Session 8, questions 5-8
Alonso D. Peralta, PhD.
Staff Engineer
Materials and Process Engineering
Honeywell Aerospace

Collaborators:
HON: J. Neumann, H. Deutchman
ESI: M. Megahed
QuesTek: J. Gong, D. Snyder, G. Olson
Sigma Labs: M. Cola
SwRI: M. Enright, J. McFarland
Stratonics: J. Craig

NAS Workshop on Predictive Theoretical and Computational Approaches for Additive Manufacturing

AM Scalability, Implementation, Readiness, and Transition

October 8, 2015

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DARPA Contract No and disclaimer

Some of the material presented here was developed under the Honeywell DARPA OM Program.

This material is based upon work supported by the Defense Advanced Research Projects Agency under Contract No. HR0011-12-C-0037.
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Questions to be Addressed

- (5) What measurements of quality or systems are appropriate that correlate computational and analytical methods to practical implementation?
- (6) Software architecture and data-bases for AM model development
- (7) Careful design of validation experiments for model validation, uncertainty quantification, and in situ process monitoring
- (8) Software development, integration with precision engineering, and integration into engineering work flow

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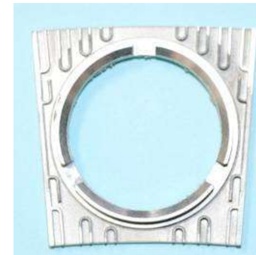
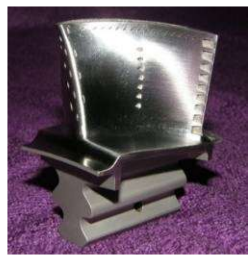
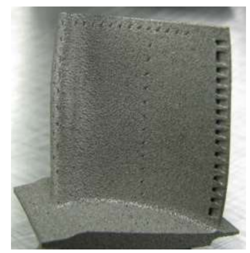
Examples of DMLS Built Components at Honeywell

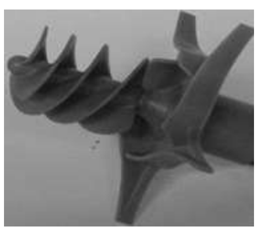
Various Part Complexities were Manufactured



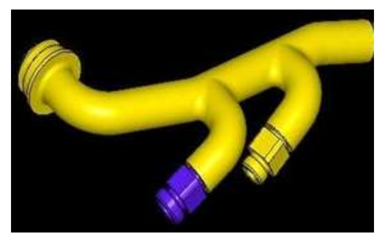







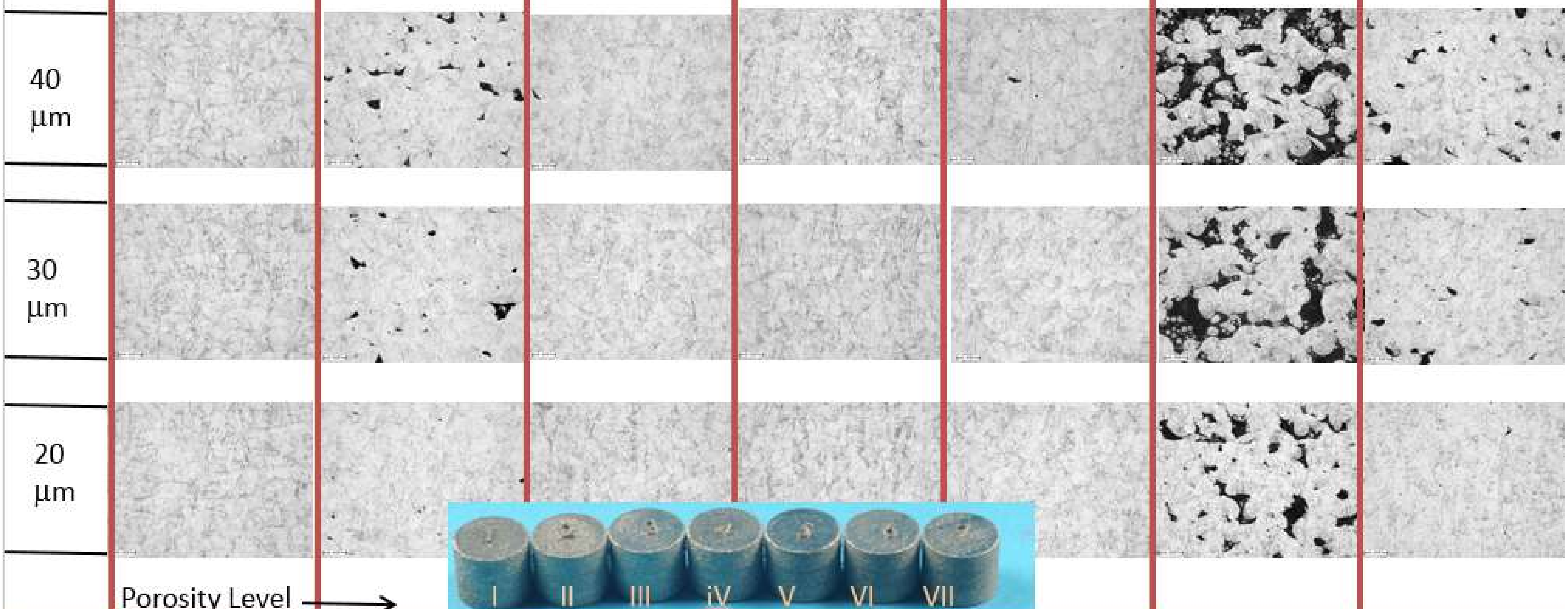



Functional Testing Substantiations ranging from rig to engine testing

Exploratory EOS M280 Build Condition Outcomes

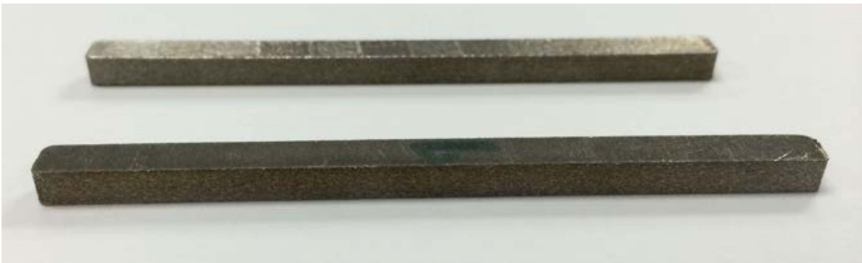
Power=370W, Speed in mm/sec

Disp-lace-ment	I	II	III	IV	V	VI	VII
	GED=3 Hatch=140µ Speed = 880	GED=1.2 Hatch=140µ Speed=2200	GED=1.6 Hatch=100µ Speed=2250	GED=3 Hatch=100µ Speed=1230	GED=2 Hatch=140µ Speed=1320	GED=0.7 Hatch=140µ Speed=3780	GED=1.2 Hatch=100µ Speed=3080

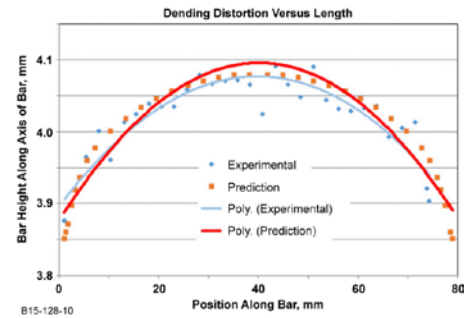


40 um	0.001-0.006%	3.03-4.83%	0.03-0.42%	0.002-0.018%	0.13-0.45%	30.13-30.86%	7.20-12.28%
30um	0.002-0.013%	2.65-3.48%	0.04-0.43%	0.01-0.02%	0.12-0.31%	20.2-23.9%	2.59-4.79%
20 um	0.002-0.008%	0.95-1.19%	0.10-0.21%	0.003-0.012%	0.05-0.56%	11.1-11.6%	0.68-8.99%

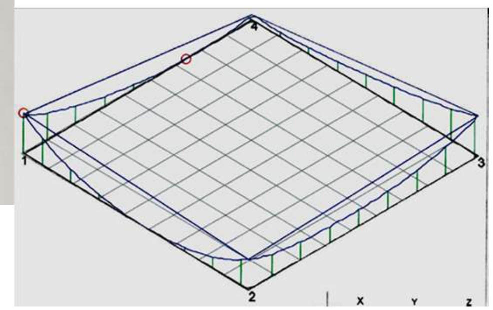
The Powder Bed Laser AM Process Inherent Residual Stresses

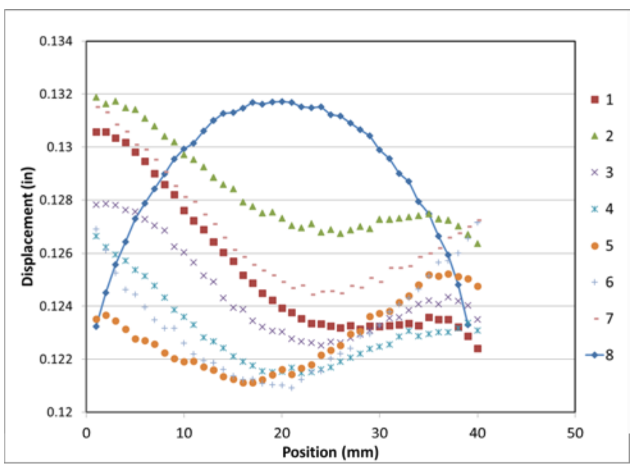


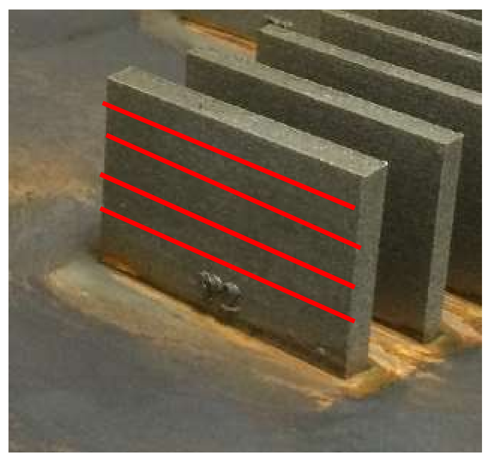
1D – residual stress



2D – residual stress







Position Dependent – residual stress (3D?)

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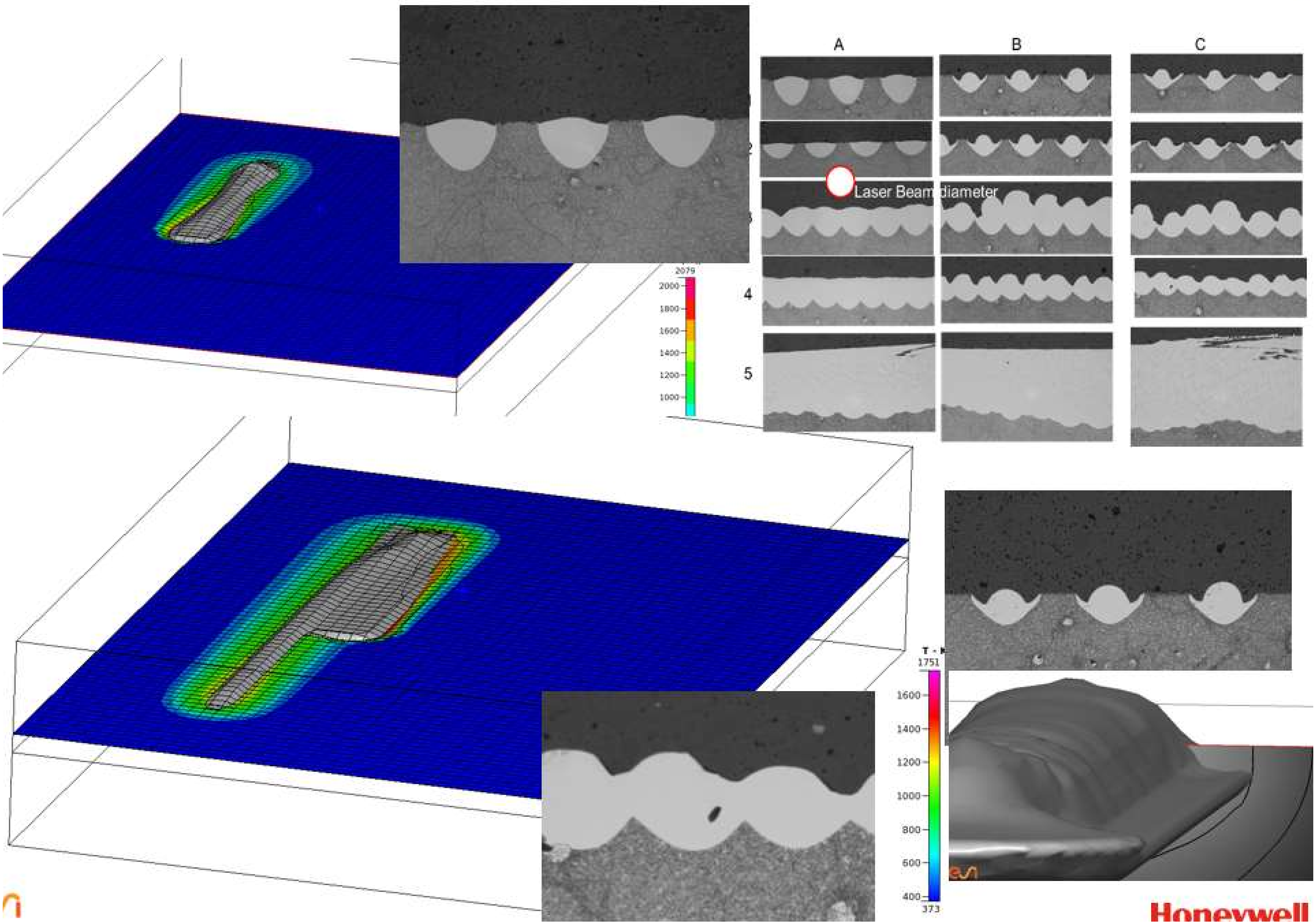
Examples of Software/Database Requirements



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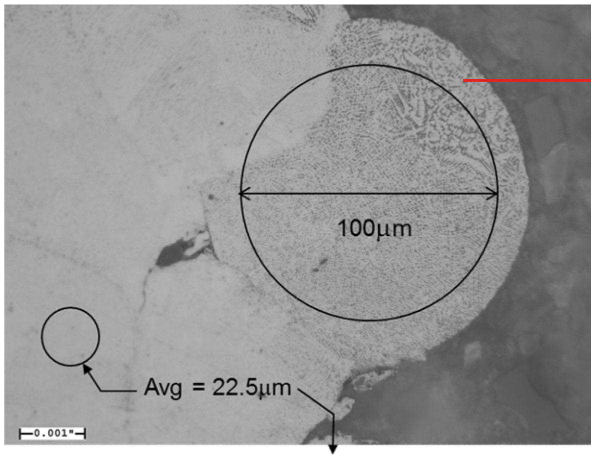
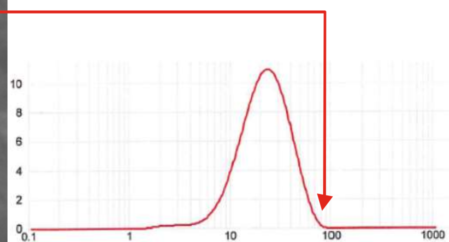
Possible Defects Found in Powder Bed Laser AM Builds

LOF- Large powder particle

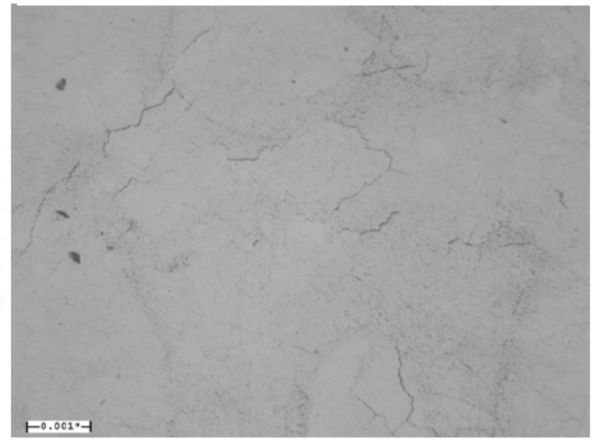
Large powder particle not melted



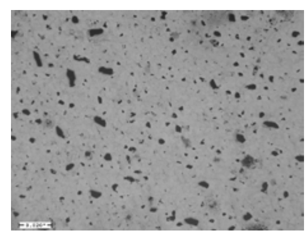


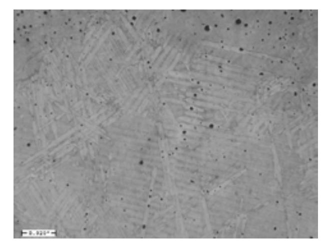
IN718+ DMLS
Powder Distribution

Liquation micro-cracking



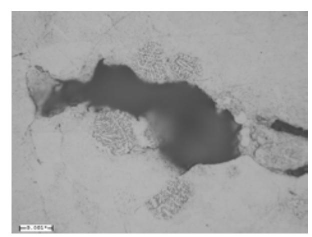
Types of Porosity

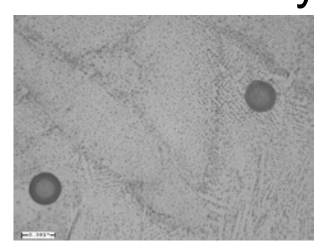




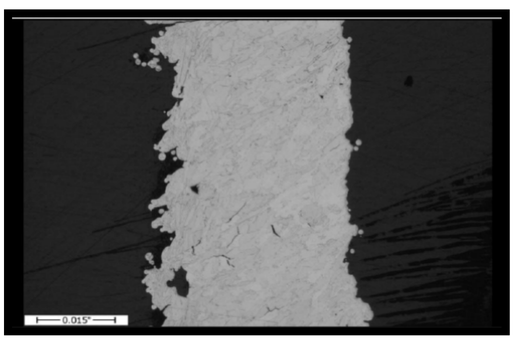
Lack of Fusion

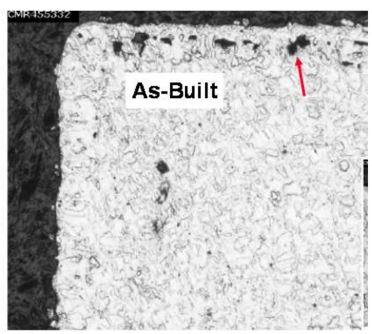
Gas Porosity/ KW



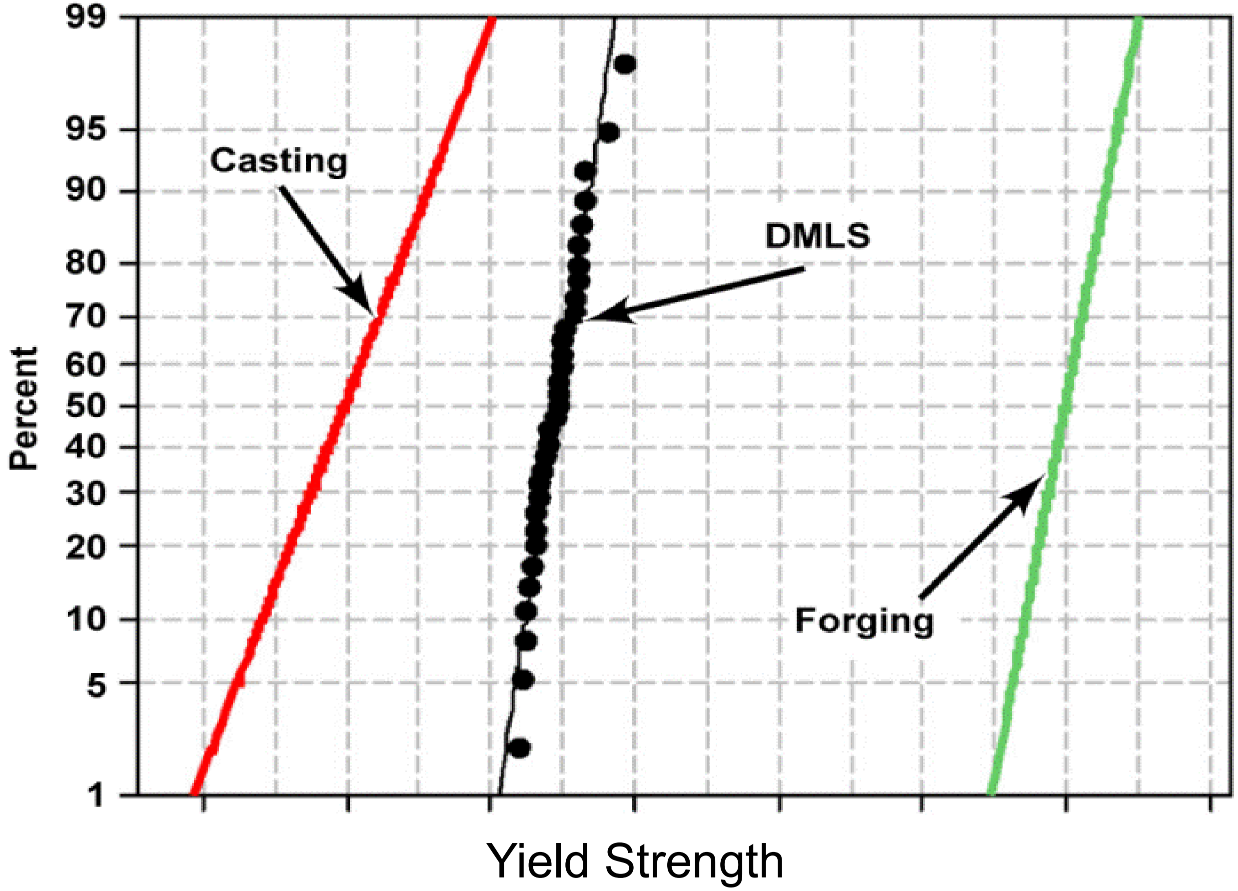


Surface roughness





AM 718Plus Yield Strength Comparison



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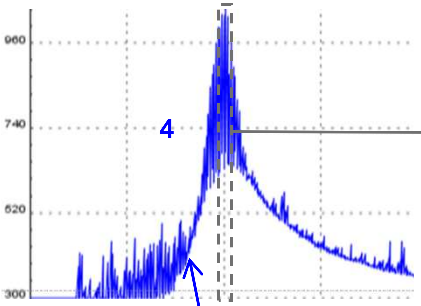
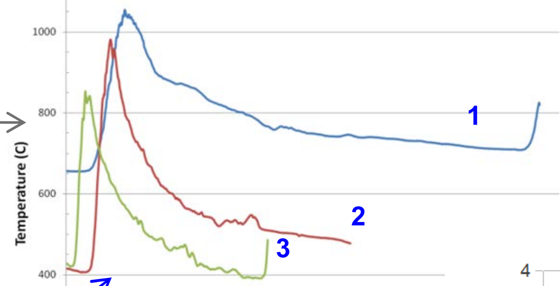
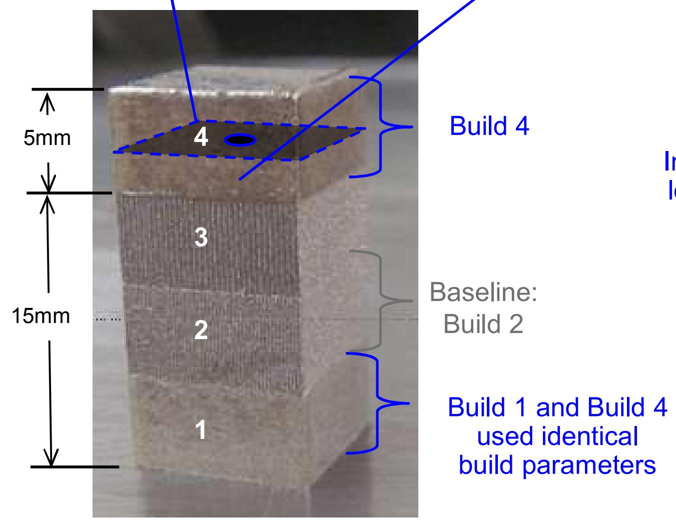
Task 2: PrintRite3D Quality Metric Analysis
Results: New pyrometers: IMPAC IGA 740-LO

Data from a single build layer



Data from single peaks





Layer	Condition	G [J/mm²]	Assumed Porosity Level [%]
1	DOE 1, Set 6	6.24	3.3% (Boiling)
2	DOE 3, Set 5	1.95	None
3	DOE 1, Set 3	0.69	8.5% (LOF)
4	DOE 1, Set 6	6.24	3.3% (Boiling)

Six Quality Metrics extracted from pyrometer data:

- QM1 & 4 are related to peak temperature (C)
- QM2 & 5 are related to heating rate (C/s)
- QM3 & 6 related to cooling rate (C/s)

New Pyrometers Provided Data Capable Of Distinguishing Differences Between The Various Build Parameters As Well As Provide Additional Voice Of The Process Information

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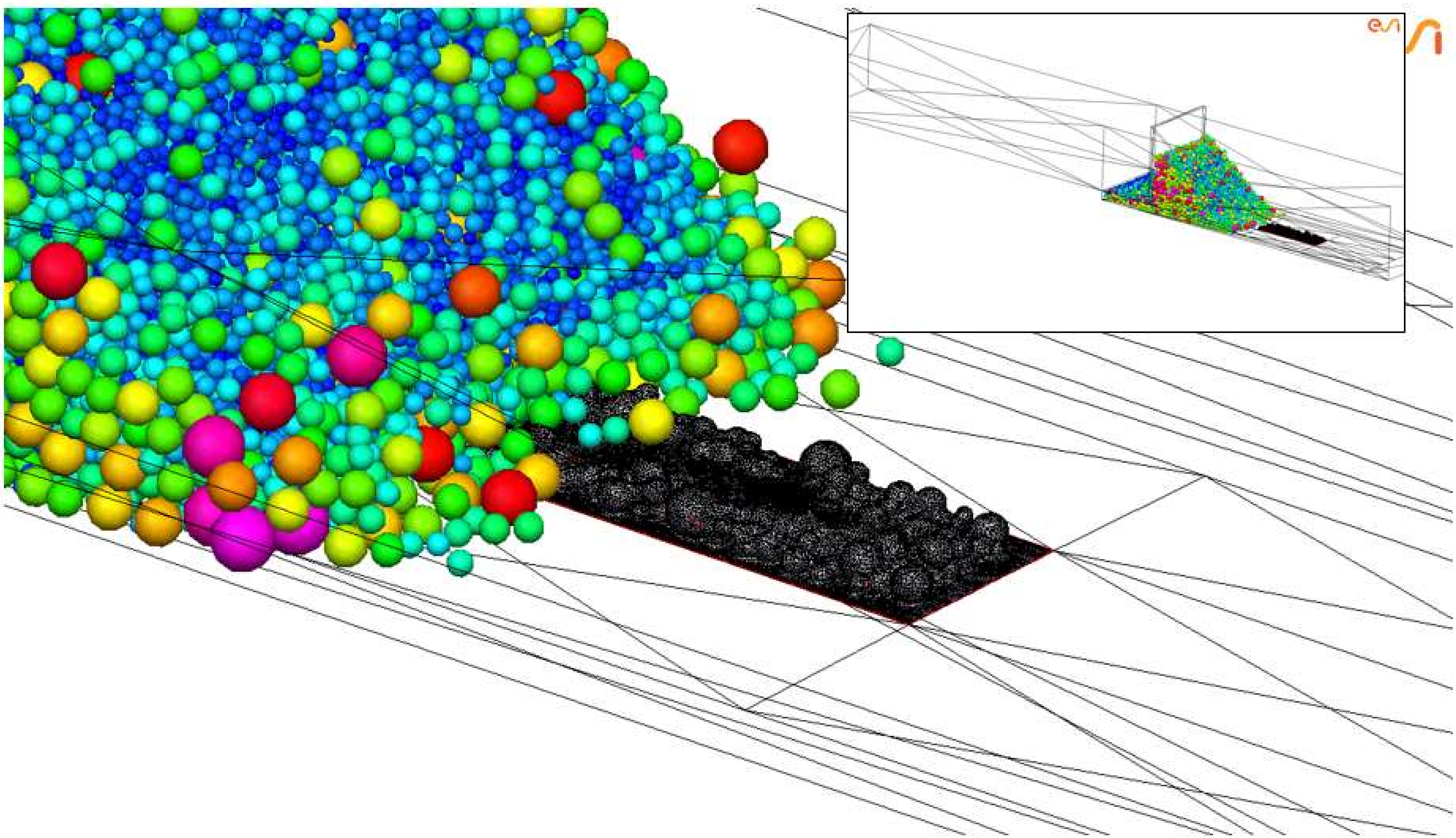
5. What measurements of quality or systems are appropriate that correlate computational and analytical methods to practical implementation?

- Requirements are driven by Design Intent
- Manufacturing requirements and controls need to be commensurate with the design intent
- For the most part, the requirements for components tend to be:
  - Functional
  - Dimensional
    - accuracy of the process,
    - Distortion due to the process
    - surface finish capabilities of the process, etc.
  - Service life related
    - failure modes
    - material defects
    - Material microstructure / phases
    - Grain size, etc.

Computational methods must have the capability to simulate the process

- Replicate the process, follow the laser and simulate the melting and solidification
- deformation during the build, to predict dimensional qualities of the process
- surface roughness, which is a function of the build layer thickness, the powder size distribution, the randomness of the powder spreading, the laser beam diameter, the hatch spacing, the laser power, etc.

Recoating of the powder layer, 2nd Layer



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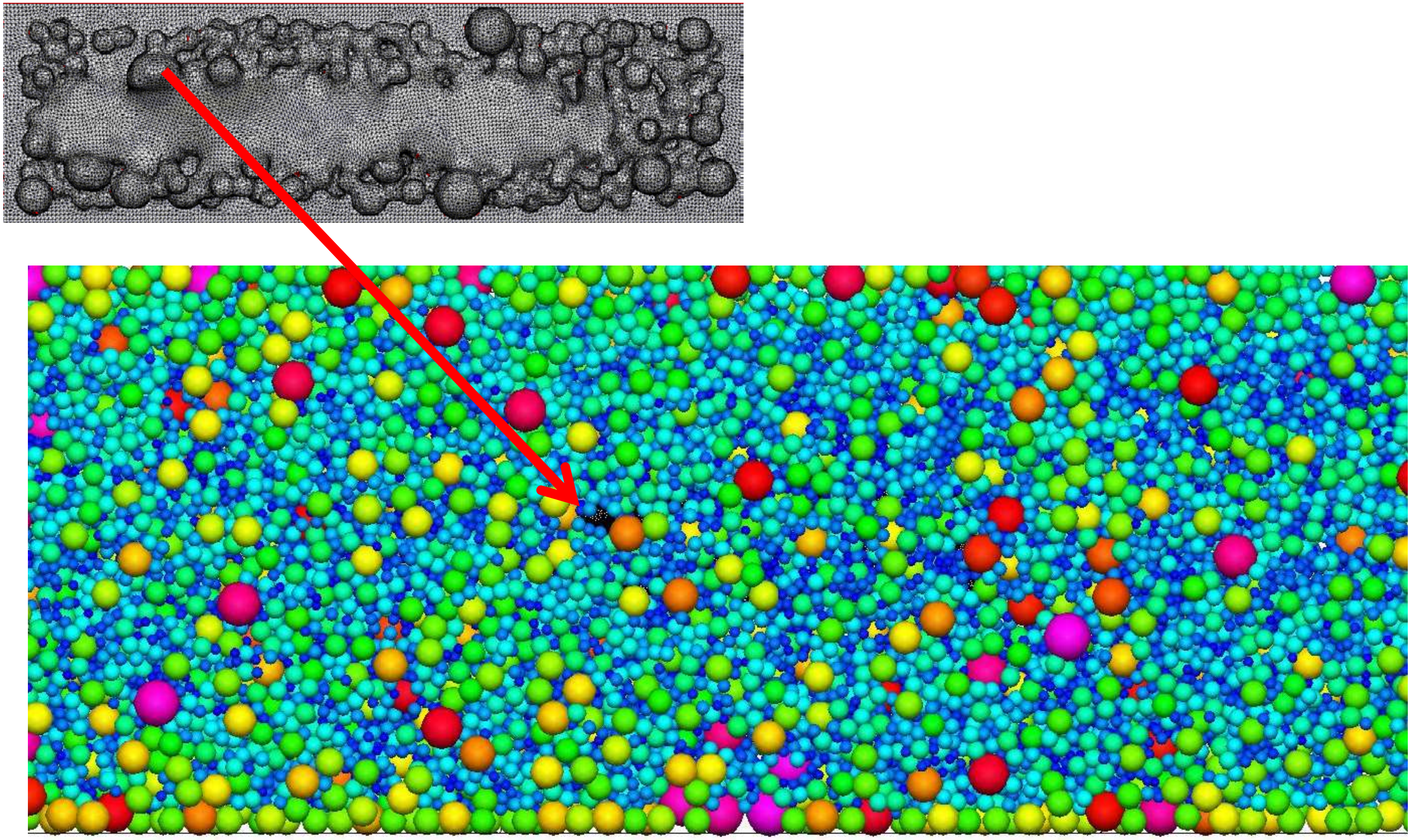
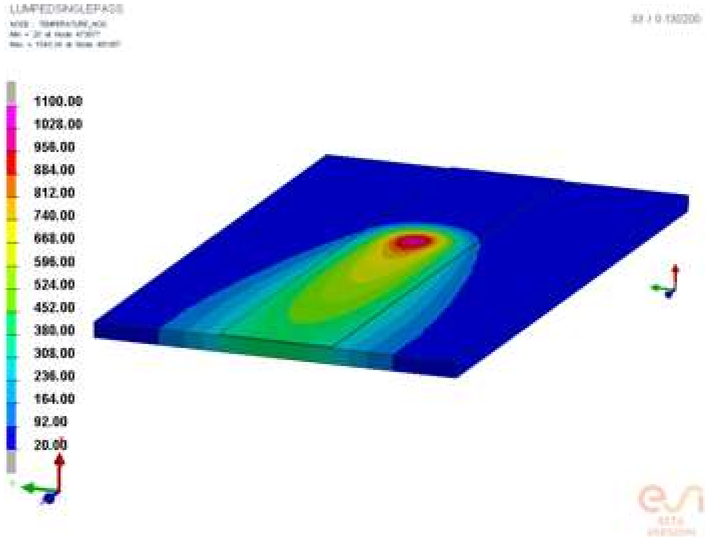
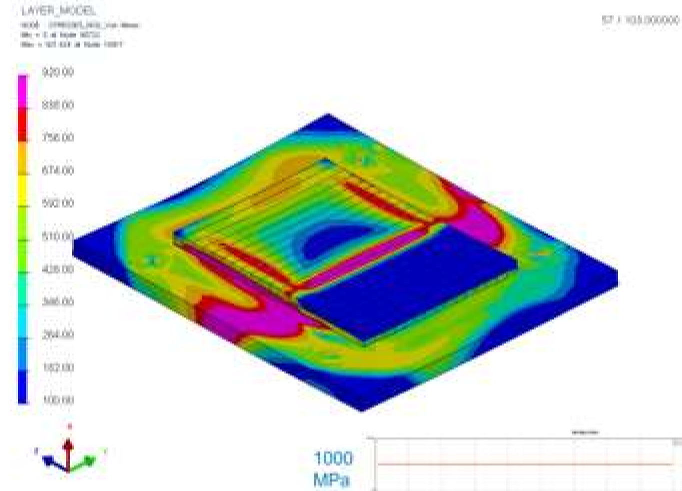
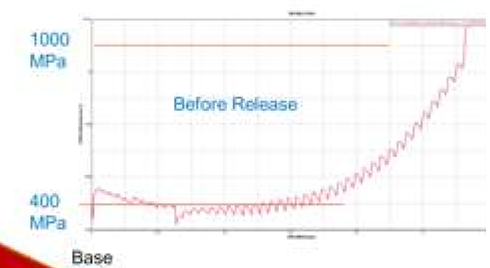
Recoating a 2nd Layer: Large particles can lead to recoater blade crashes

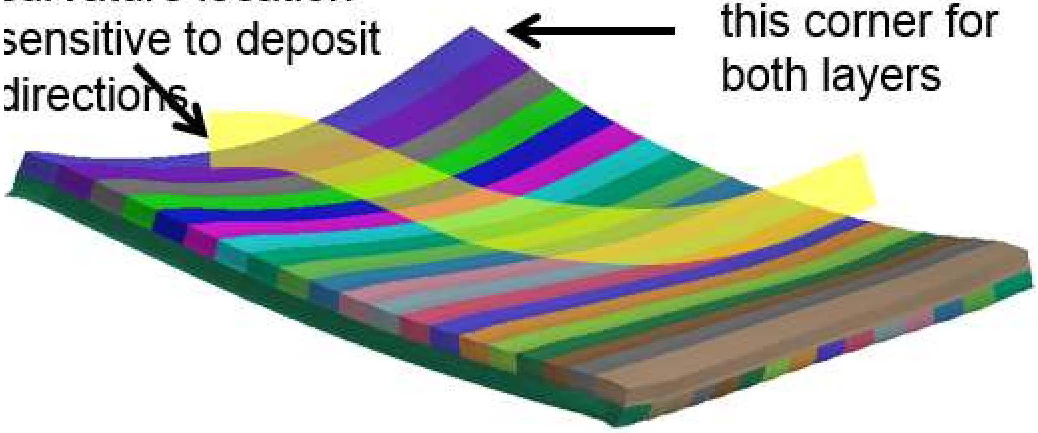


hermal Animation and Residual Stress Model: Hatch and Stripe Model



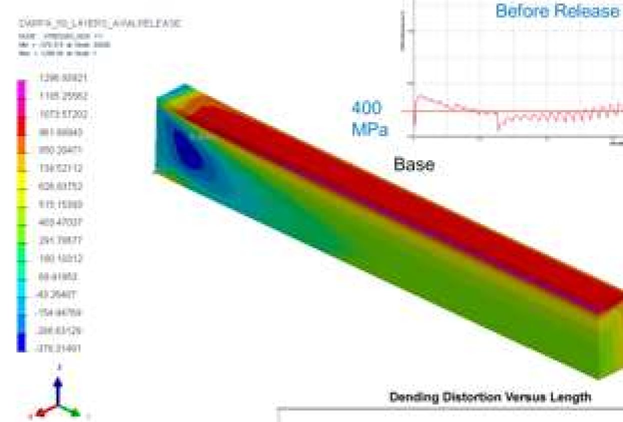


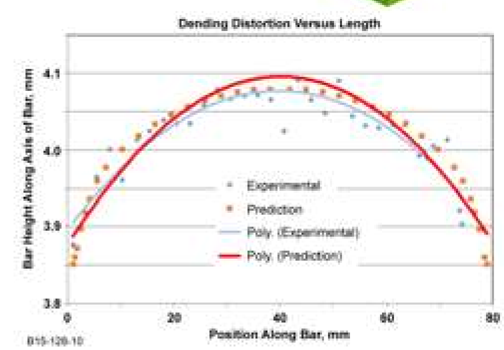




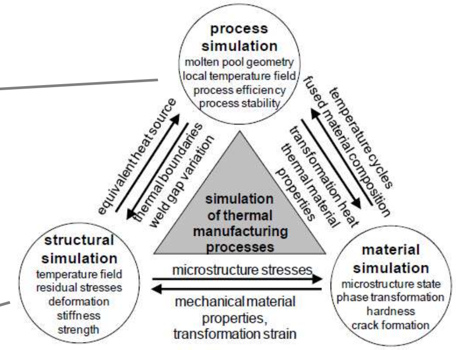
Maximum concave curvature location sensitive to deposit directions

First deposit at this corner for both layers





6. Software architecture and data-bases for AM model development



- Software requirements
  - Melt pool
    - ➢ Model the power size distribution
    - ➢ Model the powder spreading
    - ➢ Model the laser – powder interaction
    - ➢ Model the CFD – melting and solidification, heat transfer, Marangoni forces, etc.
    - ➢ Model defect generation, i.e porosity, micro cracking
    - ➢ Model the micro scale residual stresses, at the melt pool level
  - Structural
    - ➢ Model the macro scale residual stresses, at the structural level
    - ➢ Deformation, at the structural level
  - Microstructure
    - ➢ Model the material microstructure evolution, i.e. phases, grain growth, defects
  - Properties
    - ➢ Yield, Ultimate, fatigue, crack growth, creep, environmental effects
- Location and orientation specific prediction capabilities
- Software may be self standing or integrated, but information shared

6. Software architecture and data-bases for AM model development

Database requirements

Material properties needed for use in the Computational models

- From room temperature to boiling point
- For non equilibrium conditions
- At very high rates

MatProp1P

Mat. Prop Solid:
- Density, ρ
- Thermal conductivity, k
- Specific heat, Cp
- absorptivity , α
- Emissivity, ε
- Coeff .of thermal exp., α
- Young Modulus, E
- Shear Modulus, G
- Poisson's ratio, ν
- Melting Temp, lower and higher limits per phase
- Melting latent heat

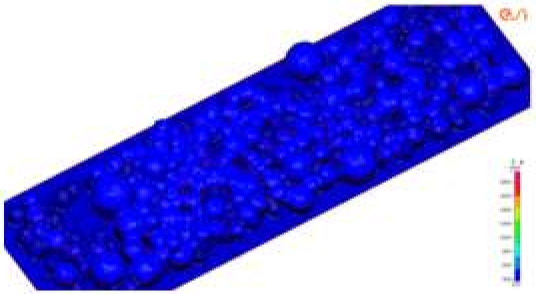
Powder properties
- Apparent Density, ρ
- Apparent Thermal conductivity, k
- Apparent Specific heat, Cp
- Melting Temp, lower and higher limits per phase
- Melting latent heat

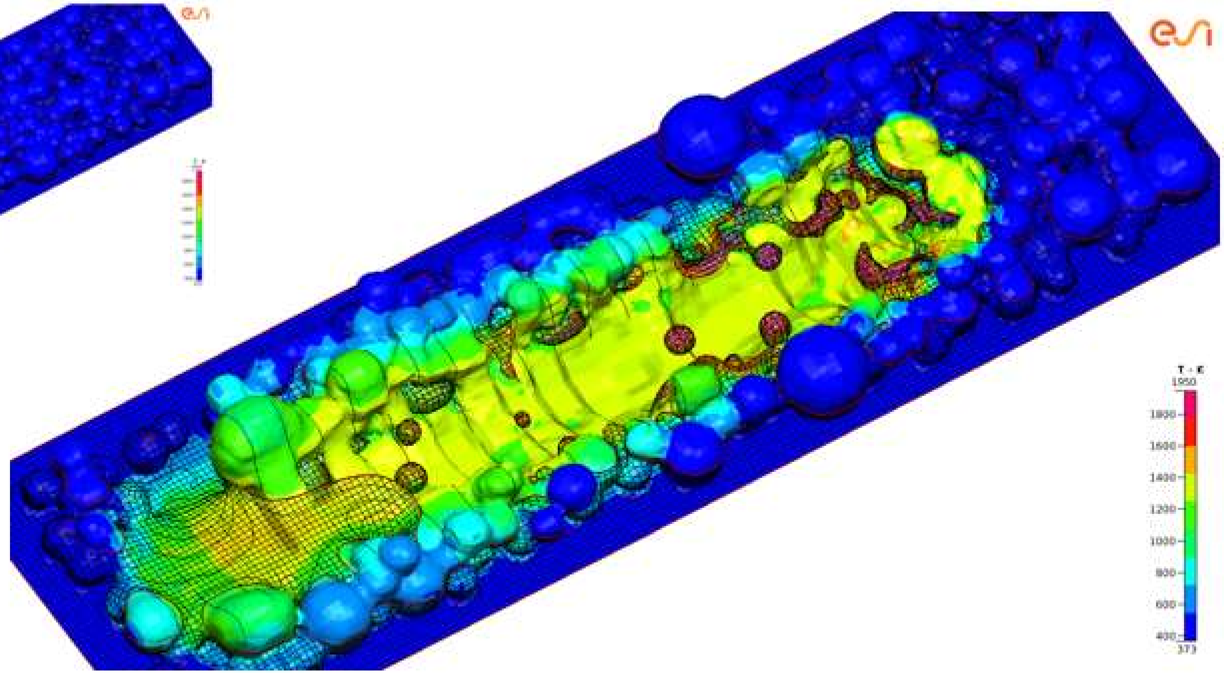
Mat. Prop Liquid:
- Density, ρ
- Thermal conductivity, k
- Specific heat, Cp
- absorptivity , α
- Emissivity, ε
- viscosity, ν
- Melting Temp, lower and higher limits per phase
- Melting latent heat
- Boiling point for each phase
- Surface energy / tension

Experiments to verify the relevant physics of the process

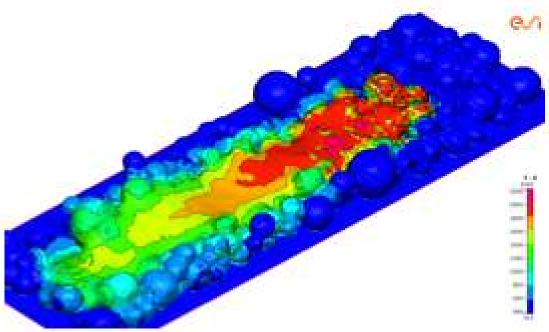
- Laser scribing/ melting on solid
- Laser scribing/ melting on powder
- At various processing conditions
- Build simple shapes and determine deformation – 1D i.e. beams
- Build more complex – 2D i.e. plates
- Build components – 3D i.e. airfoils,
- As build microstructure characterization
- As stress relieved microstructure
- As HIPped, as Solution, as Aged microstructures
- …

δ: 30μm, H: 100 μm, v: 2250 mm/s (10.5.3)

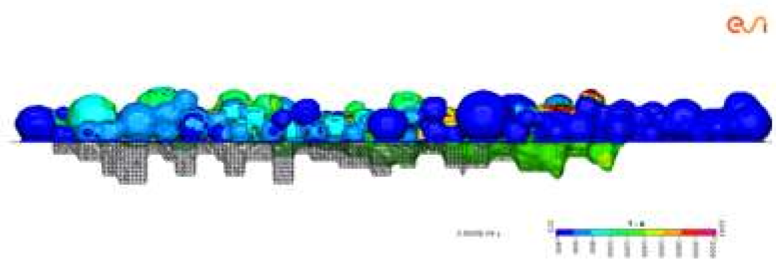




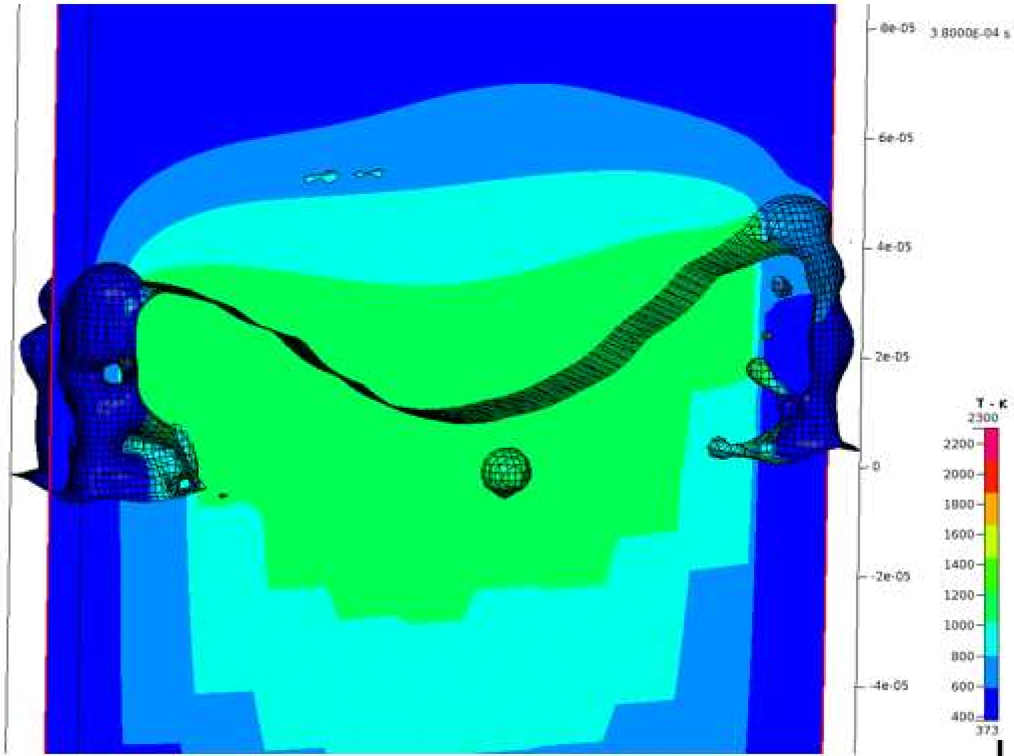
Top surface



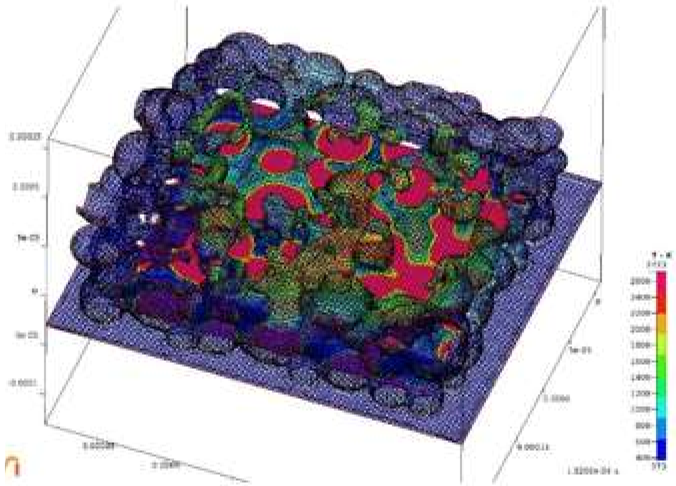
Side View



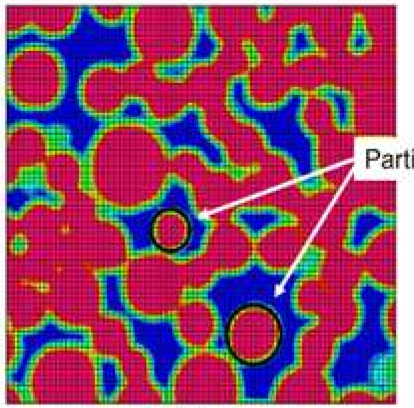
Micro-Model Defect Prediction



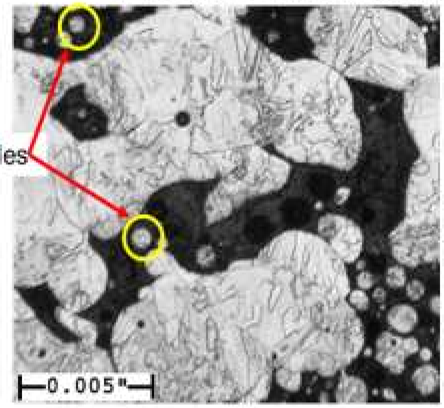
Gas Porosity



Lack of Fusion Porosity

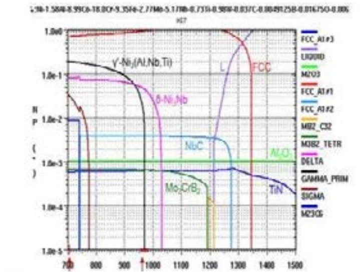


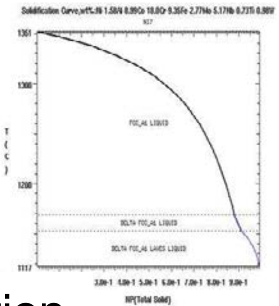
(a)



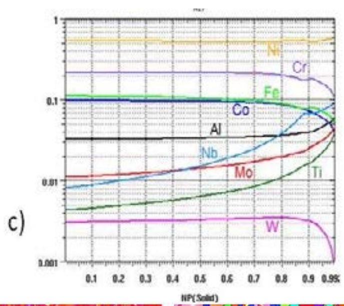
(b)

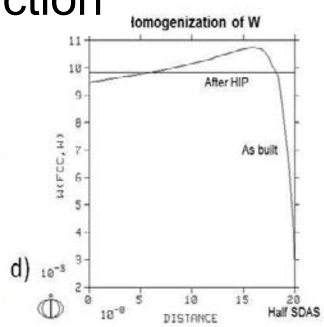
Examples of Software and Experimental databases for Materials Modeling

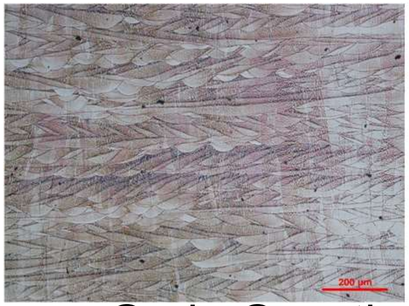




Phase quantity prediction





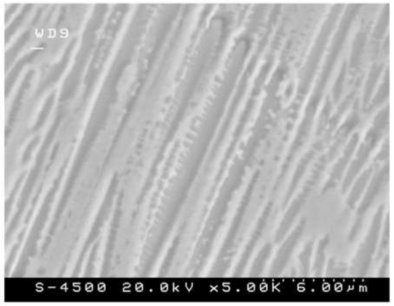


(A)

(B)

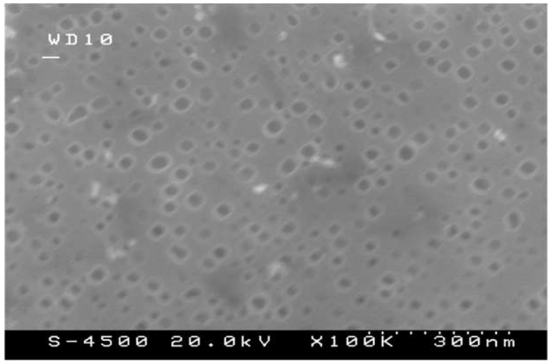
Grain Growth and Solidification

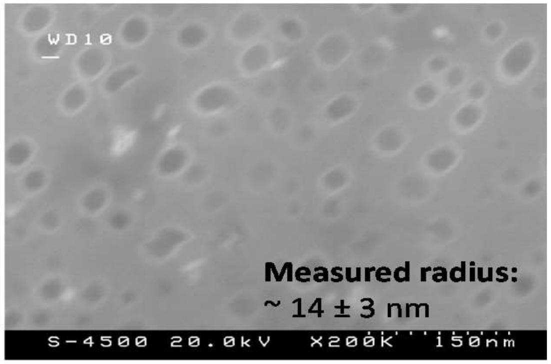
(C)



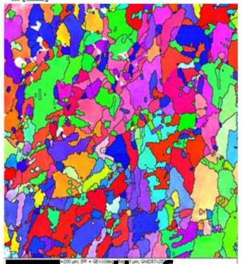
(D)

Gamma Prime size prediction





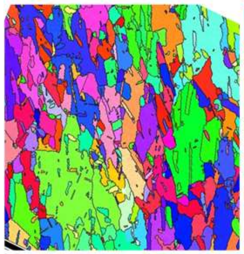
(A)



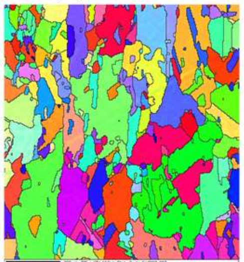
(B)

(C)

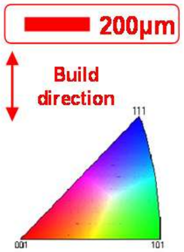
Effect of Stress relief



(D)



(E)



(F)

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Final Microstructure: Phase Fraction & Compositions

Final microstructure after double step aging (varying solution temperature):

phase fraction

Solution temperature in F

f %		1750	1775	1800	1950
	δ-Ni3Nb	5.93%	5.39%	4.66%	
	γ'_p-Ni3(Al,Nb,Ti)	3.67%	1.60%		
	γ'_s-Ni3(Al,Nb,Ti)	20.07%	20.85%	21.16%	22.93%

Compositions (1775F solution treatment):

Composition in at%		Ni	Cr	Fe	Co	Mo	Al	W	Nb	Ti	RMS
matrix	prediction	45.65	26.92	12.80	10.79	2.17	0.92	0.36	0.35	0.03	0.66
	LEAP*	44.30	26.40	13.20	11.50	2.10	0.40	0.40	1.30	0.10	
γ'	prediction	70.47	1.13	1.27	2.88	0.20	11.91	0.21	8.48	3.44	0.37
	LEAP*	70.69	0.65	1.27	3.39	-	11.28	-	8.85	3.19	

*L. Viskari, K. Stiller, Ultramicroscopy 111(2011) 652–658

YS Model for 718 plus

I. Solution treated material

- Assume linear superposition of strengths of primary phases

$$\sigma_{yield} = \sigma_{yield}\left(D_{gr};\ f_{\gamma}; f_{\gamma_p'}; f_{\delta}\right)$$
$$= f_{\gamma}\sigma^{\gamma} + f_{\gamma_p'}\sigma^{\gamma_p'} + f_{\delta}\sigma^{\delta} \qquad \text{where } f_{\gamma} + f_{\delta} + f_{\gamma_p'} = 1.$$

$$\sigma^{\gamma} = \sigma^{HP}\left(D_{gr}\right) + \Delta\sigma^{SS}(C_i)$$

Strengthening in γ matrix due to grain size and solid solution strengthening.

$$\sigma^{\gamma_p'} = \sigma_0^{Ni_3Al} + \Delta\sigma^{SS}(C_i)$$

Strengthening in primary γ' due to base strength of Ni_3Al and solid solution strengthening.

Strength of δ phase extracted from YS of soln. treated material at higher temp.

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YS Model for 718 plus

II. Aged material

- Includes effect of secondary γ' precipitates.

$$\sigma_{yield} = \sigma_{yield}\left(D_{gr};\ f_{\gamma}; f_{\gamma'_p}; f_{\delta}; f_{\gamma'_s}\ ; r; \gamma_{APB}\right)$$

$$= f_{(\gamma+\gamma'_s)}\sigma^{(\gamma+\gamma'_s)} + f_{\gamma'_p}\sigma^{\gamma'_p} + f_{\delta}\sigma^{\delta} \quad \text{where} \quad f_{(\gamma+\gamma'_s)} + f_{\delta} + f_{\gamma'_p} = 1.$$

$$\sigma^{\gamma'_p} = \sigma_0^{Ni_3Al} + \sigma^{SS}(C_i)$$

$$\sigma^{(\gamma+\gamma'_s)} = \sigma^{HP}\left(D_{gr}\right) + \sigma^{SS}(C_i) + \sigma^{Precip}\left(f_{\gamma'_s}; r; \gamma_{APB}\right)$$

In addition to grain size and solid solution strengthening, secondary γ' precipitates' effect on dislocation motion mechanisms contributes to strength.

Strength of δ phase extracted from YS of soln. treated material at higher temp.

r : Radius of secondary γ' precipitates.

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7. Careful design of validation experiments for model validation, uncertainty quantification, and *in situ* process monitoring

- Example Experiments Follow, prior examples also fit as examples or this question

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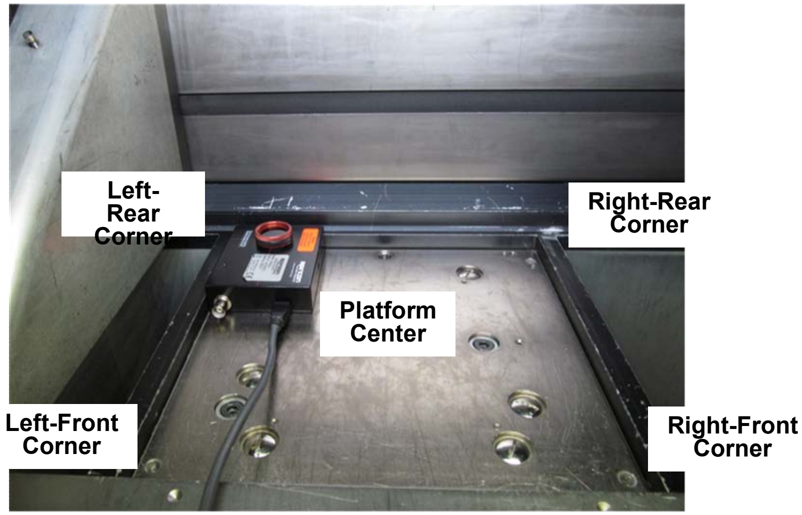
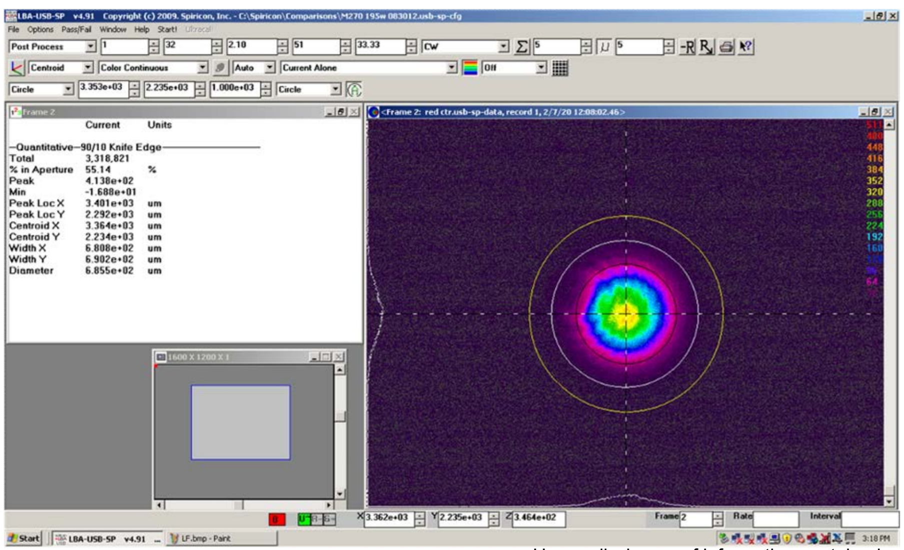
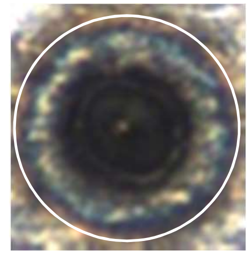
Laser Power and Size Calibration



Camera based Beam Profiler is set to re-coater height

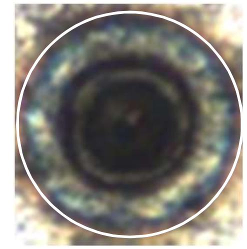
Beam sampled at center and each corner of platform



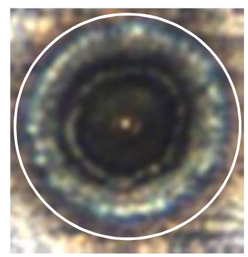


Left-Rear Corner

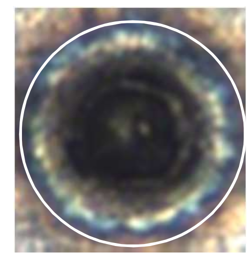
Platform Center



Right-Rear Corner



Left-Front Corner

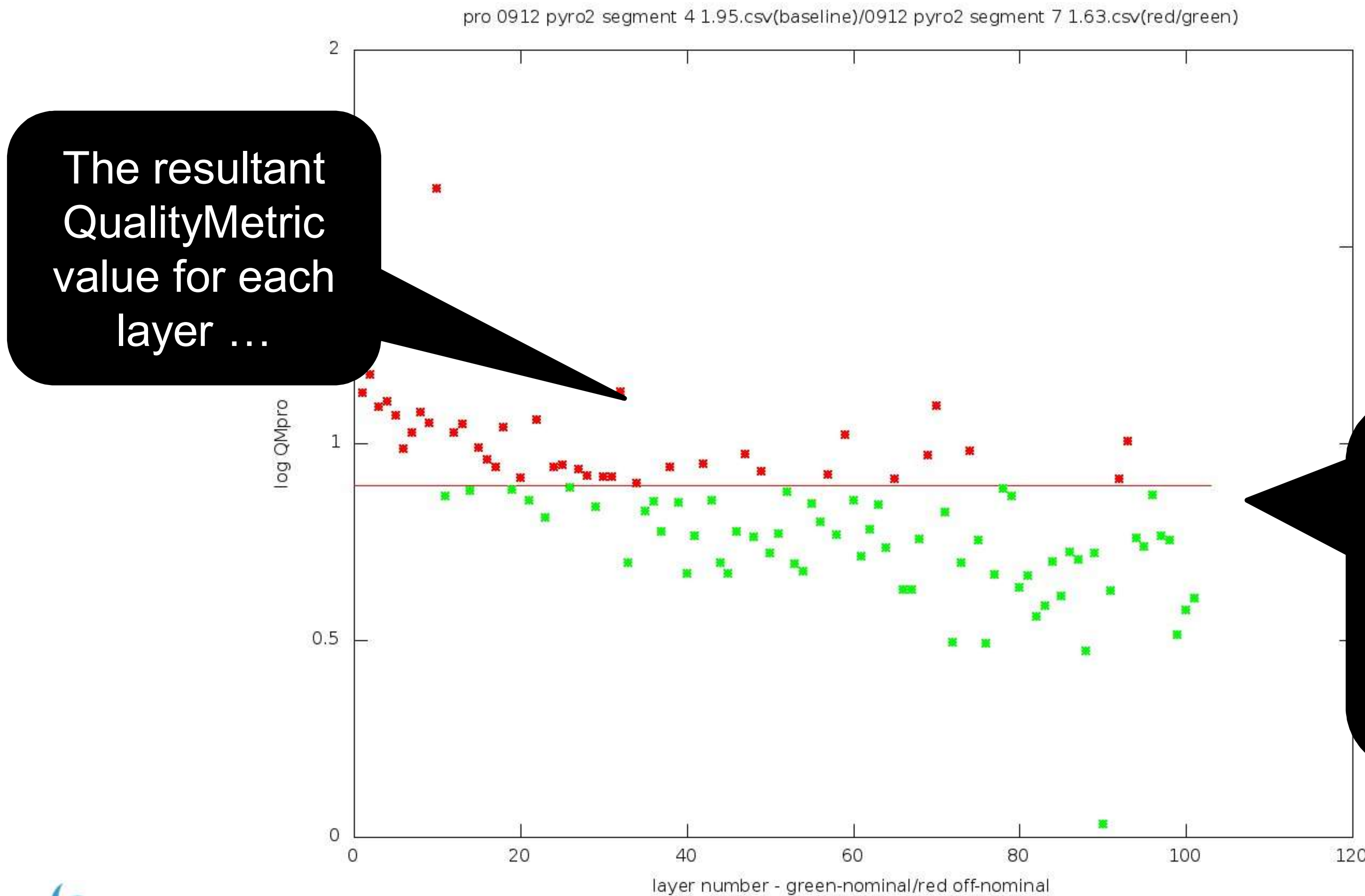


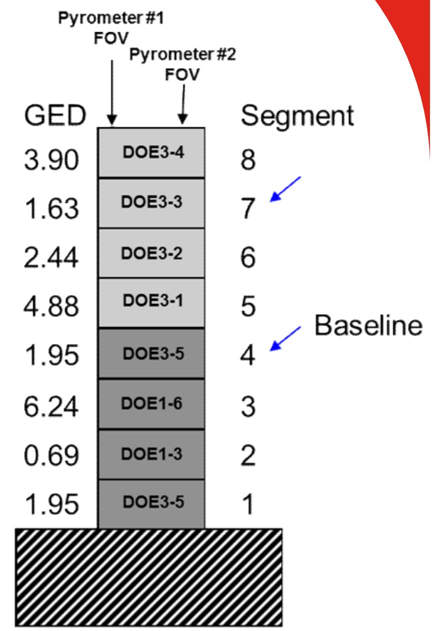
Right-Front Corner

Laser Burn Images indicate laser beam maintains a circular shape within the build platform

0912 pyro2 segment 4 baseline 1.95 vs 0912 pyro2 segment 7 candidate 1.63

Plot QMpro; 95% Confidence





SIGMA LABS

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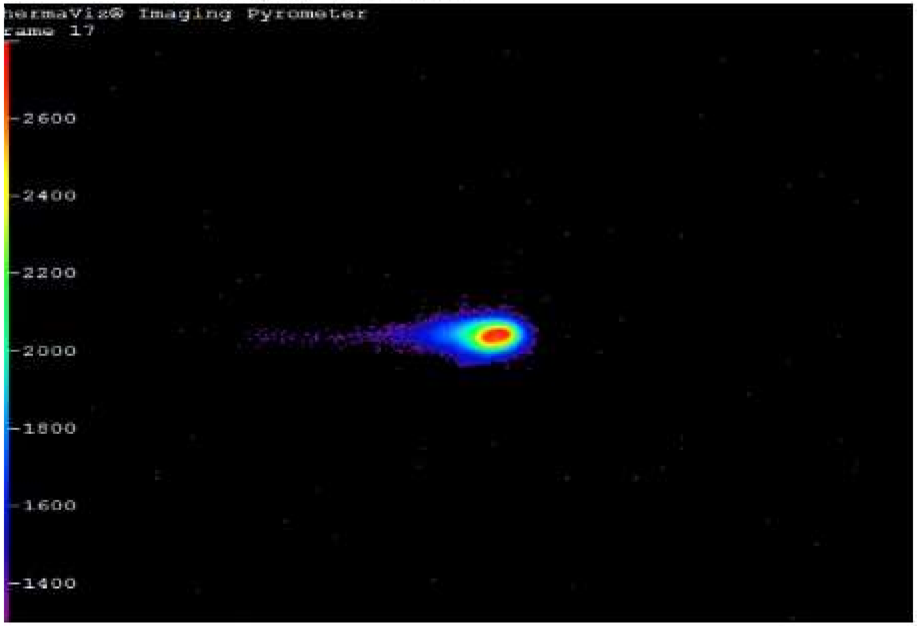
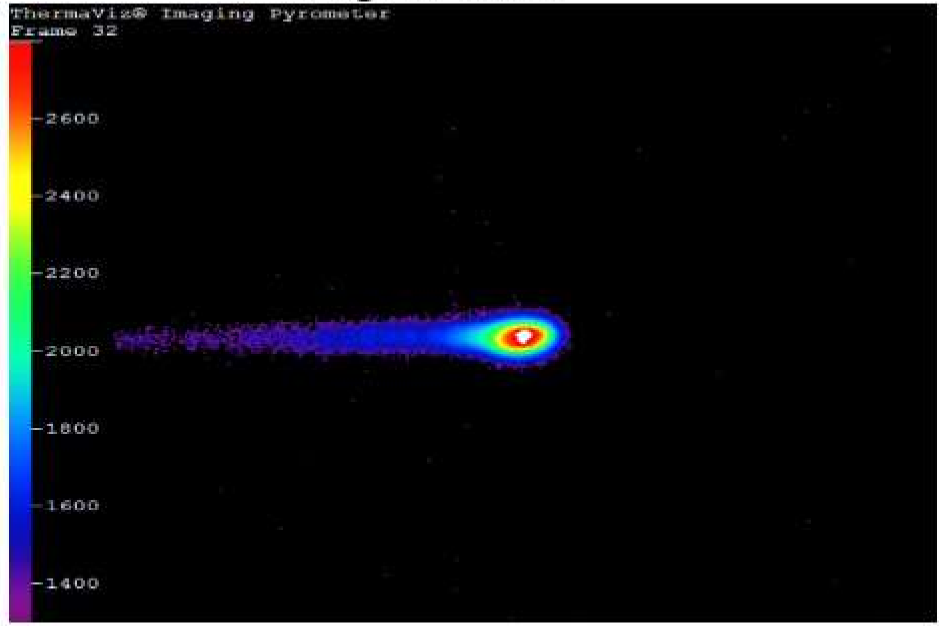
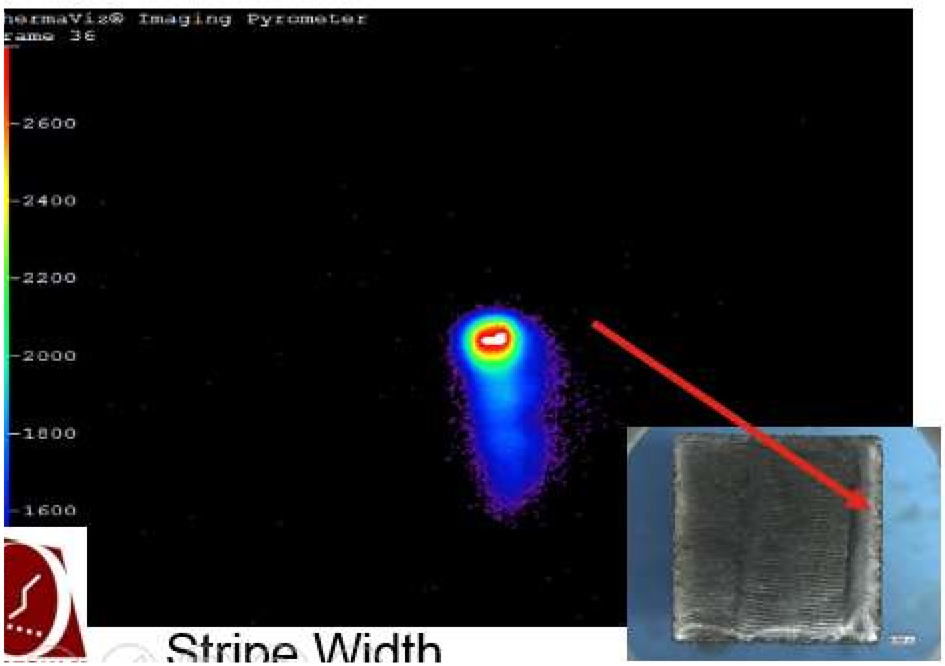
Melt Pool Shape and Temperature "Measurement"

Low Power

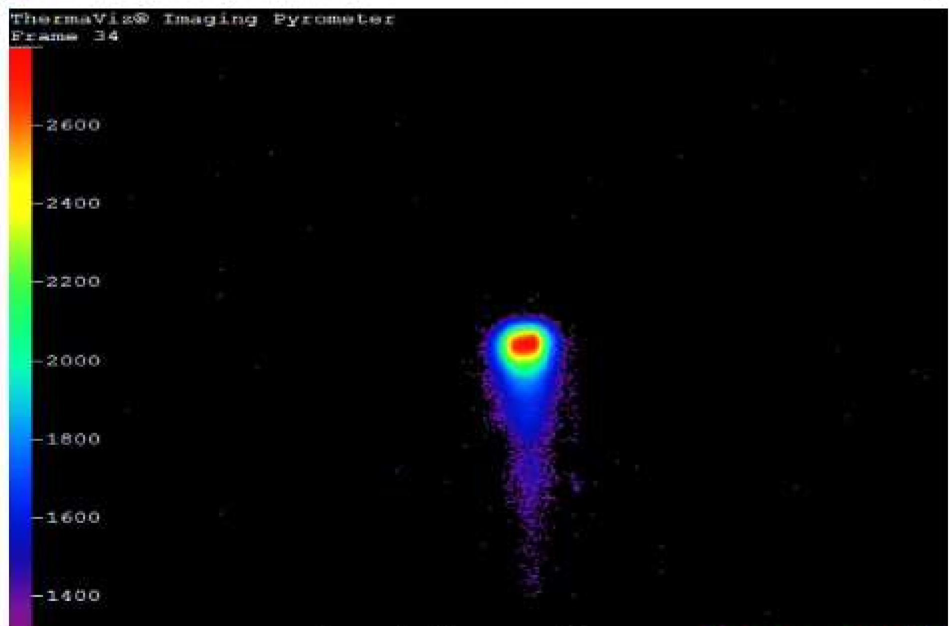


High Power



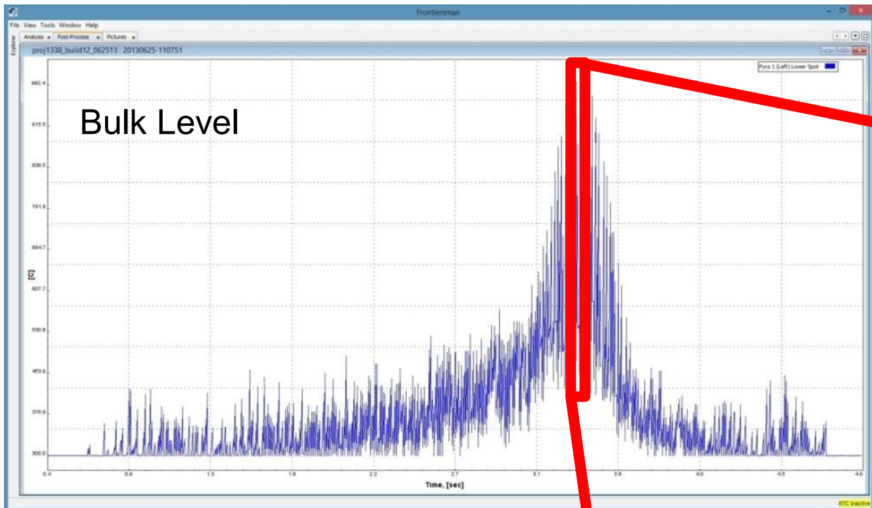


Stripe Width

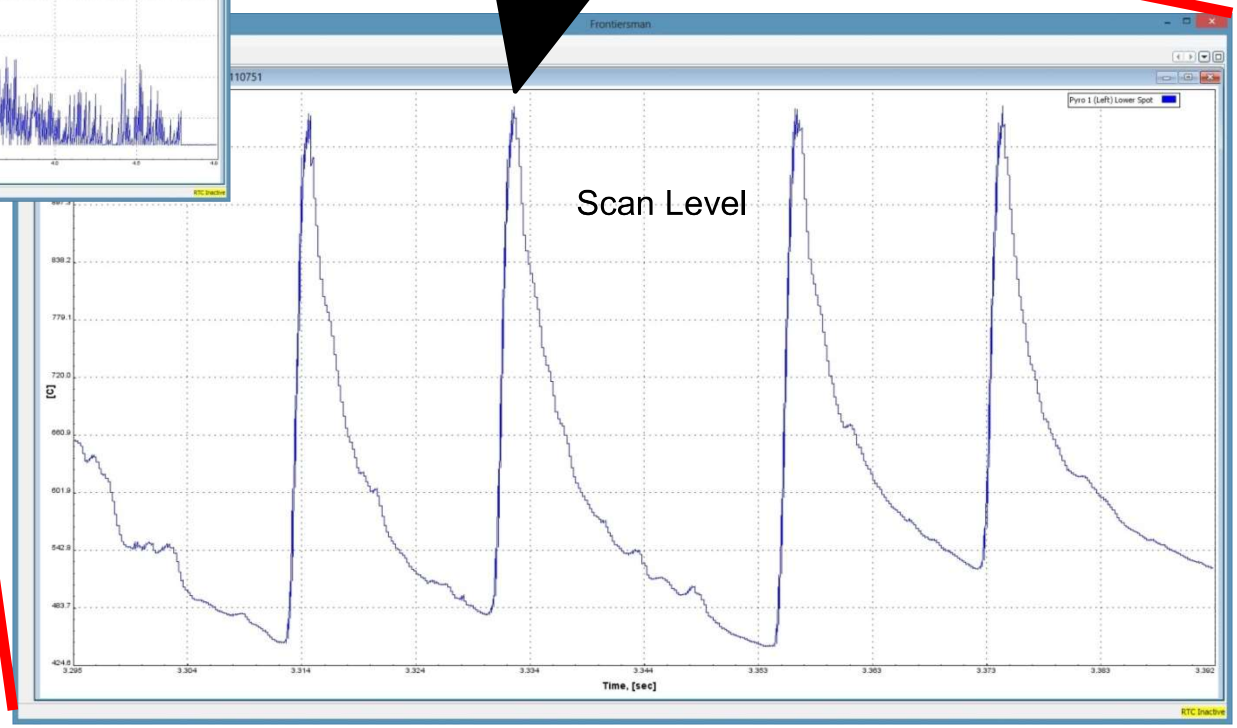


Fast Speed

Pyrometer Temperature Measurements



Melt Pool Thermal Cycle, *aka*, instantaneous thermal cycle



	Temperature
PT (C)	1,797
HR (C/s)	1,876,300
CR (C/s)	-691,340

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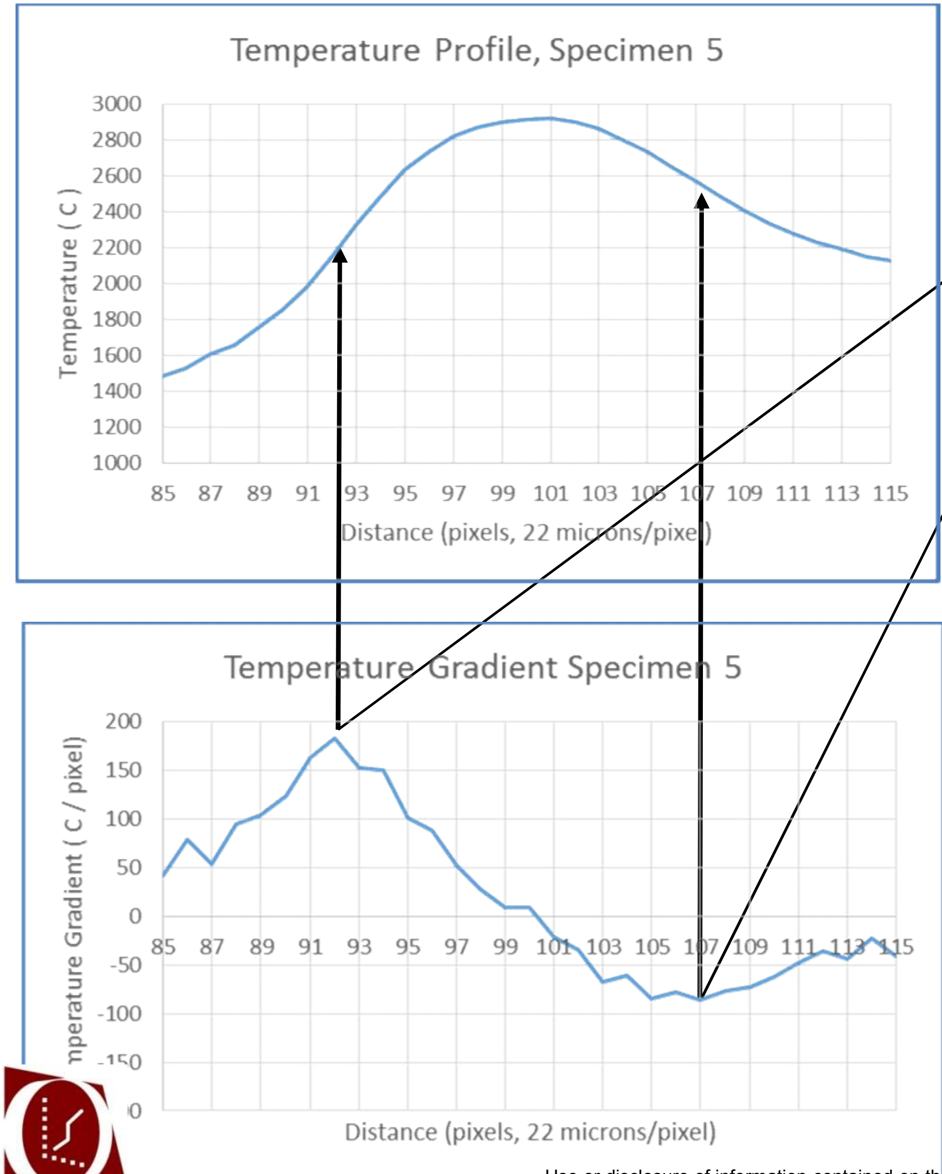
Digital Camera Temperature Measurements



Peak <u>Heating</u> Rate: 183 C / pixel
8.3 M C / sec

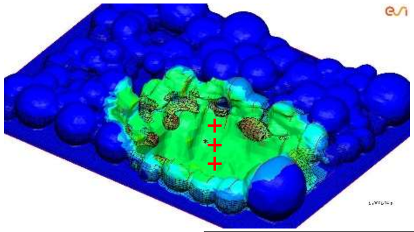
Peak <u>Cooling</u> Rate: -86 C / pixel
-3.9 M C / sec

<u>Conversion: spatial to temporal</u>
- 22 microns / pixel
- 880 mm / sec
- 40 K pixels / sec

Camera calibrated to 2500 °C source

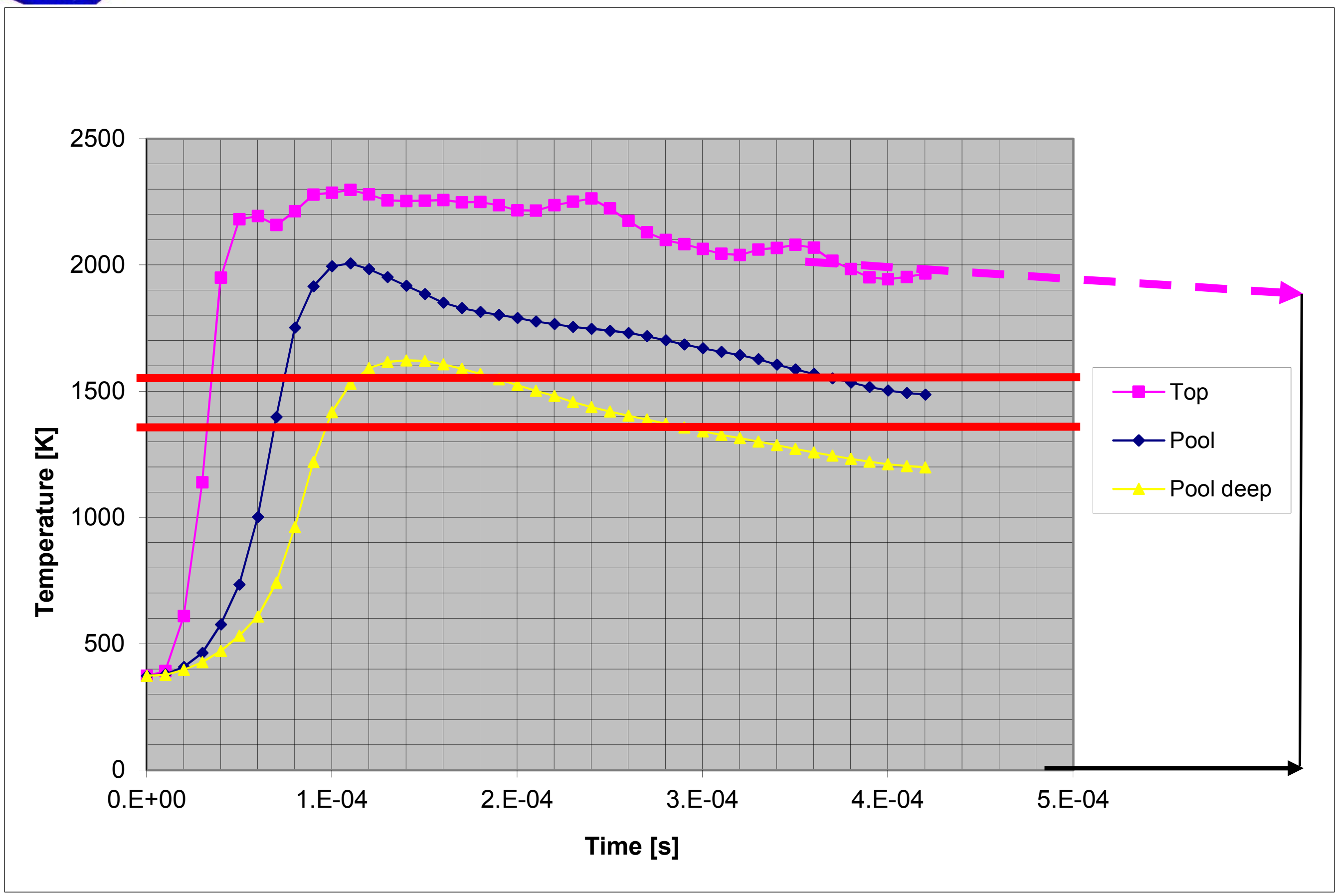
STRATONICS

δ: 20μm, H: 140 μm, v: 880 mm/s (10.4.2)
Model / Simulation Temperature Predictions

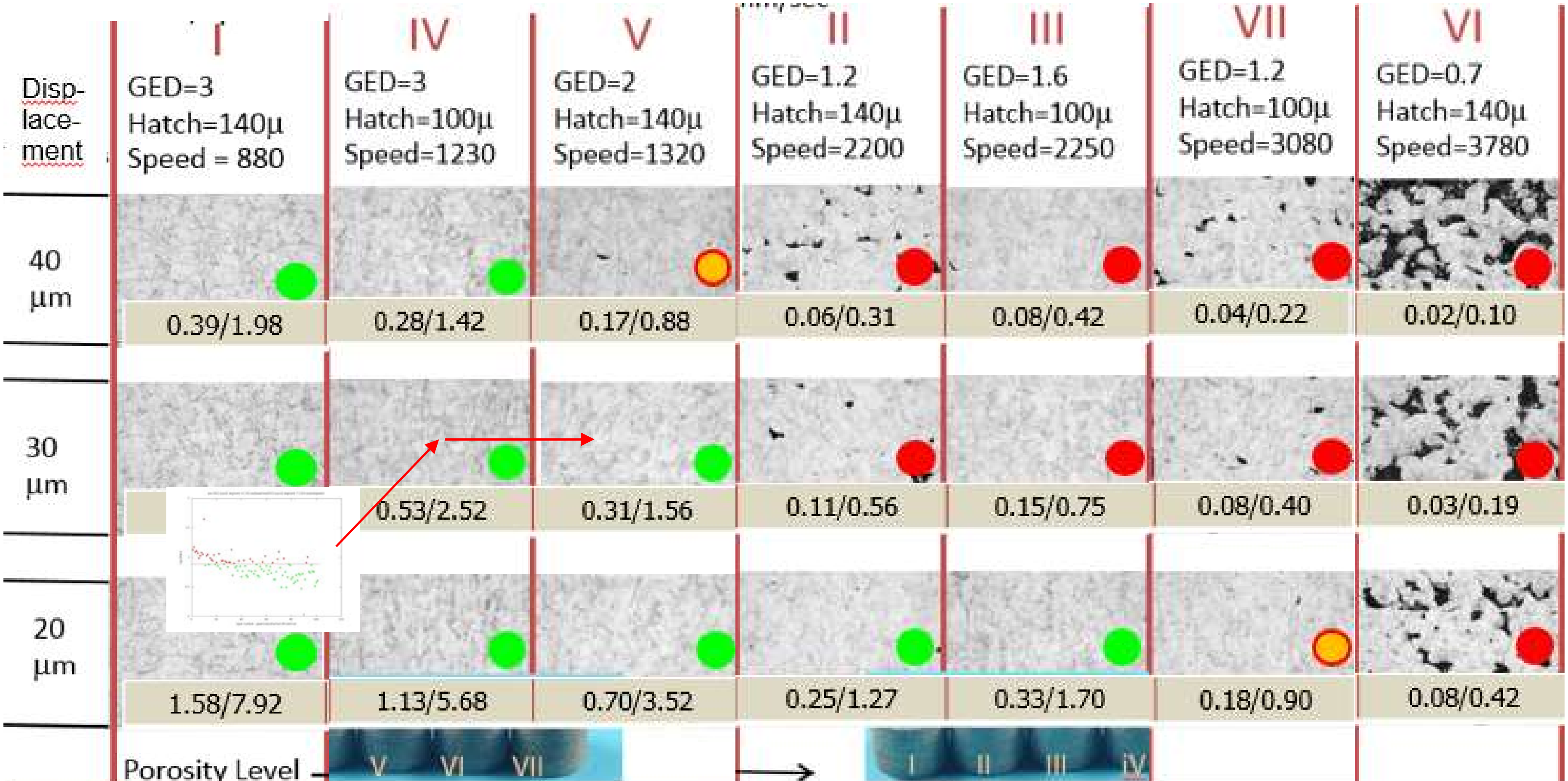


Top: Bead
Middle: Pool
Bottom: Pool deep

$\Delta T_{Heating}$ = 5 M K/s
$\Delta T_{Cooling}$ = 1.5 M K/s



ROM Predictions Build Optimization and Rearranging the columns



Porosity Level	I	IV	V	II	III	VII	VI
40 um	0.001-0.006%	0.002-0.018%	0.13-0.45%	3.03-4.83%	0.03-0.42%	7.20-12.28%	30.13-30.86%
30um	0.002-0.013%	0.01-0.02%	0.12-0.31%	2.65-3.48%	0.04-0.43%	2.59-4.79%	20.2-23.9%
20 um	0.002-0.008%	0.003-0.012%	0.05-0.56%	0.95-1.19%	0.10-0.21%	0.68-8.99%	11.1-11.6%

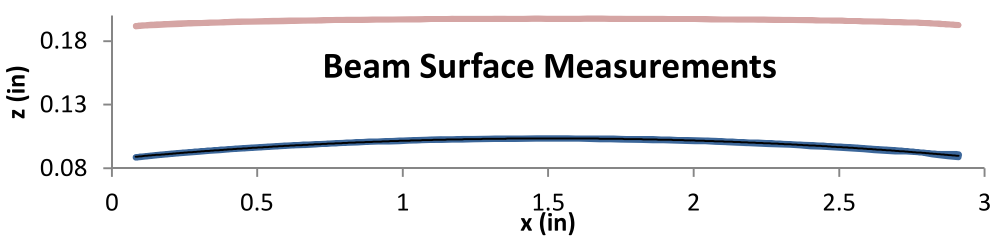
Build Parameters vs. Residual Stress

	Power	hatch spacing	speed
No	Watts	mm	mm/s
A1	370	0.09	1000
A2	300	0.09	1000
A3	250	0.09	1000
A4	200	0.09	1000
A5	150	0.09	1000
A6	370	0.09	1250
A7	300	0.09	1250
A8	250	0.09	1250
A9	200	0.09	1250
A10	150	0.09	1250
A11	370	0.09	1500
A12	300	0.09	1500
A13	250	0.09	1500
A14	200	0.09	1500
A15	150	0.09	1500
A16	370	0.13	1000
A17	300	0.13	1000
A18	250	0.13	1000
A19	200	0.13	1000
A20	150	0.13	1000
A21	370	0.13	1250
A22	300	0.13	1250
A23	250	0.13	1250
A24	200	0.13	1250
A25	150	0.13	1250
A26	370	0.13	1500
A27	300	0.13	1500
A28	250	0.13	1500
A29	200	0.13	1500
A30	150	0.13	1500

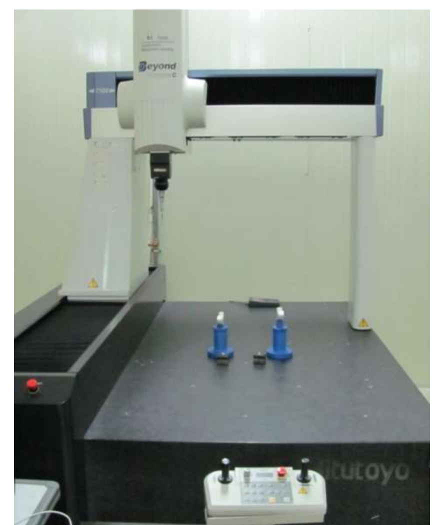
Objective: Understand the effect of Power, Speed, and Hatch Spacing on Residual Stress.

Method: Printing 90 beams with varying power, speed, and hatch spacing. Then measuring deflections using our CMM to calculate stress.

$$\sigma_{Max} = -E\kappa\frac{t}{2}$$



Coordinate Measuring Machine (CMM)



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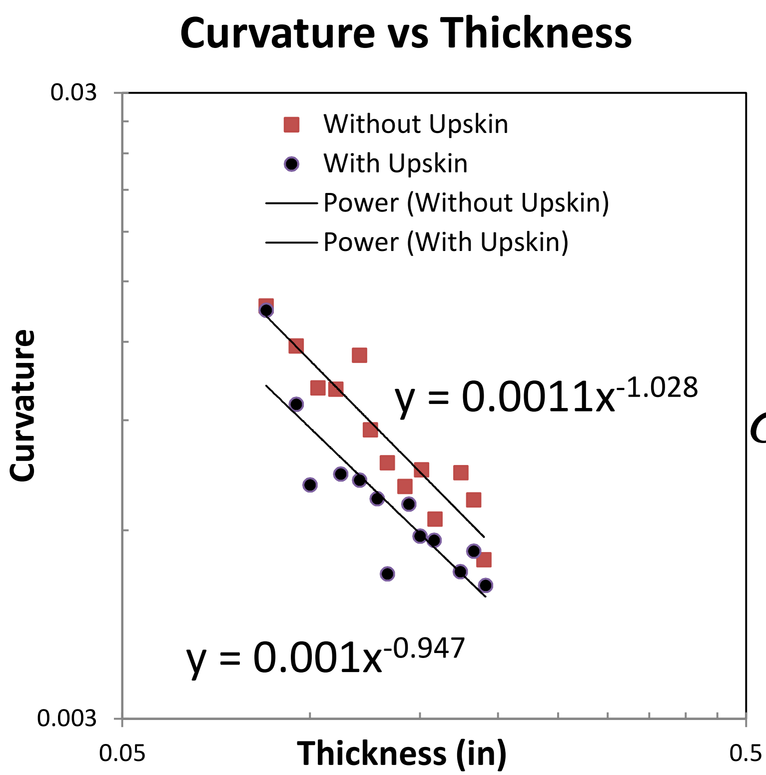
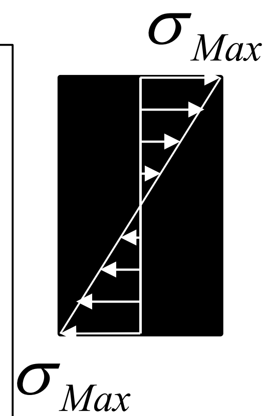
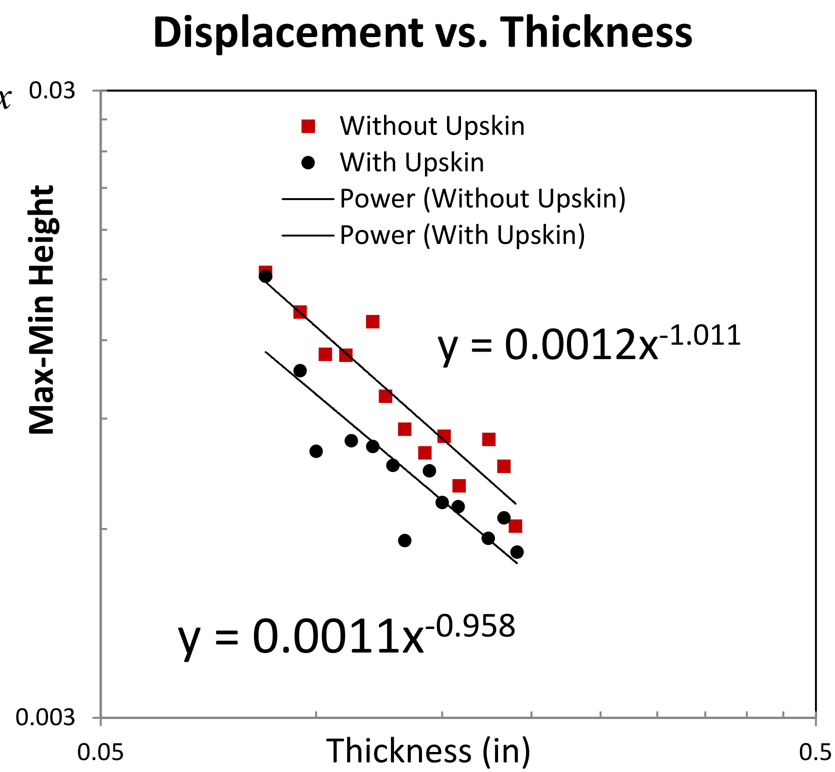
Specimens are being measured

Deformed Beam Data: Same Build Conditions







$$\sigma_{Max} = -E\kappa\frac{t}{2} \Rightarrow \kappa = \frac{-2\sigma_{Max}}{Et} \propto t^{-1} \qquad v = \frac{ML^2}{2EI} = \frac{EI\kappa L^2}{2EI} = \frac{\kappa L^2}{2} \propto t^{-1}$$

Plots confirm, an assumed constant max stress independent of thickness

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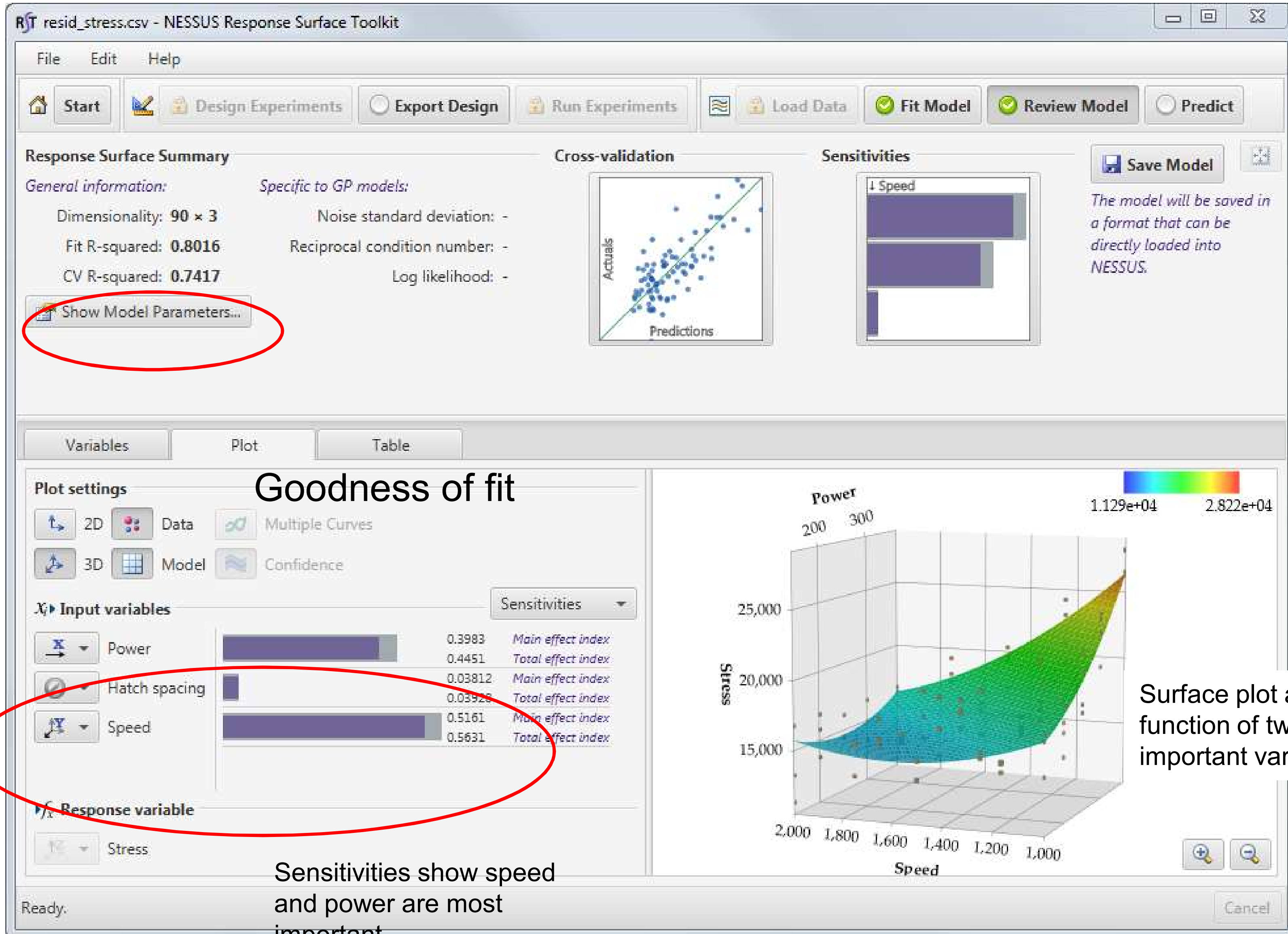
Deformed Beam Data: Different Build Conditions



Goodness of fit

Surface plot as function of two most important variables

Sensitivities show speed and power are most important

Speed and Power are most important variables, not hatch spacing

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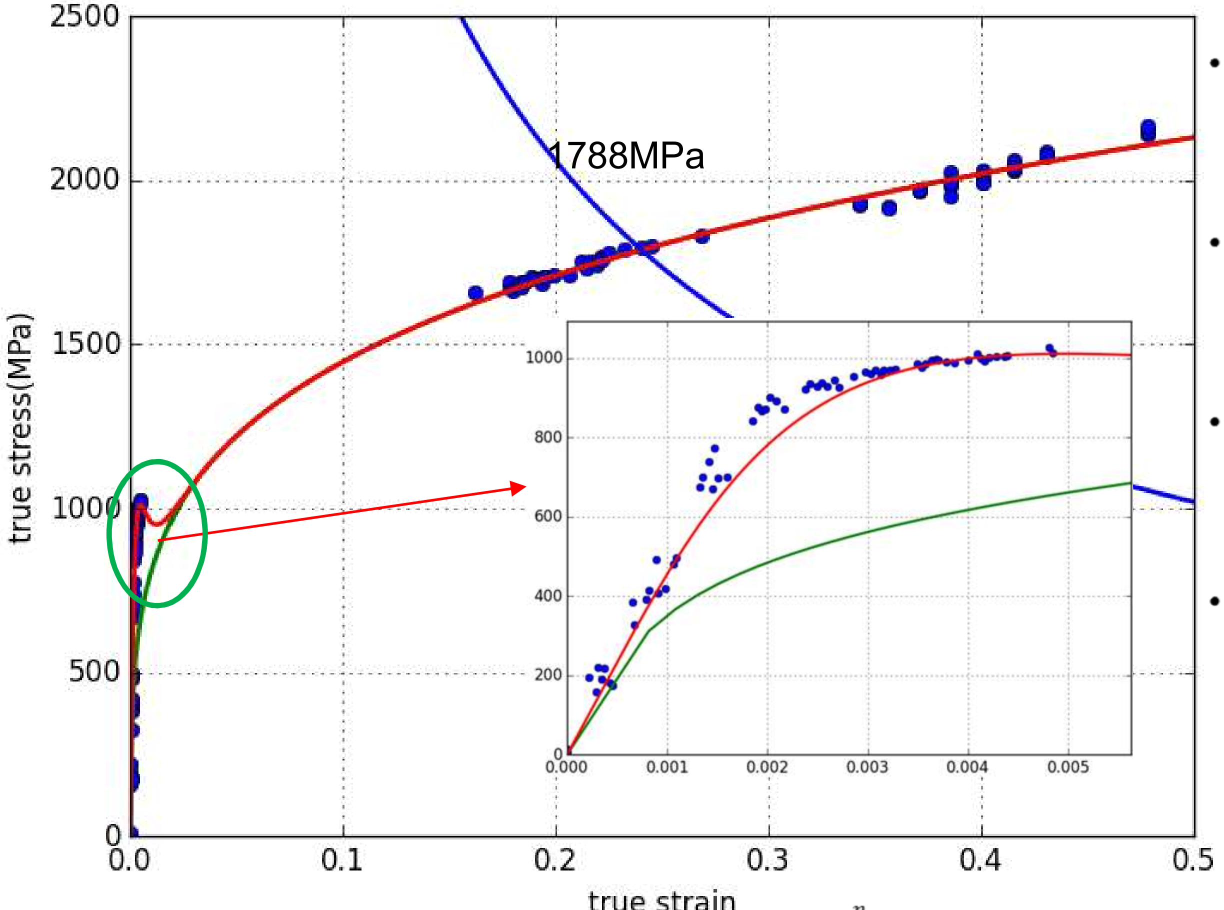
$\sigma_{true} - \varepsilon_{true}$ Curve and UTS Analysis



Standard power-law hardening $\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K_1}\right)^n$

Ramberg-Osgood model $\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^n \quad K = K_1 + K_2 e^{-m\varepsilon_p}$

For UTS calculation $\frac{d\sigma}{d\varepsilon}$

- Elastic modulus E is determined by linear fitting of elastic part of the curve.

$$E = 470GPa$$

- Standard power-law equation is used to calculate K_1 and n by fitting of UTS and FS points

$$K_1 = 2518 \quad n = 4.21$$

- Low-strain part of the curve is fitted by using Ramberg-Osgood model with drag stress K. (Manually)

$$K_2 = 2900 \quad m = 220$$

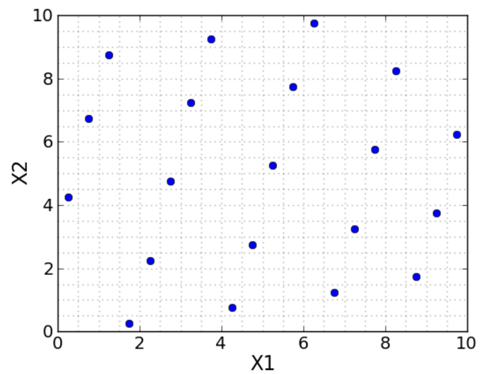
- UTS is calculated by the intercept point of $\sigma - \varepsilon$ and $d\sigma/d\varepsilon - \varepsilon$ curves.

$$UTS = 1788MPa$$

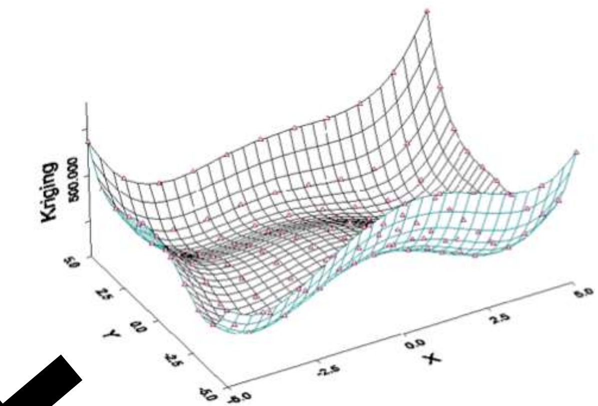
Residual Stress UQ Model

Identified **5** key input variables and uncertainty ranges

Generated set of **21** cases to run based on a Latin Hypercube design

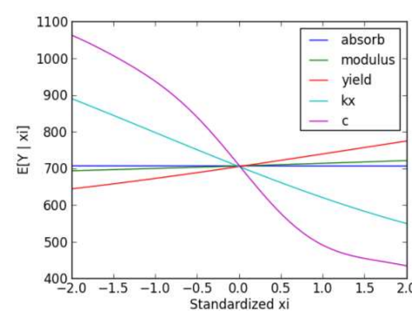


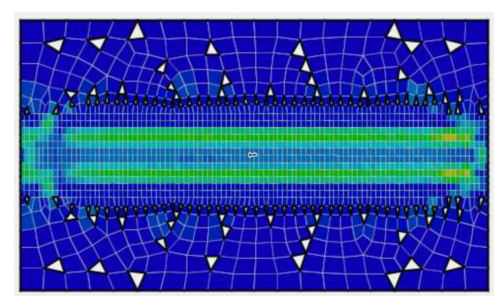
Fit Sysweld residual stress results to Gaussian Process (GP) response surfaces



Used response surfaces for:

- UQ of residual stress contours (mean/stdev.)
- Sensitivity analysis at select locations





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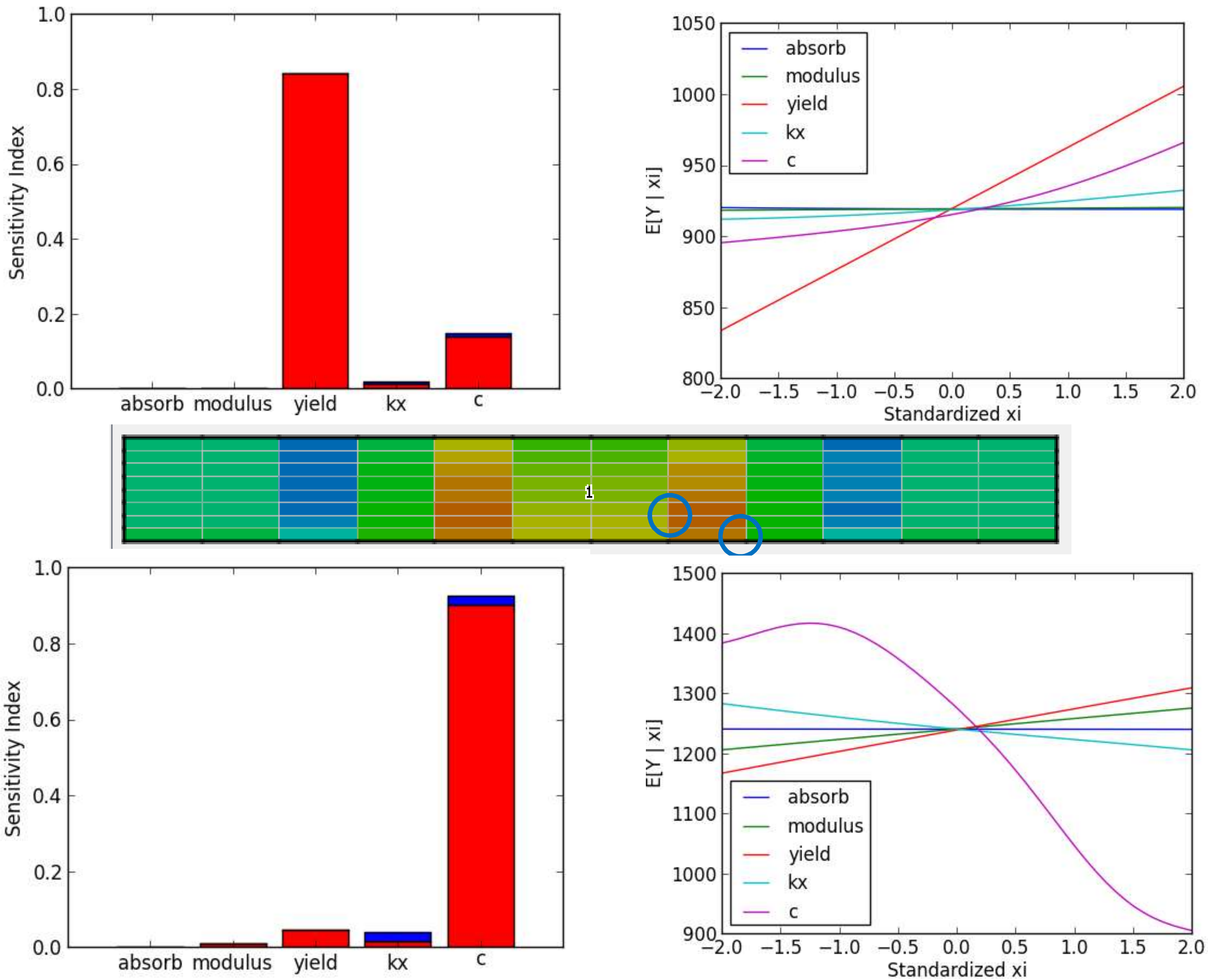
Residual Stress UQ Results – 25% Location



8. Software development, integration with precision engineering, and integration into engineering work flow

- **Develop software for realm of interest**

1) High fidelity, physics-based simulations to simulate the process at the micro scale and understand differences between build conditions and between geometrical differences
2) Computationally faster engineering simulations for component / structural simulation based on high fidelity models

Location specific material properties need to be integrated into current FE codes

ICME need to be moved over to the Analysis and Manufacturing Groups, maybe a concurrent engineering philosophy is needed.

Thank You!

Alonso Peralta, PhD.
Honeywell Engines
111 S 34th St, MS503-118
Phoenix AZ, 85034
Phone: 602-231-3982
Email: Alonso.Peralta@Honeywell.com