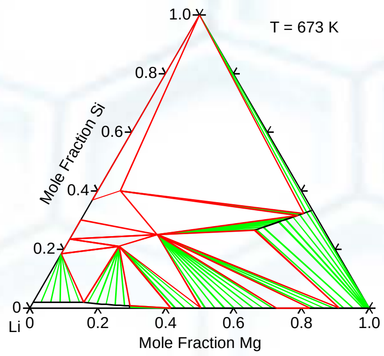
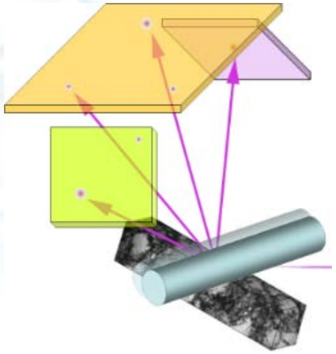




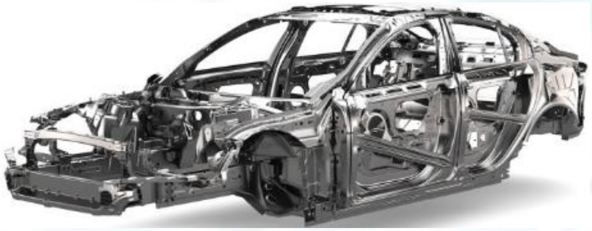
Session 4, questions 5-8

Lyle E Levine
Project Leader, Additive Manufacturing of Metals
Materials Science and Engineering Division
Material Measurement Laboratory
National Institute of Standards and Technology

NAS Workshop on Predictive Theoretical and Computational Approaches for Additive Manufacturing
AM Scalability, Implementation, Readiness, and Transition
October 7, 2015

NIST National Institute of Standards and Technology U.S. Department of Commerce

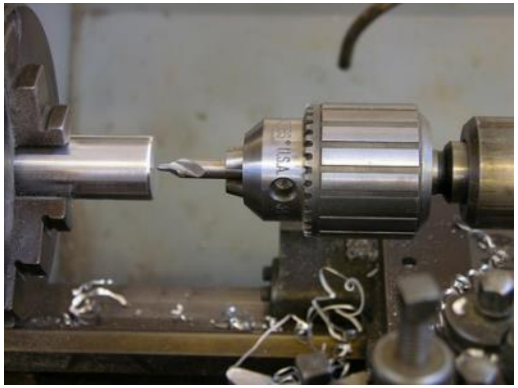
5. What measurements of quality or systems are appropriate that correlate computational and analytical methods to practical implementation?



Conventional alloys

- Many decades of experience and study
- Controlled composition, thermal history, deformation history
- Controlled microstructure, properties, **failure knowledge**

Conventional Manufacturing

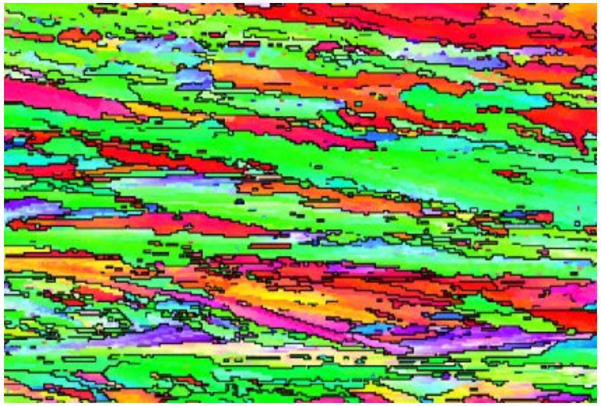


- Controlled dimensions
- Controlled surface finish
- Virtually no material or build flaws

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

Additive manufactured alloys

- Uncontrolled microstructure (phases, grain sizes, texture)
- Huge stresses (macro and micro)
- Extreme compositional gradients
- Reproducibility issues, build flaws



1. **Dimensional accuracy and precision**
    - Geometry, macro-scale stresses, difficult features, etc.
2. **Mechanical behavior of final part (after any post-build processing)**
    - Microstructure, local stresses, etc.

      (computational bridge to mechanical behavior)

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

Micro-level build simulations, Multiphysics

Macro-level build simulations

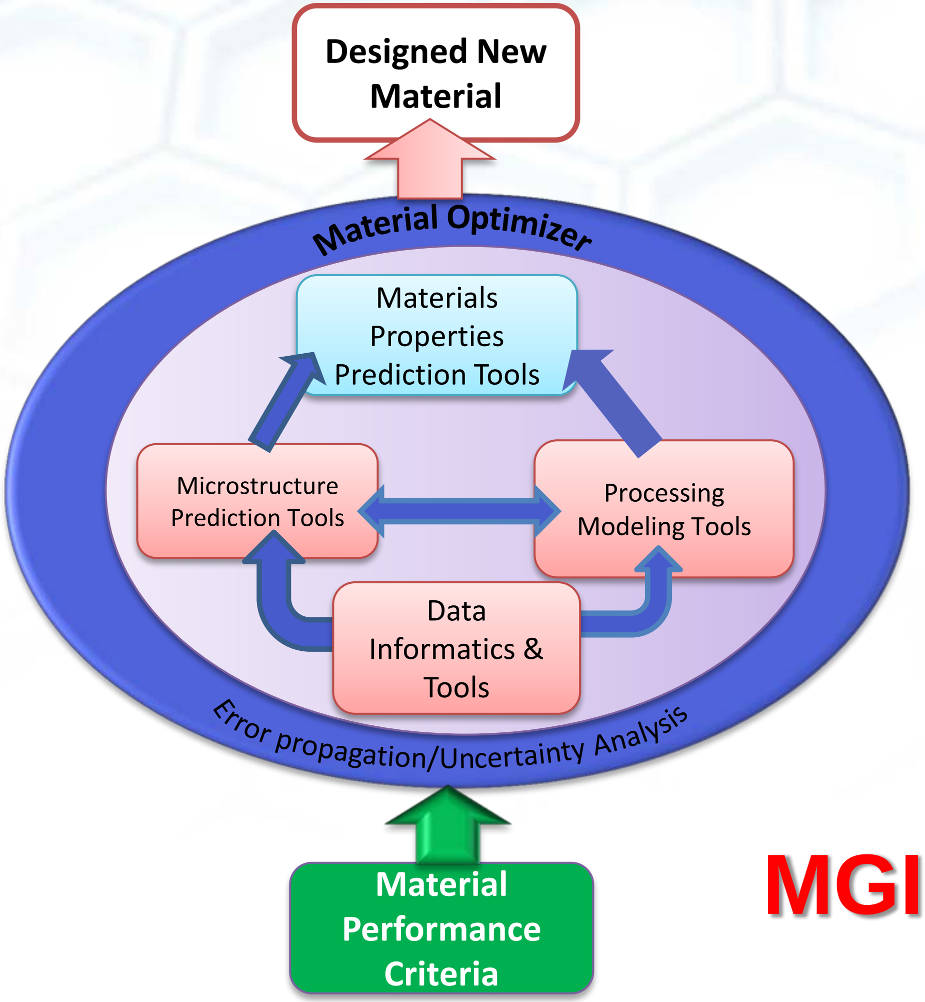
Macro Residual Stress Simulations (Build and post build)

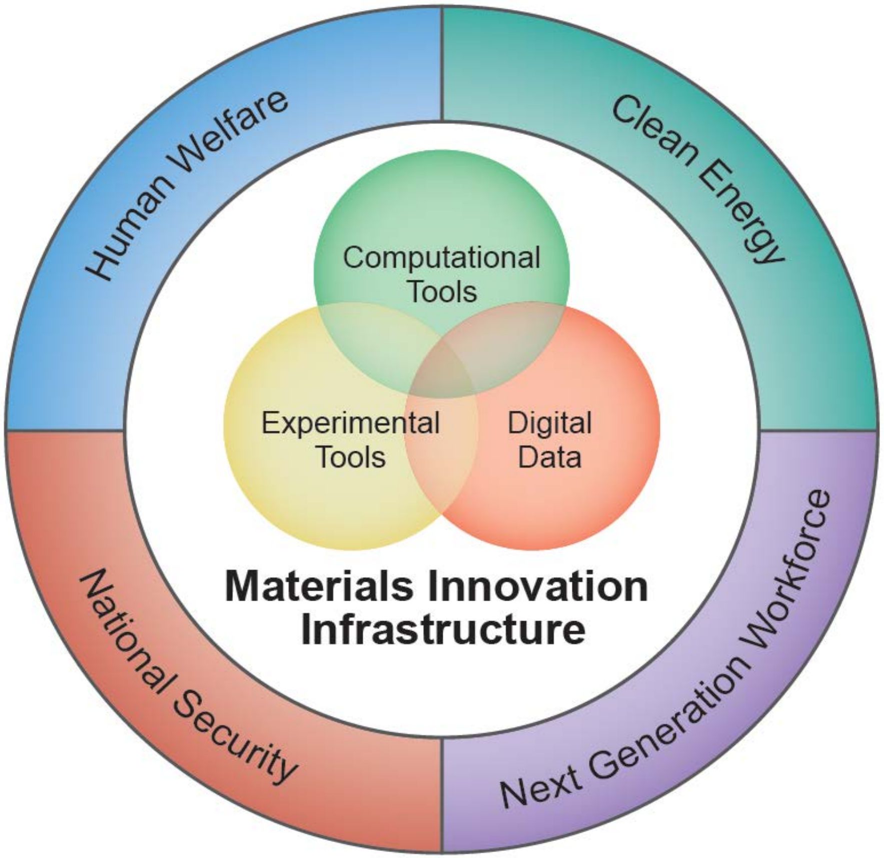
Microstructure Evolution Models (Build and post build)

Micro Residual Stress Simulations

Material Property Predictions

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





MGI Connection

Jim Warren and Carelyn Campbell, NIST

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

1. ***In situ* process monitoring (test beds, not all commercial)**
    - Thermography
    - Secondary laser probes
    - *In situ* X-ray fluorescence and diffraction
2. **Dimensional accuracy and precision**
    - Standard test artifacts
    - Direct dimensional measurements, traceable to SI
    - Round robins
    - Standard test method development
    - Macro-scale residual stresses measurements
2. **Mechanical behavior of final part (after any post-build processing)**
    - Microstructure characterization, micro-scale residual stresses
    - Mechanical testing (tensile, fatigue, fracture, etc.)

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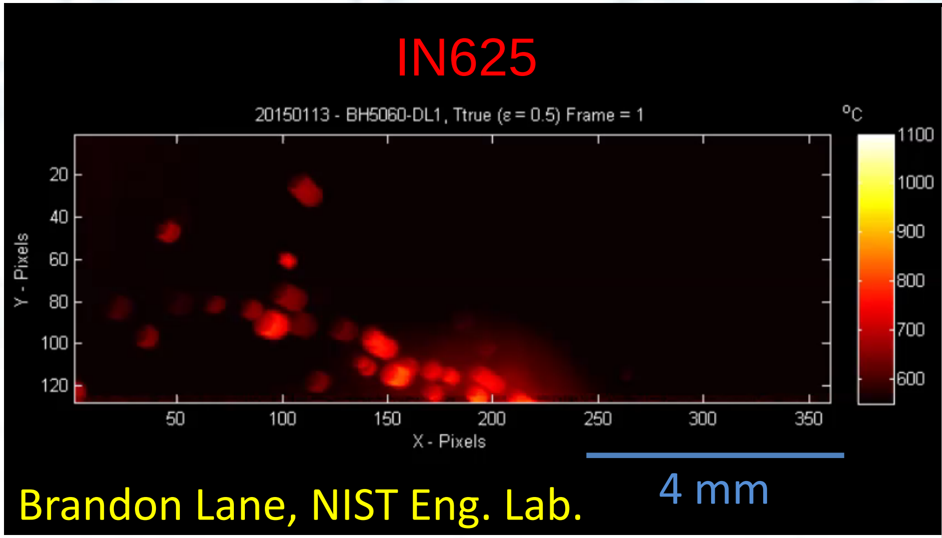
    - Standard test method development
    - *Macro-scale residual stresses measurements*
2. **Mechanical behavior of final part (after any post-build processing)**
    - *Microstructure characterization, micro-scale residual stresses*
    - Mechanical testing (tensile, fatigue, fracture, etc.)

Validation methods

Unexpected problems we have run across that impact simulations

Thermography and FEA Modeling

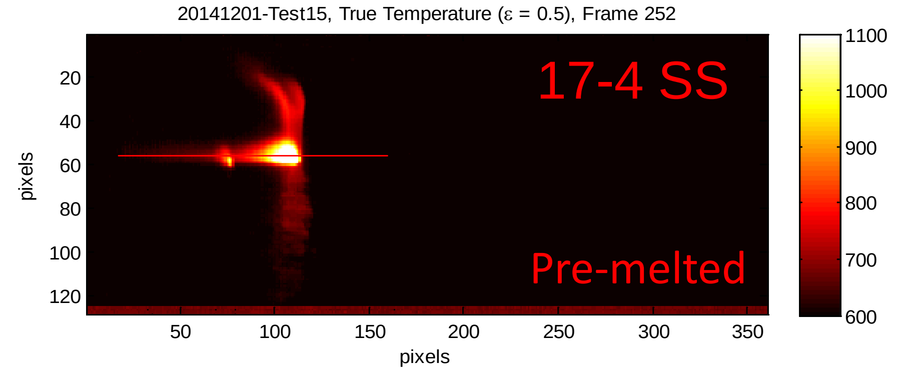


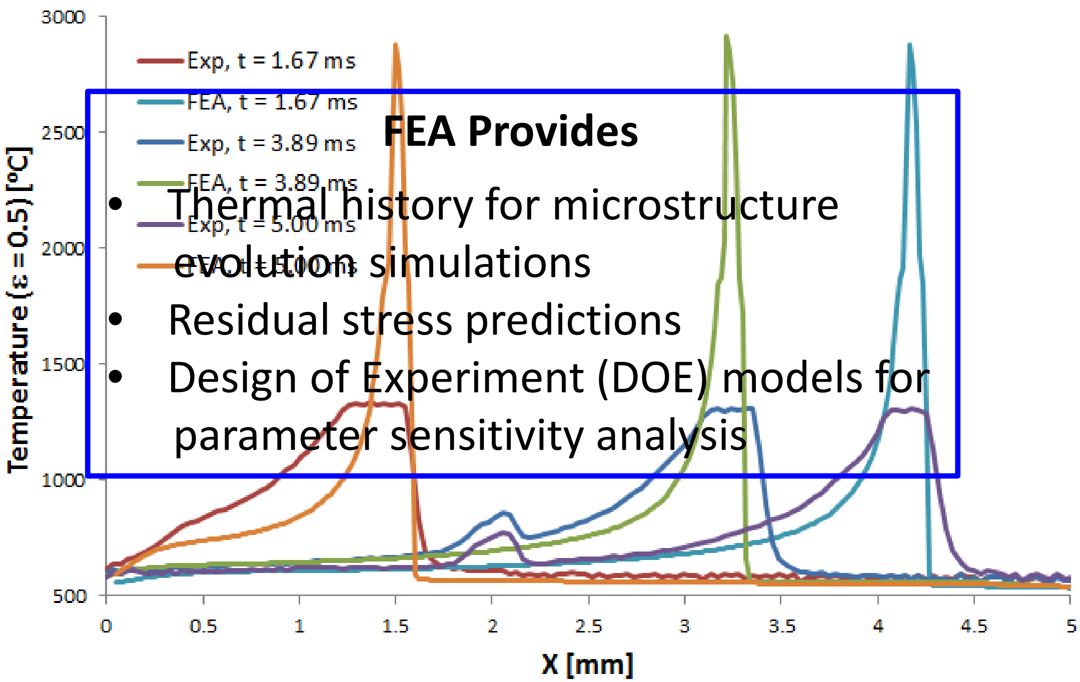
- Transient heat conduction simulation: ABAQUS
  - One layer multiple hatch scanning simulation
    - Scan on one layer of powder on the solid substrate
  - Laser heating source: Gaussian
  - Includes liquidus, solidus -> latent heat of fusion
  - Heat conduction change from powder to melt/solid
  - Still missing a lot of critical physics!

Thermography and FEA Modeling

- Thermography Challenges: acquiring ‘true’ object temperature, T_{ob}
  - ‘True’ temperature requires measurement equation (model of all radiant sources)
  - Need surface <u>emissivity</u> and <u>reflected source temperature</u> (maybe more)
  - Other sources of error (blur, pixel noise,…)

- Modeling Challenges:
  - Physics inputs
  - Material properties
  - Simulation parameters

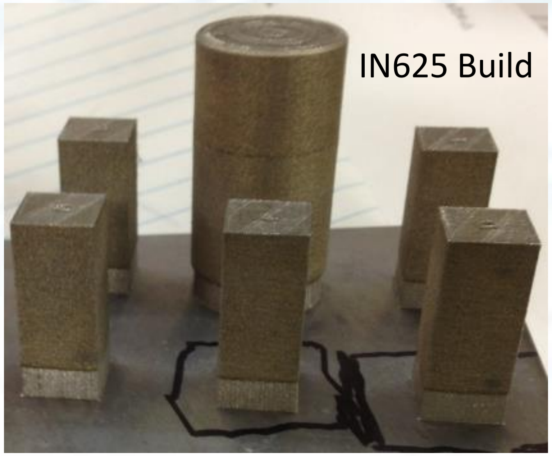


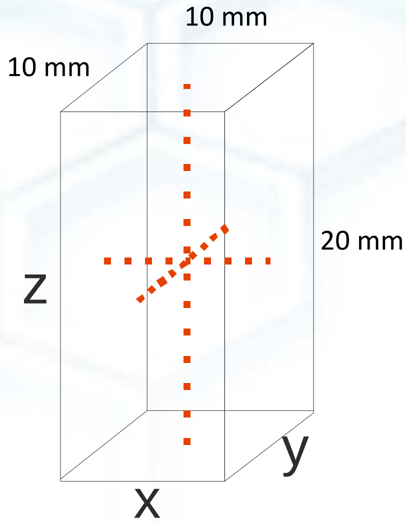


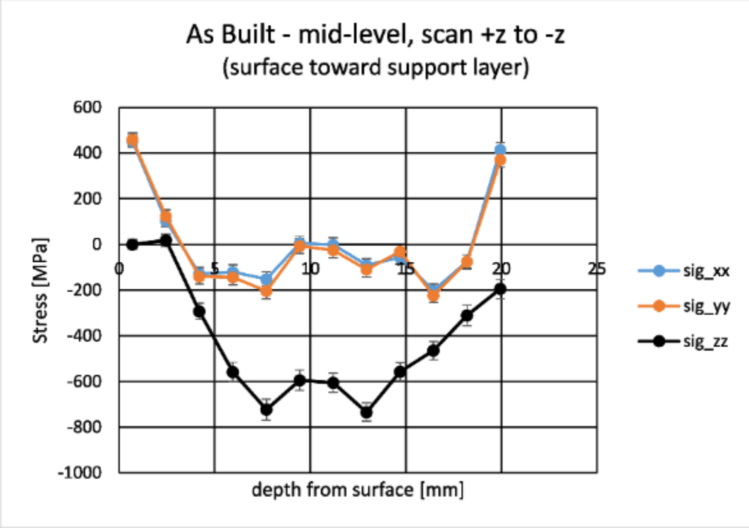
FEA Provides

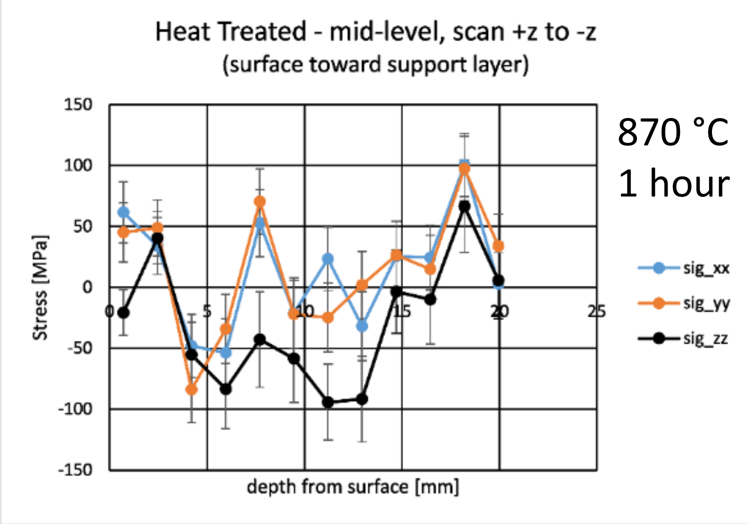
- Thermal history for microstructure evolution simulations
- Residual stress predictions
- Design of Experiment (DOE) models for parameter sensitivity analysis

Macro-scale Stresses Measured by Neutron Diffraction

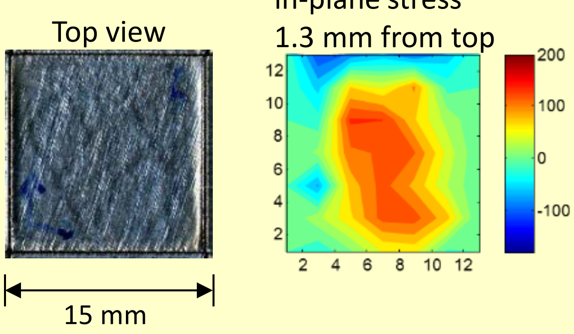








IN625 Cube



T. Gnaeupel-Herold, NIST Center for Neutron Research

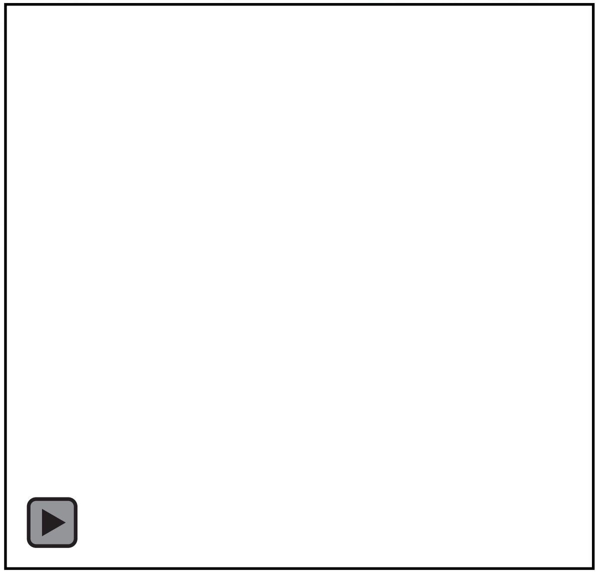
Micro-scale residual stresses using synchrotron X-rays

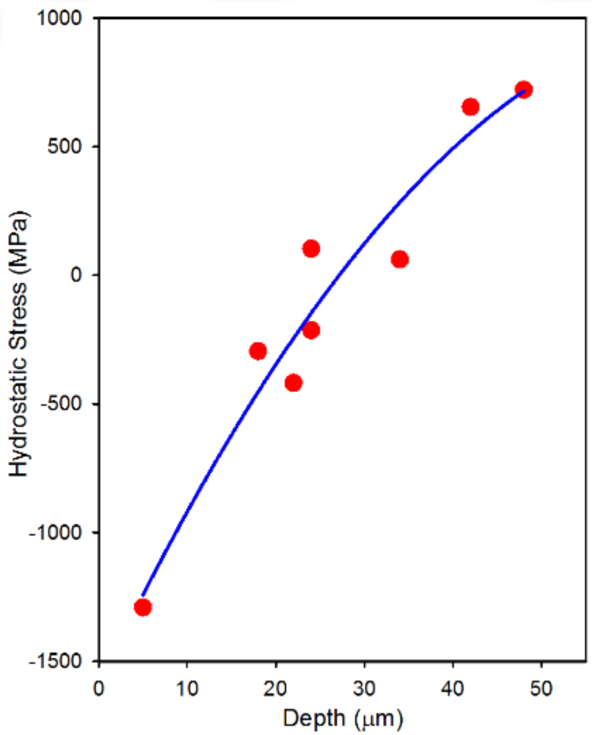
Advanced Photon Source, Argonne National Laboratory, 34-ID

With Honeywell, Questek
718+ annealed 1066 °C, 1.5 h

Local stresses can drive microstructural evolution

22 μm × 22 μm × 80 μm





Measurement method:
L. E. Levine, *et al.*, IUCrJ, in press

Depth = 5 μm

Unit cell parameters

a_1 = 0.3576608 nm ± 0.000026 nm
b_1 = 0.3574790 nm ± 0.000061 nm
c_1 = 0.3582020 nm ± 0.000007 nm
α = 89.9080° ± 0.0039°
β = 90.0200° ± 0.0034°
γ = 89.8658° ± 0.0100°

Orientation

Ψ = 344.9886° ± 0.0075°
Θ = 137.9587° ± 0.0026°
Φ = 359.0648° ± 0.0035°

Infinitesimal strain tensor components

e_{11} = $(-2.93 \pm 0.07) \times 10^{-3}$
e_{22} = $(-3.44 \pm 0.17) \times 10^{-3}$
e_{33} = $(-1.42 \pm 0.02) \times 10^{-3}$
e_{23} = $(8.00 \pm 0.34) \times 10^{-4}$
e_{13} = $(-1.74 \pm 0.30) \times 10^{-4}$
e_{12} = $(-1.17 \pm 0.09) \times 10^{-3}$

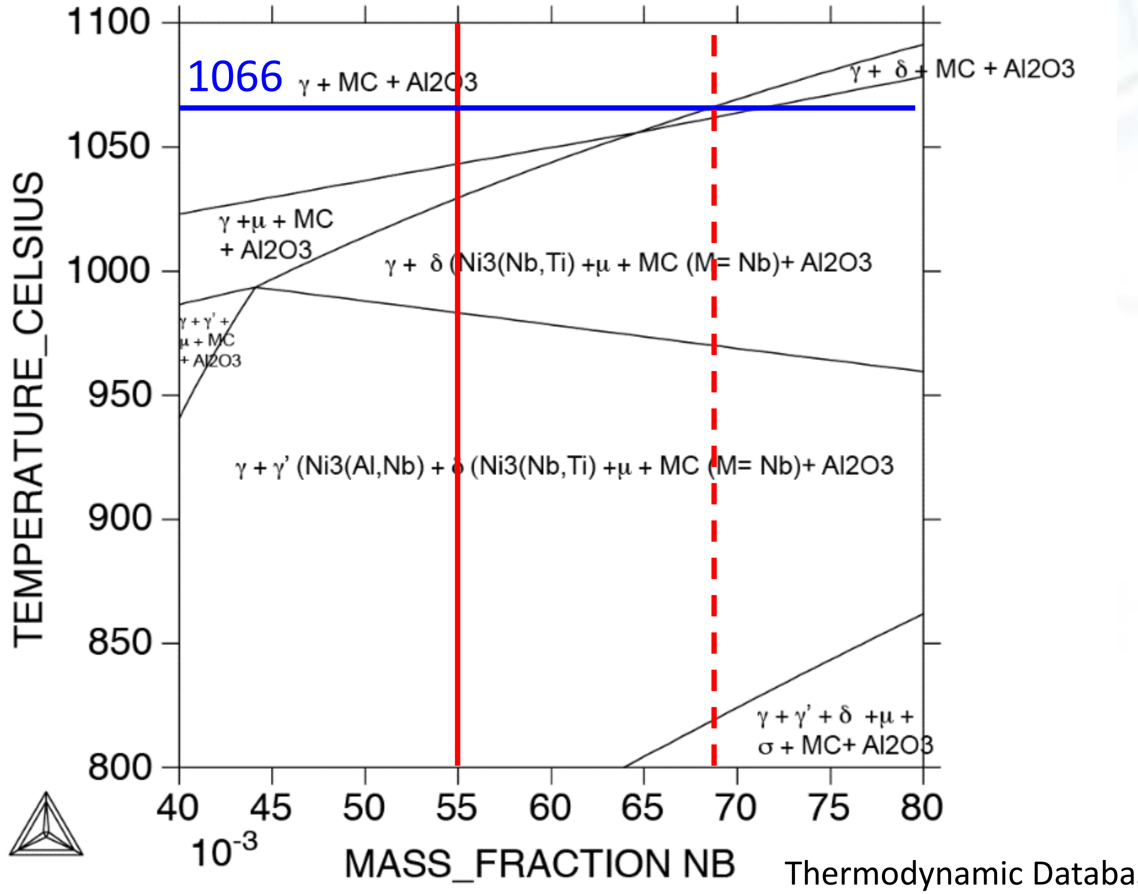
Stress tensor components in MPa

s_{11} = -1390 ± 30
s_{22} = -1440 ± 42
s_{33} = -1230 ± 25
s_{23} = 167 ± 7.6
s_{13} = -36.3 ± 6.2
s_{12} = -243 ± 19

Unexpected phase evolution in 718+

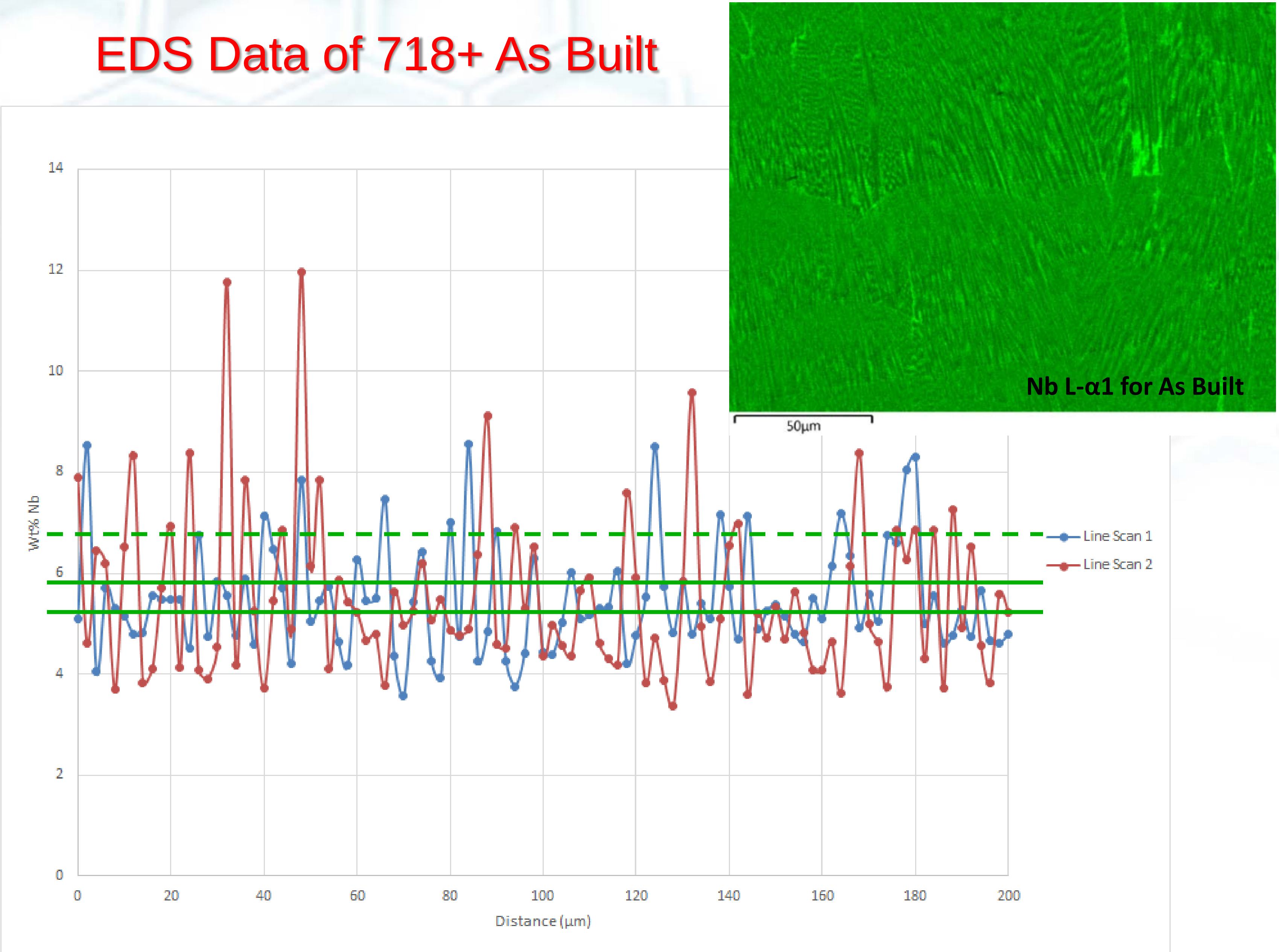
Nominal 5.2 % to 5.8 % Nb

Ni-16.98Cr-9.42Fe-9.03Co-(4-8)Nb-2.75Mo-1.72Al-1.13W-0.81Ti-0.042Si-0.023C-0.017O



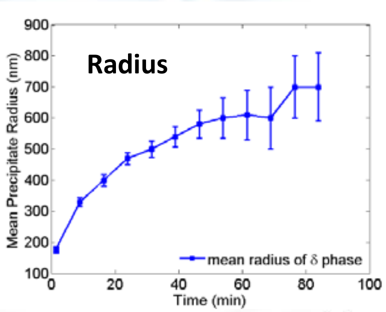
Thermodynamic Database: TNI6

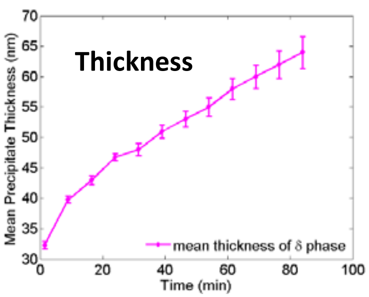
EDS Data of 718+ As Built

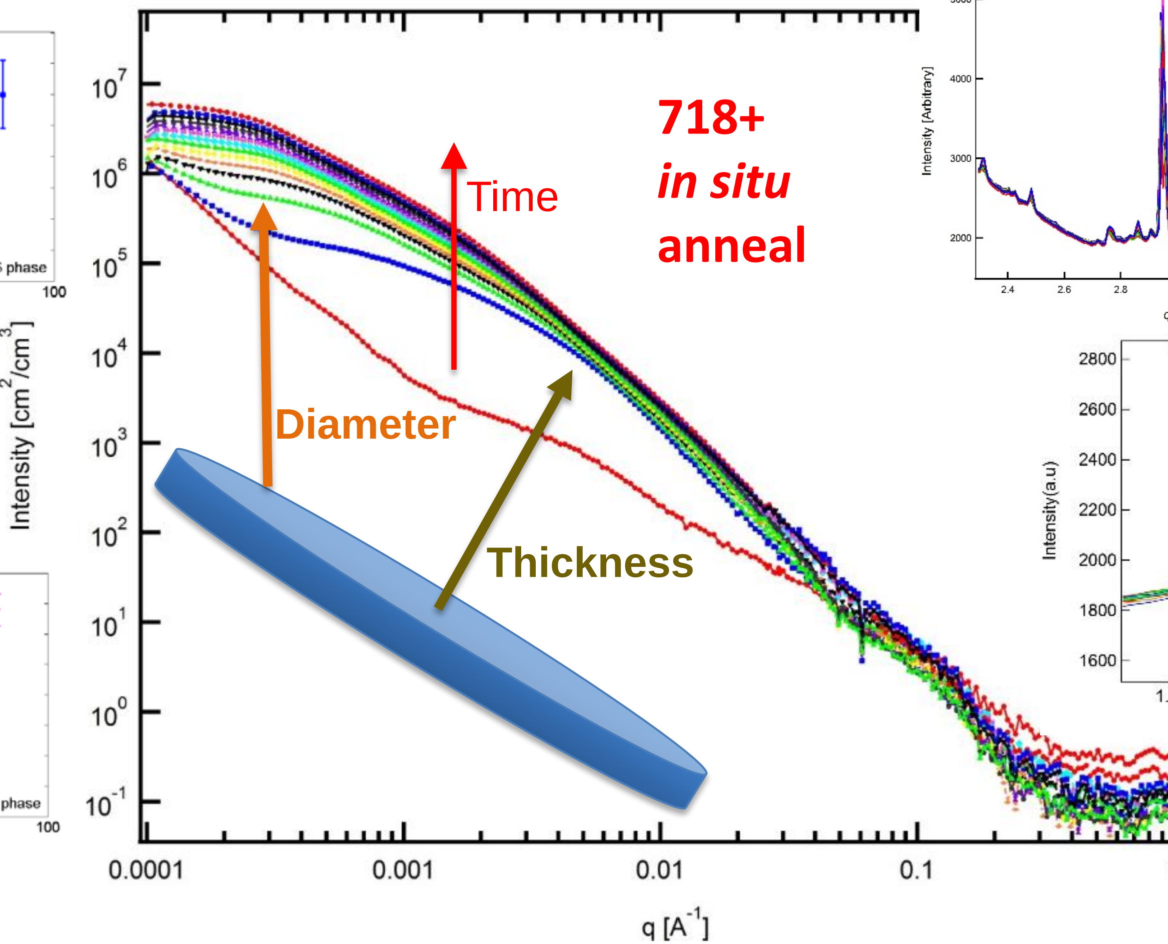


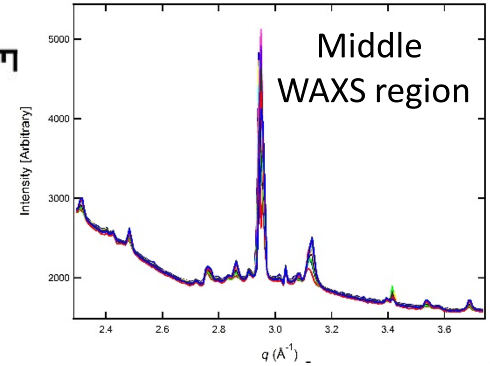
Combined USAXS/SAXS/WAXS

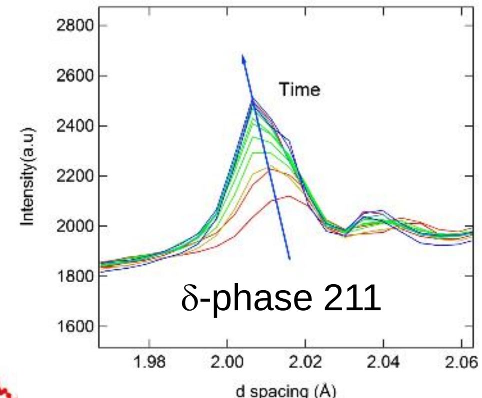
Advanced Photon Source, Argonne National Laboratory, 9-ID

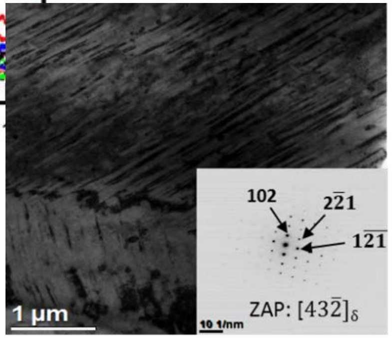












Y. Idell, L. E. Levine, F. Zhang, A. Allen, NIST Mater. Meas. Lab.

Additive Manufactured17-4 Heat Treatment Failure

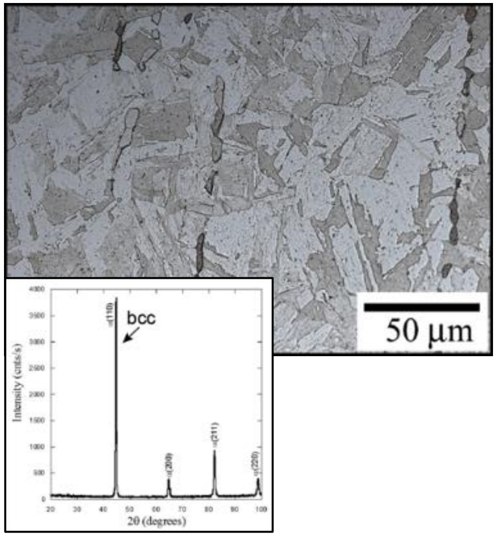
What is 17-4?

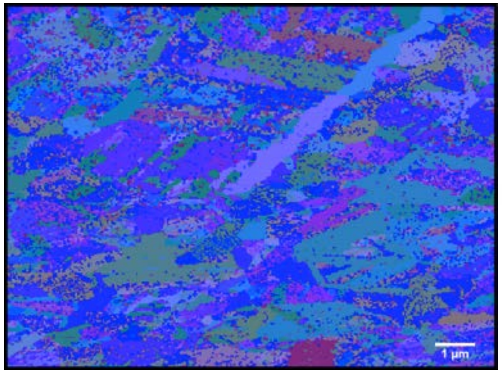
A weldable stainless steel with high strength and good corrosion resistance.

How is it processed?

1. When annealed at around 1050 °C, 17-4 becomes fully austenitic (fcc)
2. After quenching to room temperature, 17-4 becomes fully martensitic (bct)
3. Subsequent annealing between 480 °C and 760 °C produces Cu-based precipitates

Wrought 17-4

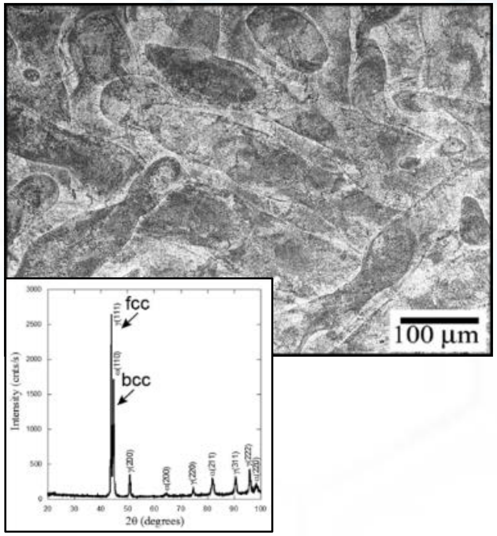




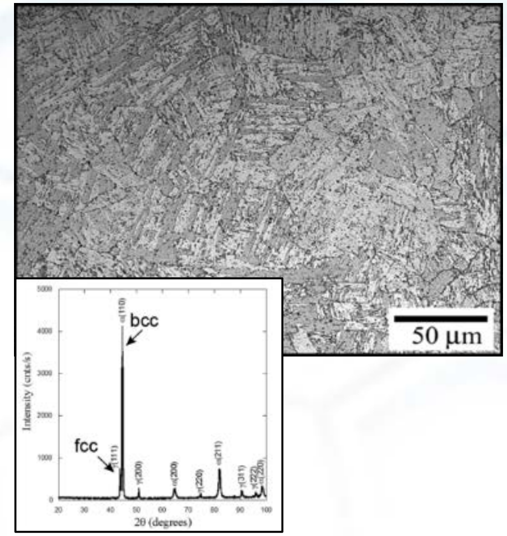
Wrought EBSD phase map showing all martensite

Additive Manufactured17-4 Heat Treatment Failure

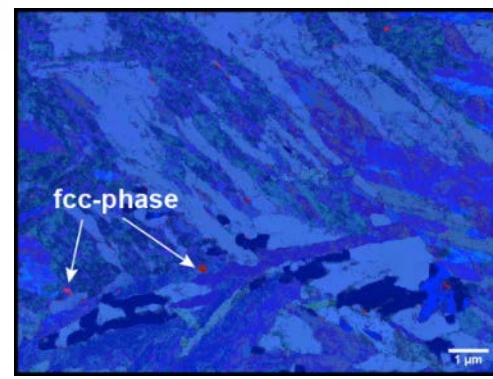
As-Built AM 17-4



Our heat-treated AM 17-4



- Conventional heat treatment leaves ≈ 15 % fcc!
- Well known that nitrogen stabilizes austenite
- Atomization/AM build in N_2 alters the chemistry, affecting the final properties of the AM-built part



AM post HT EBSD phase map showing ≈ 0.95 % martensite

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

Many pitfalls exist –

1. *Macro-scale stresses* can affect part shape
2. *Local stresses* can affect microstructure evolution
3. *Local composition gradients* affect microstructure evolution
4. *Composition changes from atomization and AM build* affect microstructure evolution
5. etc., etc., etc.

"Predictive" simulations need to get these right

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

Separate software into three categories:

1) High fidelity, physics-based simulations to train computationally faster engineering simulations

2) Pre-build engineering simulations to identify potential build problems (overhangs, thin walls, etc.) and design specific AM build process (run before each new build)

3) Rapid, real-time, simulations for *in situ* adjustment of build parameters – requires feedback loop with in situ process monitoring (e.g. T profile, melt pool width, etc.)

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

Proposal:

Put together a dedicated conference series on "Simulations for Additive Manufacturing" *with **computational benchmarks*** as a key component.

modeled after the NUMISHEET benchmark

Robert Wagner, J. K. Lee, Eiji Nakamachi, Norman Wang (1988)

- Single laser trace on single powder layer of known composition and size distribution
  - Melt pool width and geometry
  - Spatter size distribution and ejection velocity distribution
  - phases present
- Right angle intersection of two walls, 3 mm thickness
  - part geometry
  - distribution of stresses
  - etc.
- Overhang geometry…

Thank You !!!

Please feel free to contact me at:

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Lyle.Levine@nist.gov

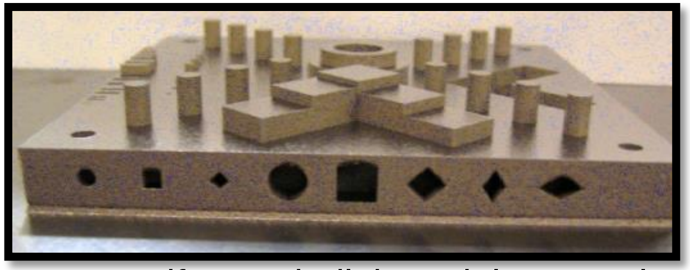
5. What measurements of quality or systems are appropriate that correlate computational and analytical methods to practical implementation?

1. **Dimensional accuracy and precision**
   - build accuracy, precision, and surface finish
   - internal and external features, thin walls, overhangs
   - reproducibility (build-to-build, machine-to-machine)
   - “geometric” residual stresses → part distortion

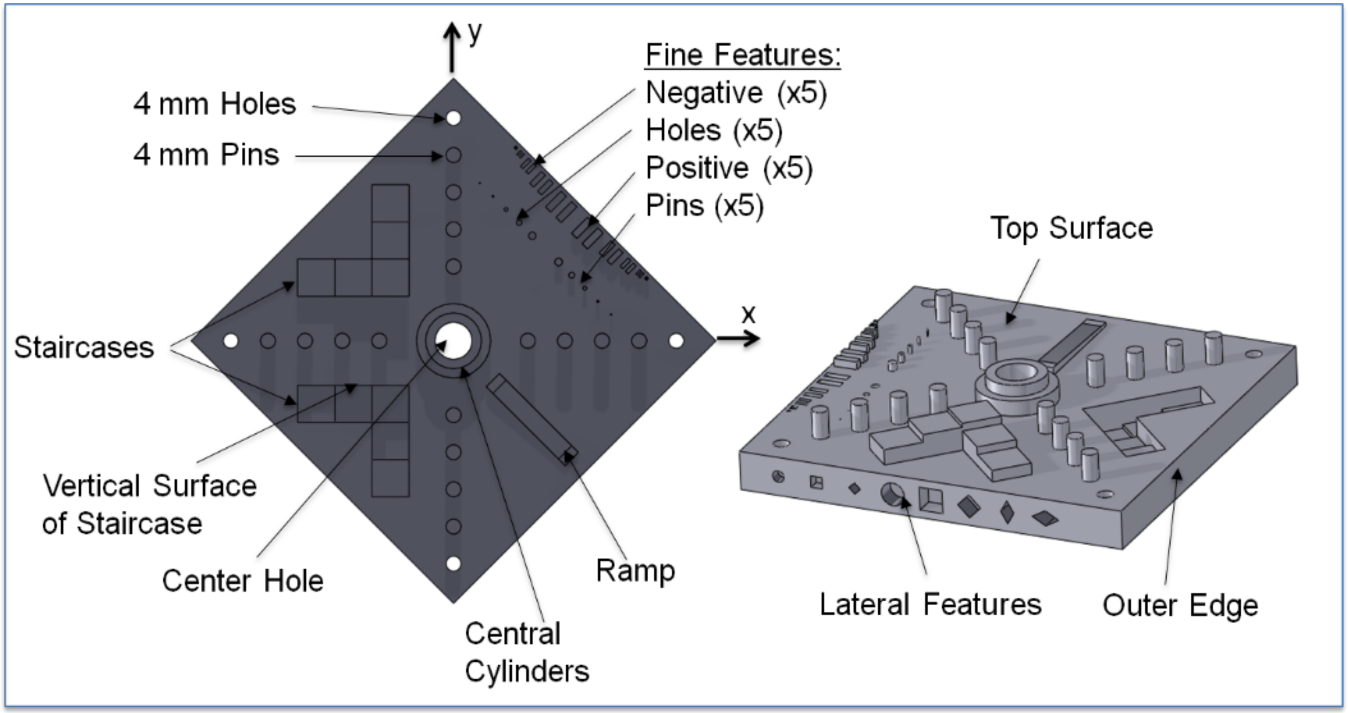
2. **Mechanical behavior of final part (after any post-build processing)**
   - Yield stress, UTS, fatigue behavior, fracture, hardness, hardening behavior, environmental effects (e.g. corrosion)
   - Local variations (intentional and unintentional)
   - Build flaws
   - Microstructure

Standard test artifacts

- Provide a common benchmark for:
  - Assessing and highlighting capabilities
  - Providing a basis for process optimization
  - Identifying problem areas to spur innovation



test artifact as built in stainless steel



NIST Proposed AM Test Artifact

ASTM F42 + ISO/TC 261

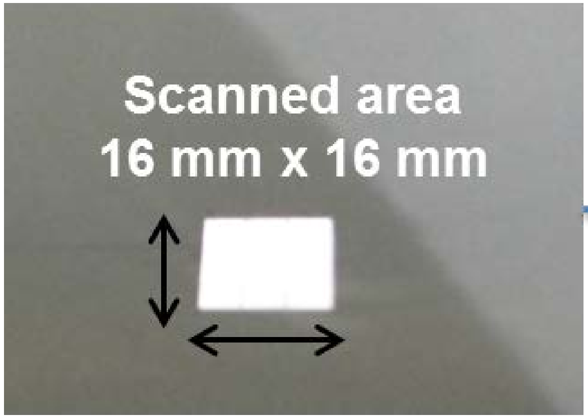
Shawn Moylan
NIST Eng. Lab.

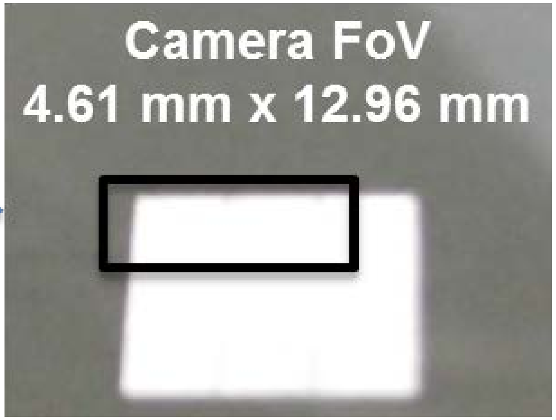
Results – Test 11 'Intensity'

- What are we looking at?

Camera Parameters:
iFoV: 36 μm/pixel
FoV: 128x360 pixels
(4.61 mm x 12.96 mm)
Frame Rate: 1800 fps
Integration time: 0.05 ms
Spectral range: 1640 nm to 2400 nm

Build Parameters:
Material: EOS PH1 Stainless Steel
Mean Particle Size: 20 μm
Hatch Spacing: 100 μm
Hatch Width: 5 mm
Laser Power: 195 W
Scan Speed: 800 mm/s





- 1st video: melting single powder layer
- 2nd video: no powder; scan over solidified surface