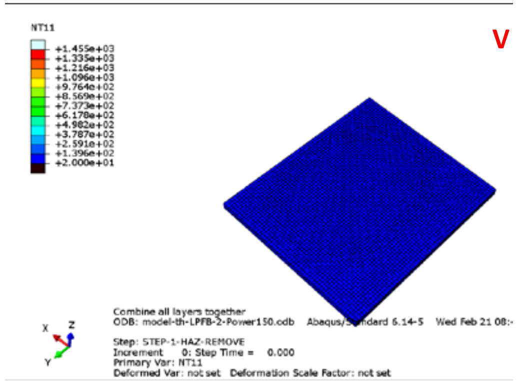
3rd Build – Good Part

Optimized build changes:

1. Mark speed increased
2. Hatch spacing increased
3. Hatch shifted layer to layer (avoids overlap)
4. Support thickness increased

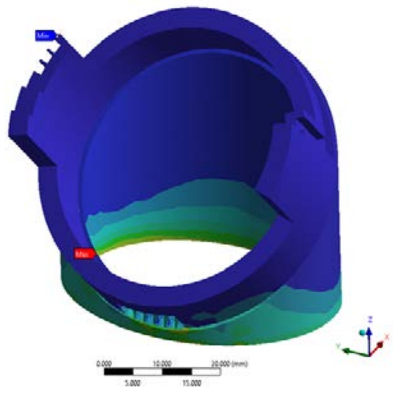
Lower Residual Stresses ⇨ *Smooth, Warp Free Part*





Mount Ring Virtual Quality Assessment

Net Shape, Defects

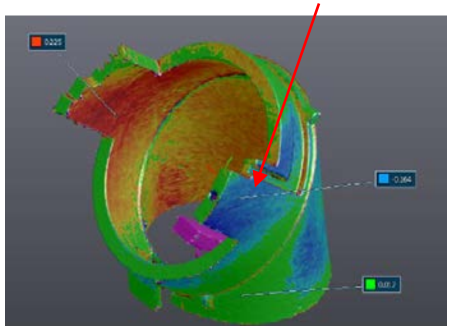


- Detailed stress model for part optimization
- Utilizes mapped void content
    - reduced stiffness and strength
- QUALIFY AS BUILD PARTS

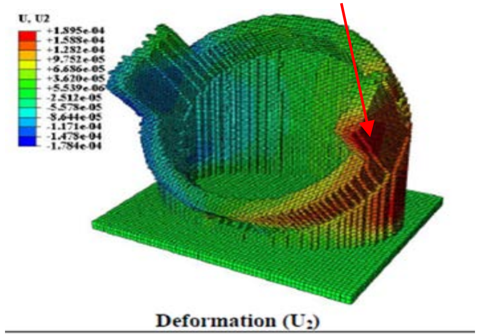
Layer 50 % Voids Content Computed

Voids detected form path coverage amount mapped to detailed stress model

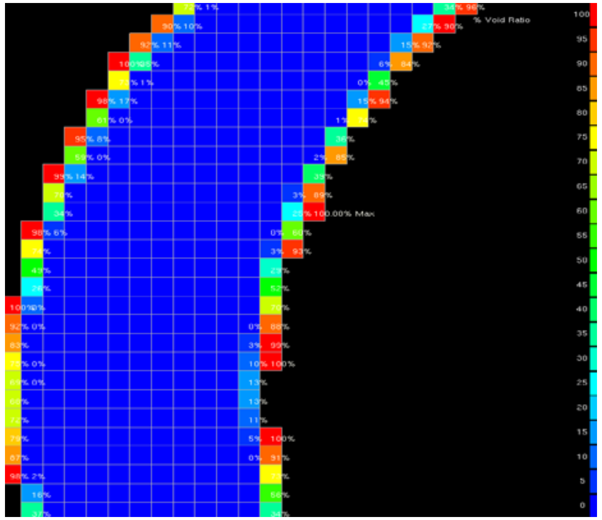
Net shape scan (0.0164"in)

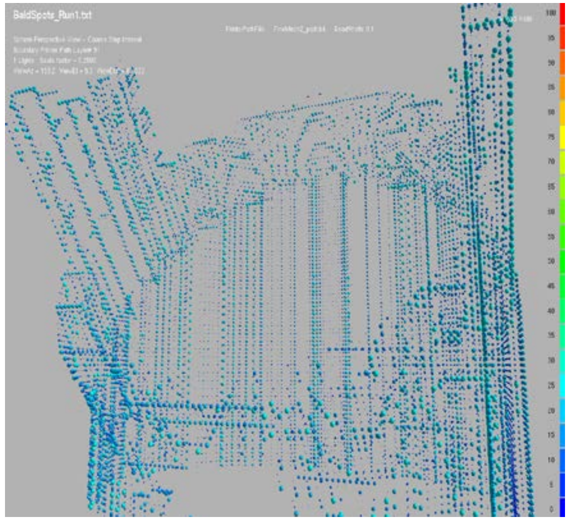


Net shape sim (0.0189"in)



2D/3D Defect Computed





Conclusion

ICME: Simulated AM Process Considering Defects and Inclusion

- ❑ **Metal Material Model:**
  - ✓ Effect of Defects,
  - ✓ **Mechanical Properties:** Prediction (Strength-Stiffness) Fracture Properties,
  - ✓ **Fracture Control Plan**: Toughness, Fatigue, Diffusional Creep, Allowables
  - ✓ **Creep Diffusion**: Surface Roughness, Internal Voids and Defects.

- ❑ **Process Simulation for Residual Stress and Deflection:,**
  - ✓ Void and Defect Prediction and Effect on Mechanical Properties;
  - ✓ **Local Void / Roughness / Oxidation Models,**
  - ✓ **Path Coverage Module:** Detect Voids from Gcode/FEM, Predicts Reduced Properties

- ❑ **Qualification Service Model:**
  - ✓ Static, Fatigue, PSD, Impact
  - ✓ Probabilistic Analysis Module: Consider Defects & Uncertainty to Qualify Printed Part

- ❑ **In-Situ Monitoring:**
  - ✓ **Visualization & Calculation**
  - ✓ **Data Driven:** Profilometer and IR Thermograph Camera available on AM Printer
  - ✓ **Data Driven Thermal Management:**
    - ✓ Heat Affected Zone, Melt Pool, Material State (Void, Density)

- ❑ **Surrogate Model Optimization – Data or Simulation Driven Optimization**

- ❑ **Integrated with CAE Standard:**
  - ✓ ANSYS (Work Bench), ABAQUS (CAE Plug-In) , and NX NASTRAN