Oak Ridge National Laboratory
Manufacturing Demonstration Facility

Development in Additive Manufacturing for High Temperature Alloys

U.S. DEPARTMENT OF ENERGY | Advanced Manufacturing

DOE/NETL Crosscutting Research Program
Annual Review Meeting 2015
Pittsburgh, PA

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

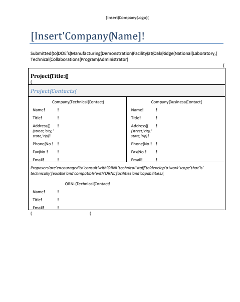
Manufacturing Demonstration Facility

Providing leading edge technology and business solutions for industry

- Public-Private Partnership
- 50+ active projects
- Addressing technical challenges across complete supply chain

Technical Collaborations	59 (ongoing) 19 (in process)

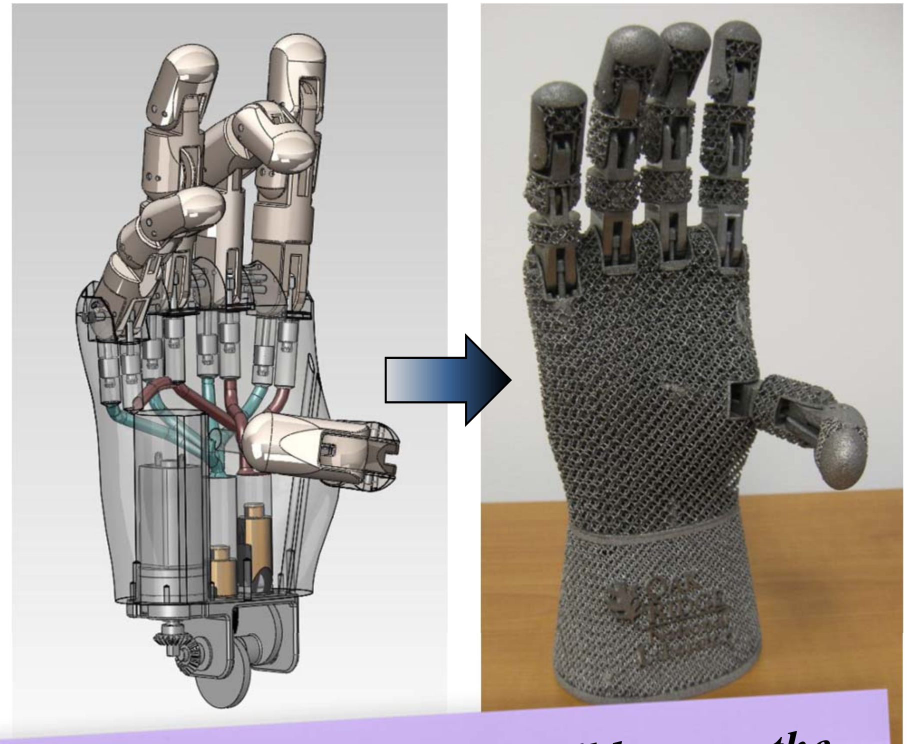
Reduce risk, accelerate commercialization of advanced technologies while reducing lifecycle energy



Proposal Form on Website
www.ornl.gov/manufacturing

Additive manufacturing

CAD Model to Physical Part



"Additive Manufacturing will become the most important, most strategic, and most used manufacturing technology ever."
Wohlers 2012

Faster. Cheaper. Better!

- Increased Complexity
- Less Material Scrap
- Shorter Design Cycle
- Reduced Part Count

Partners: AM supply chain

Materials Suppliers

- AMETEK
- ATI
- TECHMER PM POLYMER MODIFIERS
- FMC Technologies
- MPP METAL POWDER PRODUCTS
- ERASTEEL
- PolyOne
- Stratasys FOR A 3D WORLD
- TLS Technik Spezialpulver
- SANDVIK
- CARPENTER
- sabic
- CRISTAL
- TIMET
- HMI Metal Powders
- RAYMOR INDUSTRIES INC.
- FUKUDA METAL FOIL & POWDER CO., LTD.

Equipment Suppliers

- CAD TO METAL Arcam AB
- FABRISONIC
- ExOne DIGITAL PART MATERIALIZATION
- Stratasys FOR A 3D WORLD
- CINCINNATI CINCINNATI INCORPORATED
- Ajax TOCCO
- DM3D
- POM
- ECM Technologies
- MakerBot
- GRID LOGIC
- RENISHAW
- Solidoodle
- AFINIA
- SOLIDICA
- Cubify
- OBJET
- AO Applied Optimization

End Users

- LOCAL MOTORS
- Cummins
- S-RAM DYNAMICS
- BOEING
- LOCKHEED MARTIN
- PPG
- AMERICANTRIM
- GE
- EPRI ELECTRIC POWER RESEARCH INSTITUTE
- PRAXAIR
- PIEDMONT PROPULSION SYSTEMS, LLC A First Aviation Services Inc. Company
- Honeywell
- aerovalve
- Radio Systems CORPORATION
- TruDesign
- PLANETARY SYSTEMS CORPORATION
- NORTHROP GRUMMAN
- BOEING

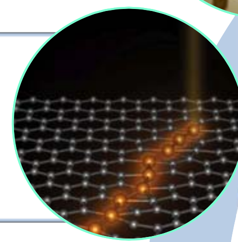
Leveraging DOE Assets at ORNL

Neutron scattering: SNS and HFIR

- World’s most intense pulsed neutron beams
- World’s highest flux reactor-based neutron source

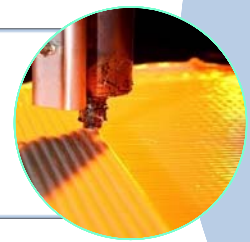
Leadership-class computing: Titan

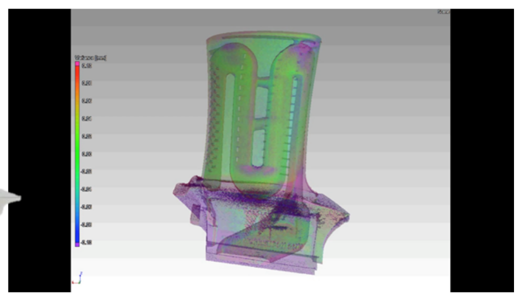
- Nation’s most powerful
  open science supercomputer

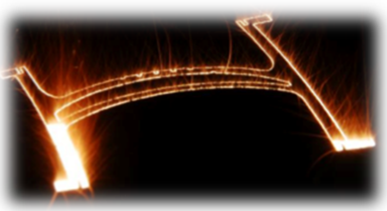


Advanced materials

- DOE lead lab for basic to applied materials R&D
- Technology transfer: Billion dollar impacts







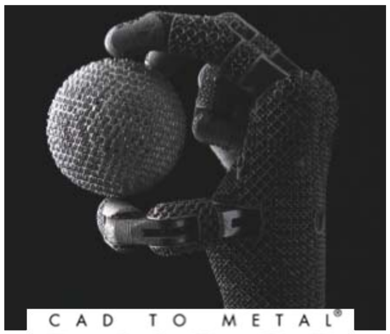
MORRIS TECHNOLOGIES
Precision. Innovation. Expertise.

Headquartered in Cincinnati, OH

- *~20 DLMS Machines*
- *18-yrs experience in laser deposition*
- *Recently acquired by General Electric*

Our additive manufacturing capabilities are comprehensive

Electron Beam Melting

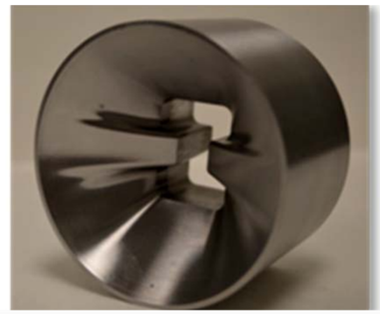


CAD TO METAL®
Arcam AB®

Laser Sintering

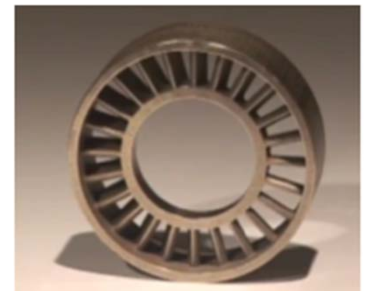
RENISHAW

Laser Blown Powder Deposition



POM
DM3D

Binder Jetting



ExOne™
DIGITAL PART MATERIALIZATION

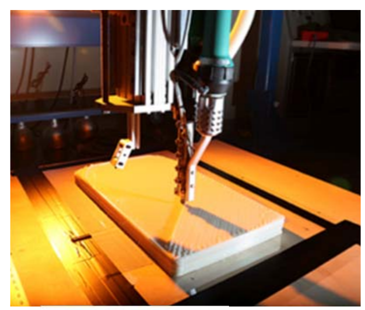
Fused Deposition Modeling

Stratasys
FOR A 3D WORLD™
AFINIA
MakerBot
Solidoodle
Cubify

Multi-head Photopolymer

OBJET
Stratasys
FOR A 3D WORLD™

Large-Scale Polymer Deposition



OAK RIDGE
National Laboratory
CINCINNATI®
CINCINNATI INCORPORATED

Future Systems

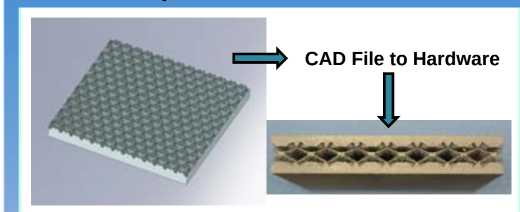
CONCEPTLASER
hofmann innovation group

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

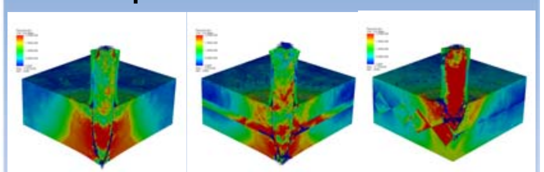
Applications of Additive Manufacturing

Prototyping, and ICME

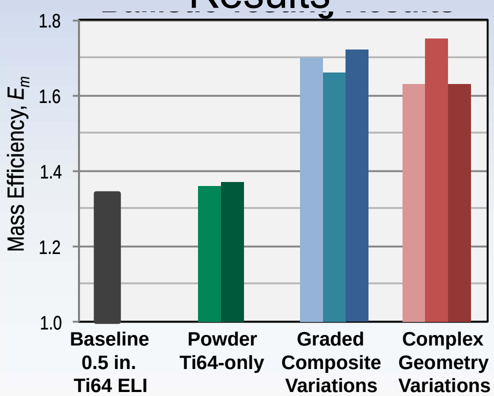
Rapid Fabrication



Computation / Validation



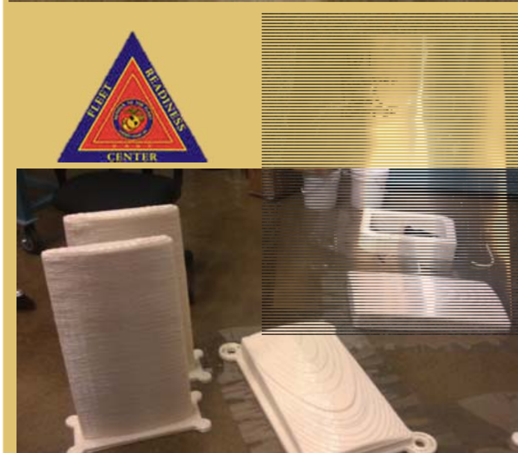
Results



$$E_m = \frac{\text{Weight of RHA Steel}}{\text{Weight of New Armor}}$$

Direct Fabrication

Tooling and Indirect Fabrication



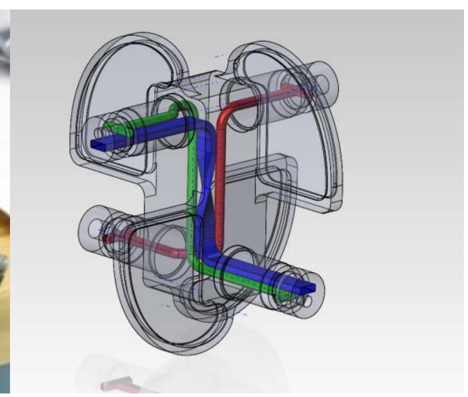
MDF Objectives in Additive Manufacturing

- Developing new design concepts
- Evolving the supply chain
- Implementing advanced controls
- Developing advanced materials
- Understanding material properties and geometric accuracy

- Exploring next-generation systems
- Training the next-generation / STEM

Additive manufacturing for robotic systems

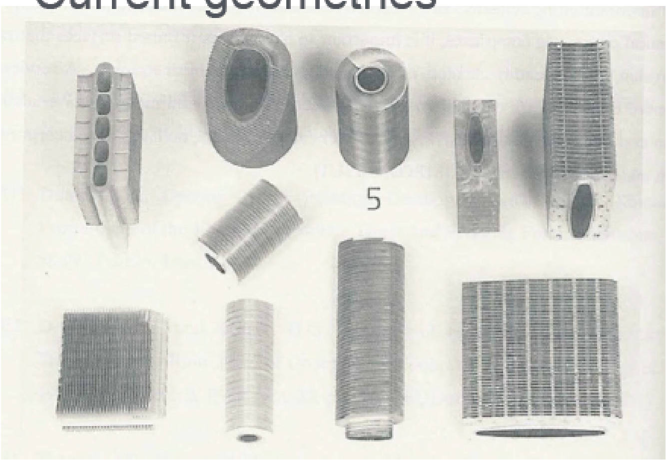
Robotic arm provided as backdrop in the White House as President Obama announced new two manufacturing innovation institutes.



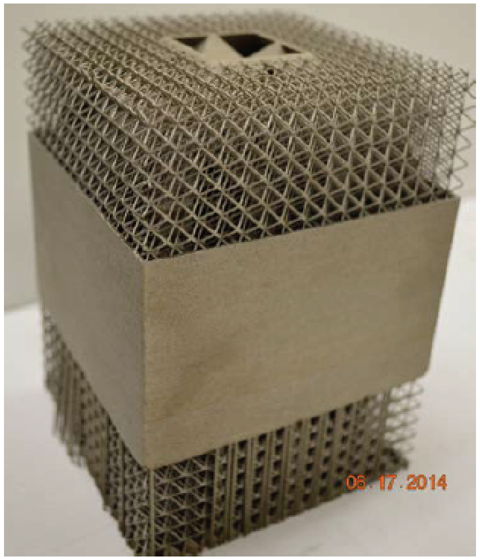
All components produced by additive manufacturing

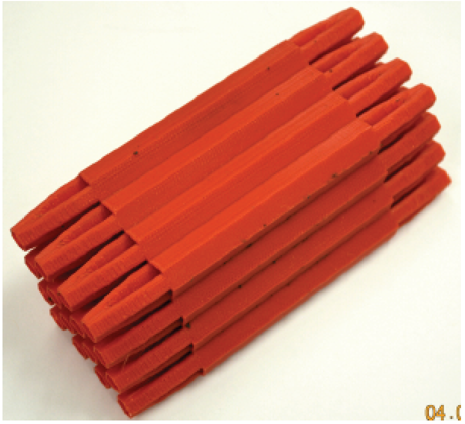
- 25-lbs total weight, 60” long arm
- Neutrally buoyant without floatation
- Fluid passages integrated into structure
- 7 degrees of freedom with 180 degree rotation at each joint
- Custom thermal valves for energy efficiency

Current geometries



Proposed geometries





Goal: attain heat transfer coefficient for the new heat exchanger of 140 W/m^2K at the same cost (2X compared with current baseline).

Sabau A.S., Klett J., Dehoff R., Bejan A. (Duke U.),
Jones J., Nejad A. (UTK), Polsky Y., Gruszkiewicz M., and Mines G. (INL)

Freeform Heat Exchangers for Binary Geothermal Power Plants

Project Officer: Tim Reinhardt

Total Project Funding: $190K and $280K (FY14, FY15)

May 12, 2015

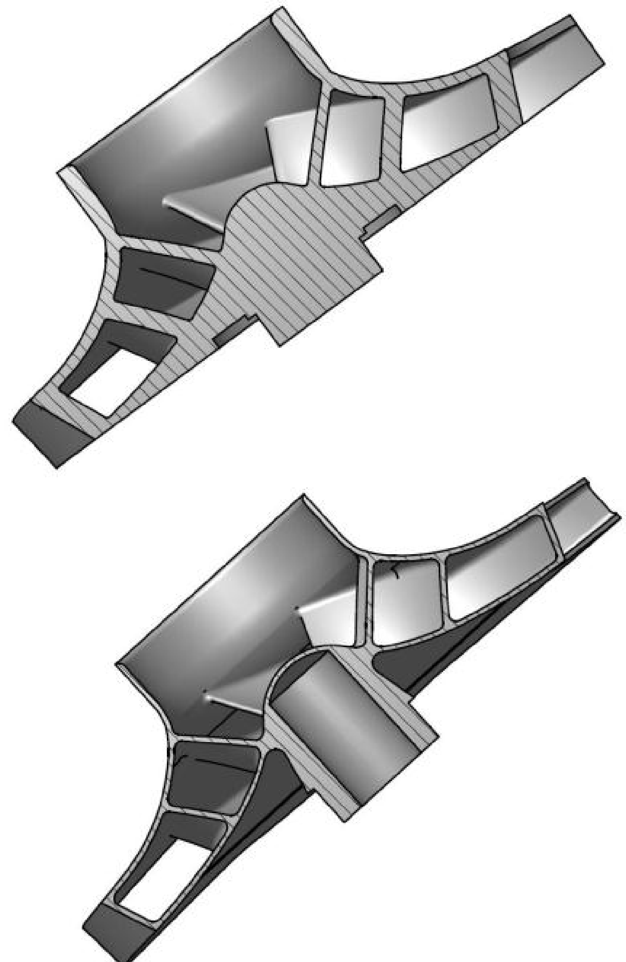
Adrian S. Sabau
Oak Ridge National Laboratory

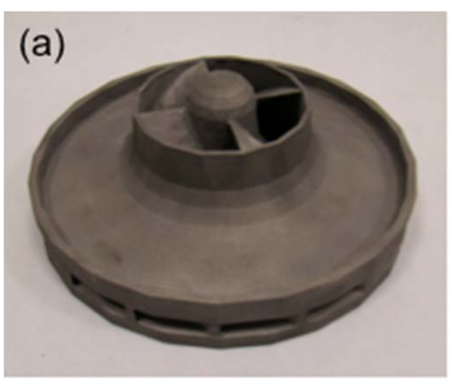
Low Temperature

Weight Reduction and Increased Performance

Example of Pump Impeller

- 55% weight savings was observed while maintaining similar function
- 75% less machining due to the high geometric accuracy of the electron beam melting process.
- Limitless possibilities for hydraulic passageways
- Hydraulic efficiency increases up to 5%





Cross section of impeller fabricated through casting (above) and newly designed impeller using electron beam melting (below)

Powder Feedstock Characteristics for AM

<u>Common PM Characteristics</u>

- Apparent Density / Tap Density
- Spheroidicity
- Flowability
- Chemistry
- Particle Size Distribution
- Porosity
- Hot Isostatic Pressing / Post Heat Treatment

<u>Unique Characteristics</u>

- Spreadability / Raking or Rolling Mechanism
- Powder Bed Density and Effect on Deposition
- Recyclability

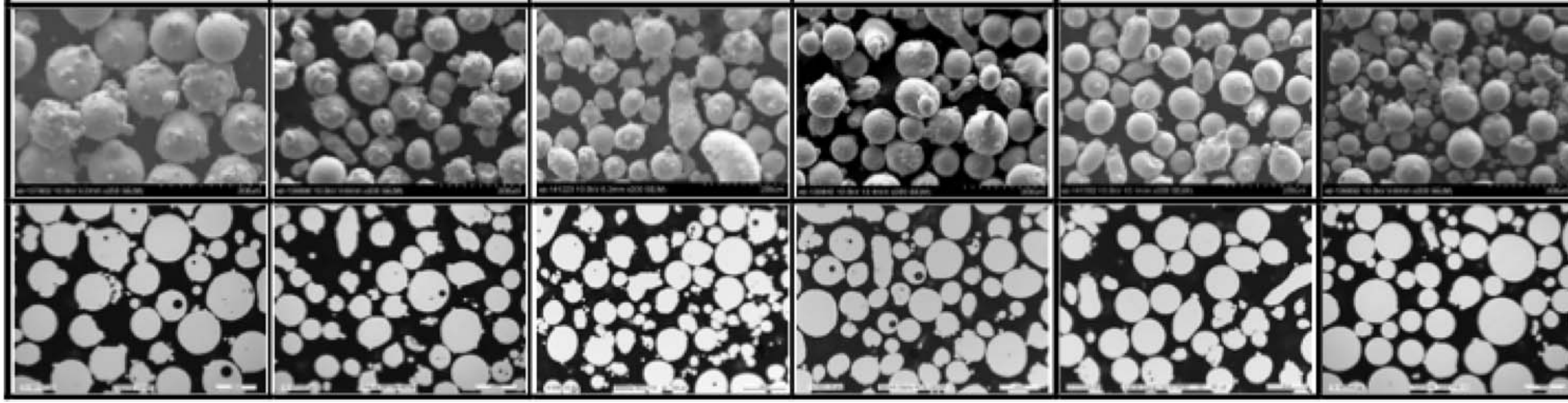
ORNL has performed powder studies for Inconel 718 and Ti-6Al-4V

Info available

SEM and OM of Multiple 718 Powders

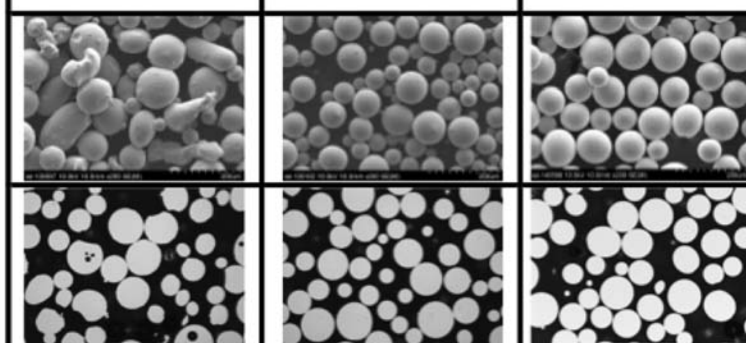
- 6 Gas Atomization Producers Represented

Table 2a: Comparison of External Microscopy Images (Top) with Cross Sections (Bottom) of Gas Atomized Ni Alloy 718 Powders					
Powder A	Powder B	Powder C	Powder D	Powder E	Powder F



- 3 Other Vendors Representing Rotary Atomized, Plasma Atomized, and Plasma Rotated Electrode
- Porosity
  - In all of the gas atomized powders
  - Some Porosity in the rotary atomized
  - No porosity in the PREP and Plasma
  - Typically in powder with dia. greater than 48um

Table 2b: Comparison of External Microscopy Images (Top) with Cross Sections (Bottom) of Other Atomization Ni Alloy 718 Powders		
Rotary Atomized	Plasma Atomized	Plasma Rotated Electrode
Powder G	Powder H	Powder I

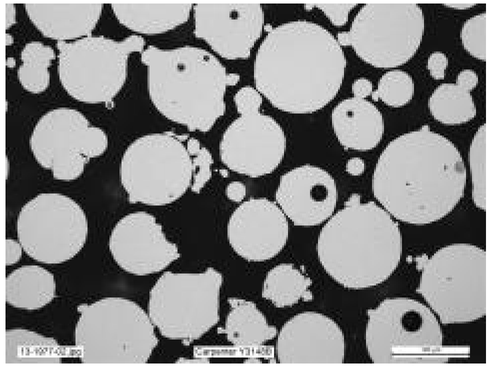


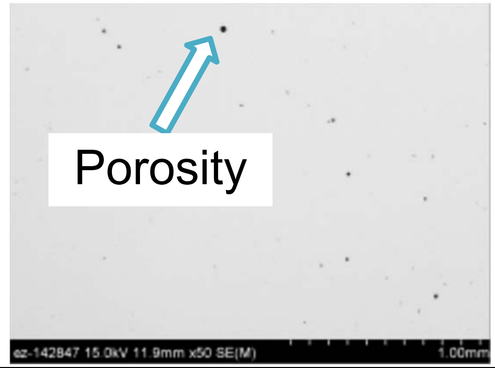
Why Look at Porosity in Powder

(E.g., Porosity in 718 Powders Can Result in Porosity in Deposit)

Powder | **As Deposited**

Gas Atomized

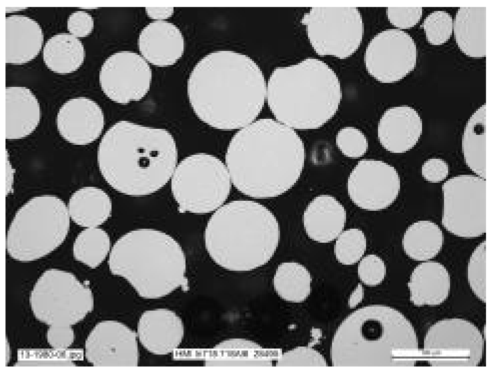


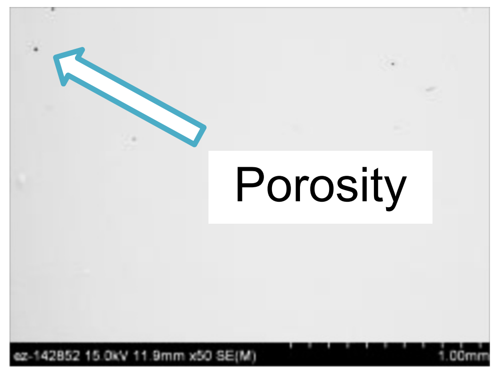


Porosity in Powder = 0.873%

Porosity in Deposit = 0.117%

Rotary Atomized

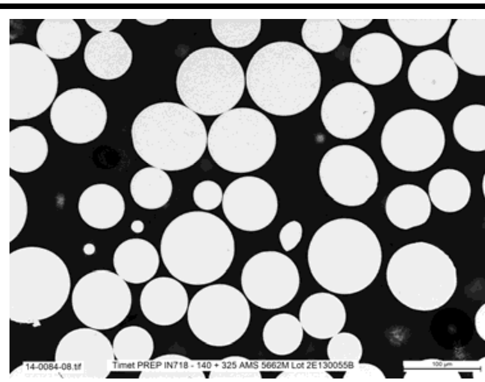




Porosity in Powder = 0.491%

Porosity in Deposit = 0.037%

Plasma Rotated Electrode



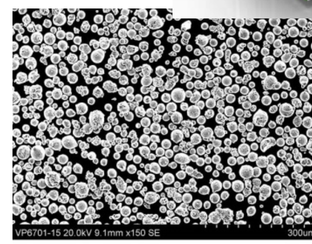
Porosity in Powder = 0.000%

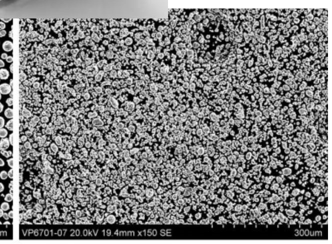
Porosity in Deposit = 0.000%

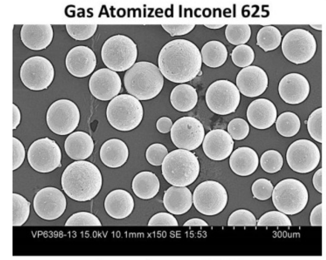
Densification of Binder Jet Inconel Alloys

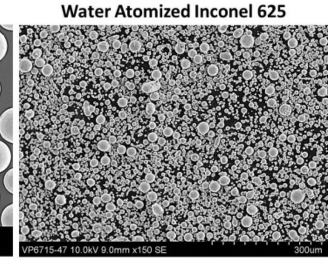
- Developing practices to increase the original low density of binder jet printed parts
  - SS316 is printed to 60% density
  - Infiltrated with bronze to achieve 100% density
- Inconel 625 has been developed for fully dense parts
  - Full density is achievable
  - Significant shrinkage and warpage
- Inconel 718 is being evaluated and compared
  - Developing powder characteristics and methodology that result in fully dense metal structures
  - Long term interest in models to predict shrinkage

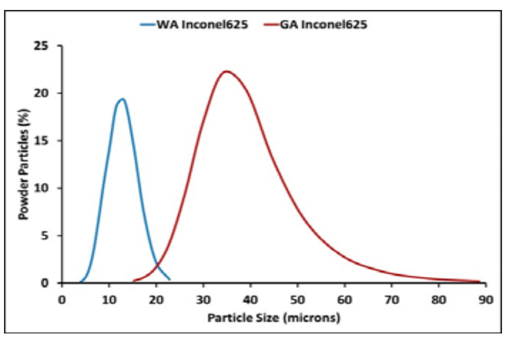
ExOne
DIGITAL PART MATERIALIZATION


Gas Atomized Inconel 625

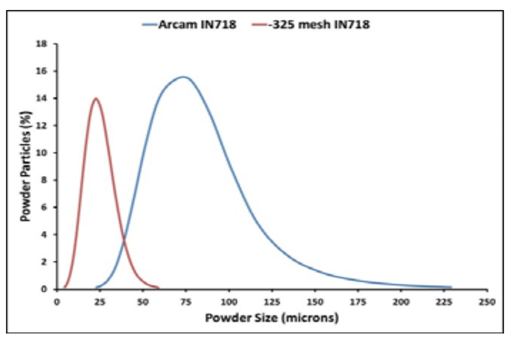

Water Atomized Inconel 625


Arcam Inconel 718

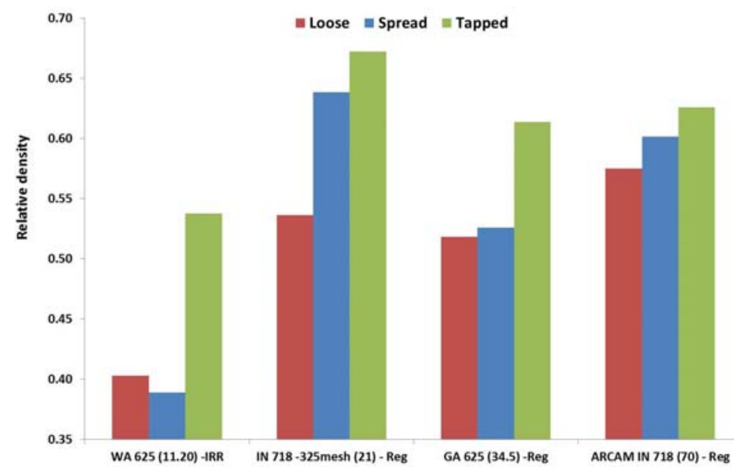

-325 mesh Inconel 718



Inconel 625

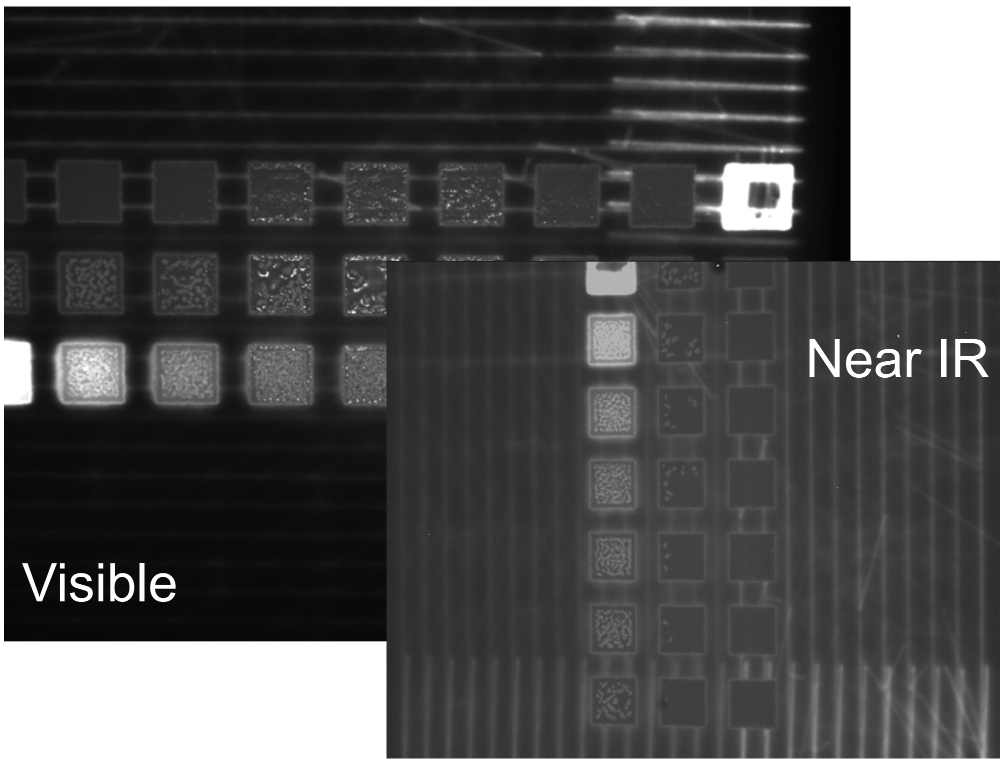


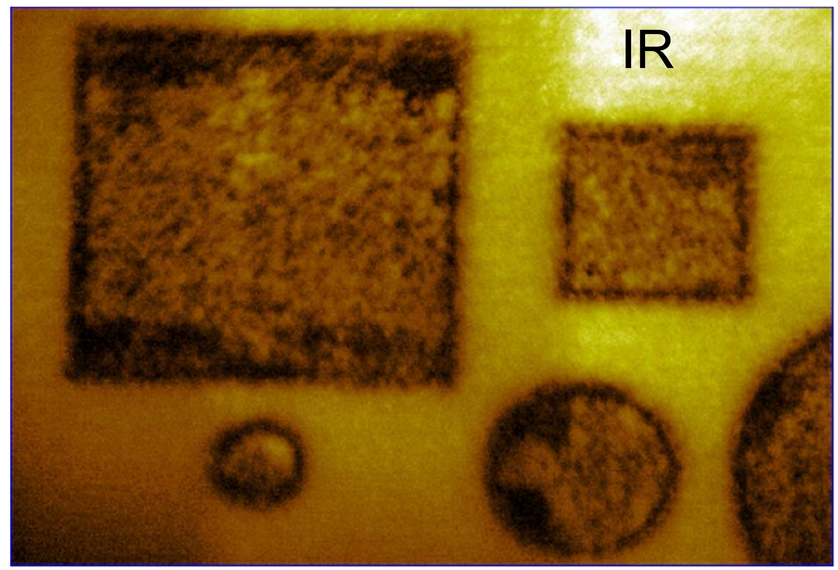
Inconel 718



In-Situ Process Monitoring

- Ability to understand defects, porosity and material behavior in each layer deposited (repair)
- Several methods examined for both R&D Environment and for cost effective manufacturing solution

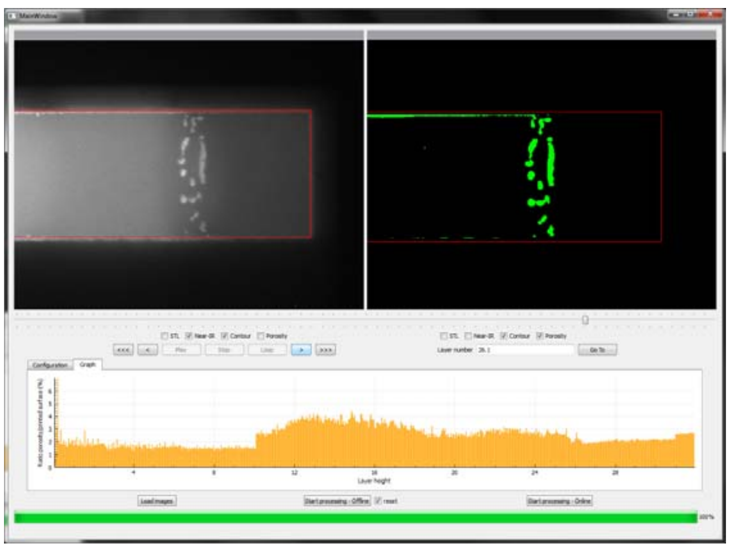




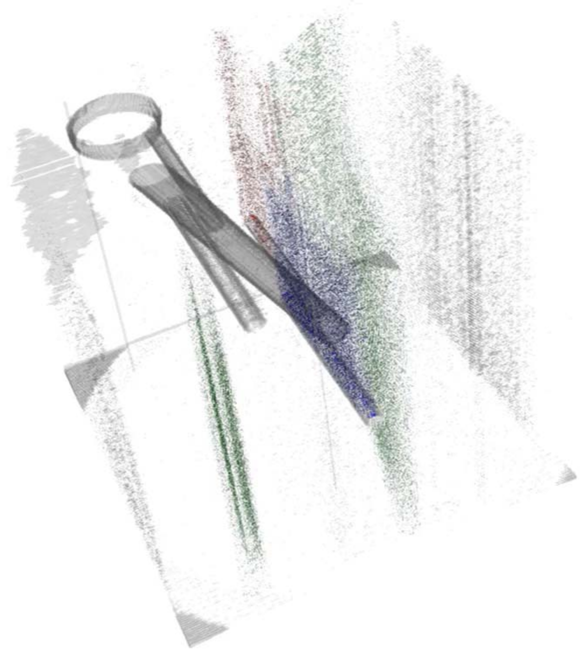
Automated In-Situ Defect Detection on the Q10 System

- Arcam has created a software called LayerQam and ORNL has independently developed software for in-situ defect detection of single images in the Q10 system.
- Intensity variations in near infrared images are used to determine porosity levels in samples

Shutter system inside chamber to eliminate metallization build up during processing



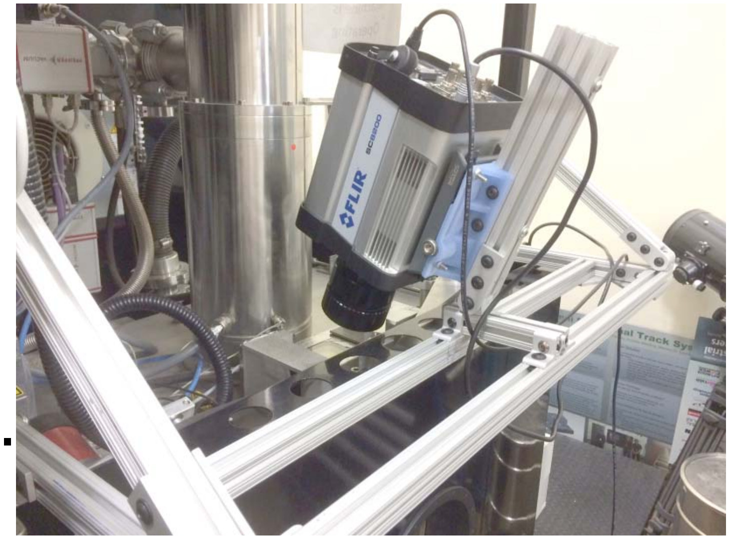
ORNL's user interface showing porosity distribution.



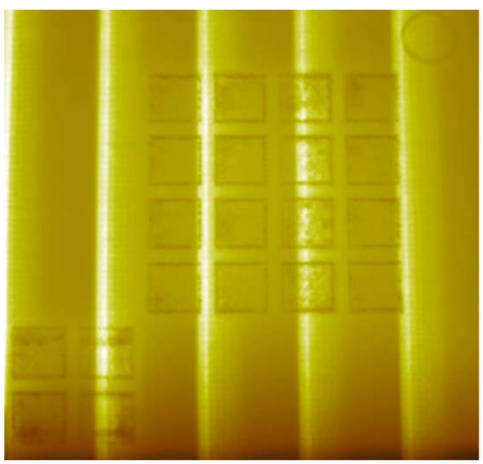
- Reconstructed porosity map based on image analysis. Defects due to experimental parameters are segmented by color.
- Currently evaluating accuracy with X-ray CT scans

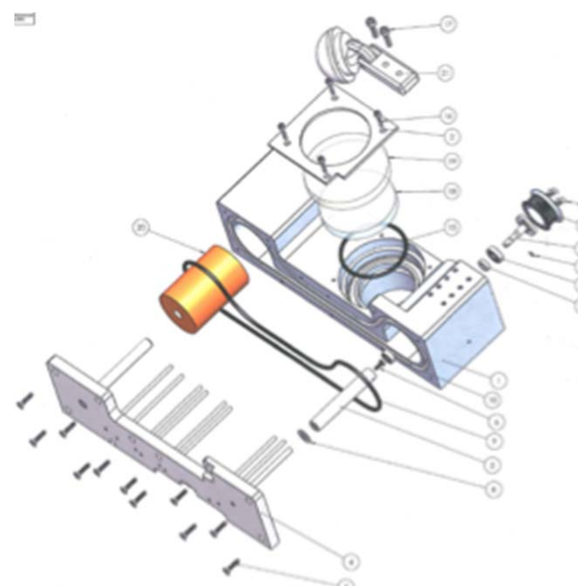
Process Monitoring Setup: Film Feeder

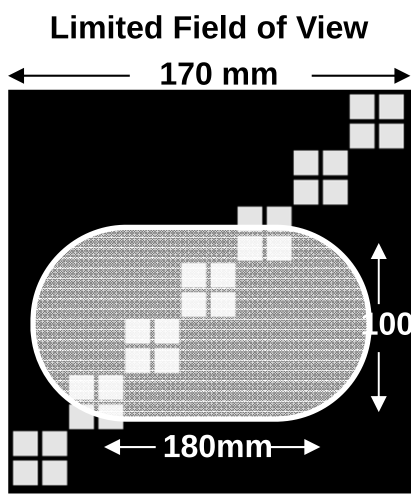
Window Material	Thickness (mm)	Transmission (3-5 microns)
Sapphire	2.0	0.863
Leaded Glass	10.1	0.00108
Kapton Film	0.060	0.787



- **Sapphire supports the pressure differential.**
- **Leaded glass reduces X-ray emissions.**
- **Kapton film shields windows from metallization.**
- **Total Transmission of window system is 0.73%**

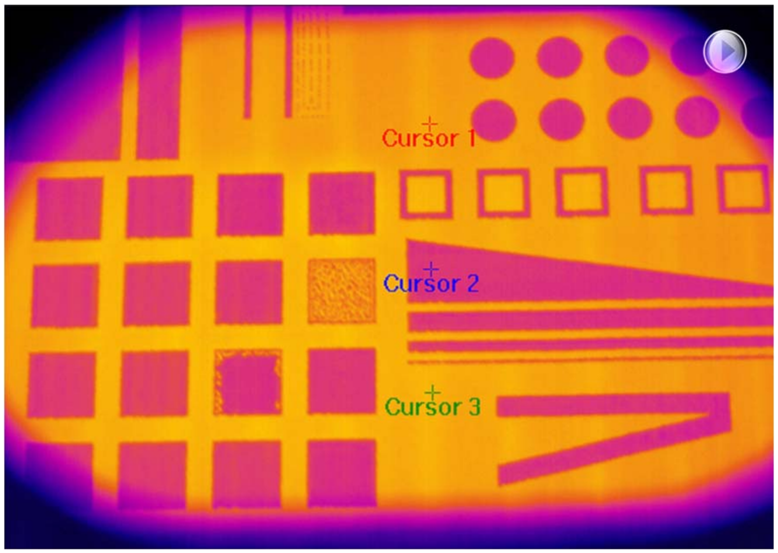






High-Infrared Imaging for defect detection and thermal history understanding

- Determination of surface temperature to understand solidification and precipitation kinetics.
- Preliminary correlation has been performed showing porosity detection correlation to x-ray computed tomography. The process is currently being automated
- Additional sensors may be required



Full chamber view with corresponding intensity

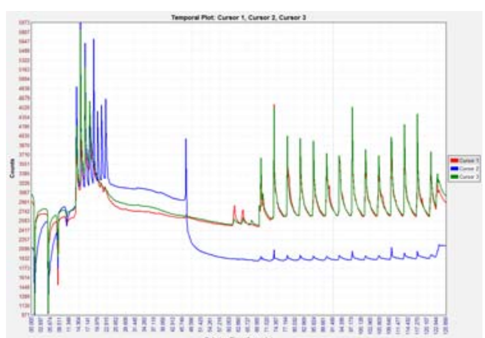
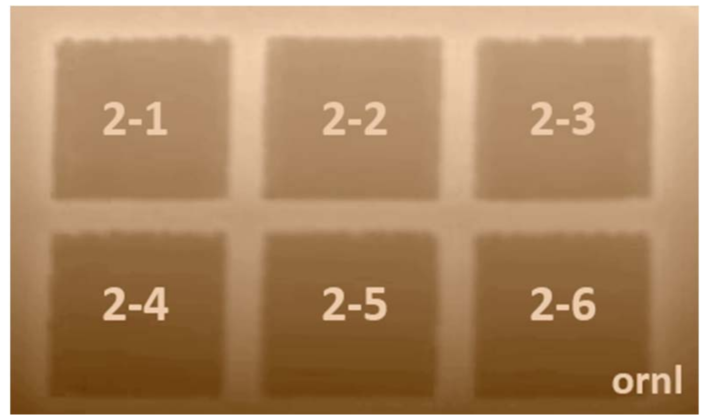
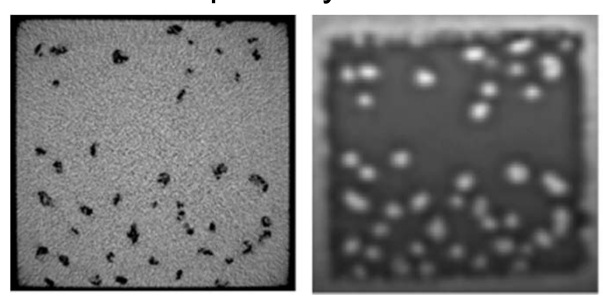


Image stack of sample showing vertical porosity from focus offset changes



Correlation between x-ray CT and in-situ identified porosity



Top View slice projection

X-ray CT Minimum Projection

Side View

ORNL Enables Commercial Release of Inconel 718 for Electron Beam Powder Bed Deposition

- ORNL development of process parameters for 718
  - Energy-speed-current-focal offset determination
  - In-situ thermal and visual defect detection
- Material feedstock study for required powder characteristics
- Release enables fabrication of e-beam netshape, complex Ni alloy components to be used in aircraft engines, gas turbines, energy systems, and other high temperature applications

Press release — Mölndal, Sweden, June 9, 2014

Arcam launches a Nickel Base Superalloy process for Additive Manufacturing with Arcam's EBM systems

Arcam today launches a process for Inconel 718® as a qualified material for use in Arcam's EBM systems. The Inconel process is initially available for the Arcam A2X platform. The machine material parameters and mechanical testing was done in collaboration with the U.S. Department of Energy's Manufacturing Demonstration Facility at Oak Ridge National Laboratory. Parts made in the new process are exhibited at the Rapid conference in Detroit, MI, June 10-12.

"With the introduction of the Inconel 718 our customers in the aerospace industry can now further expand the range of components that they produce in their EBM machines", says Magnus René, CEO of Arcam.

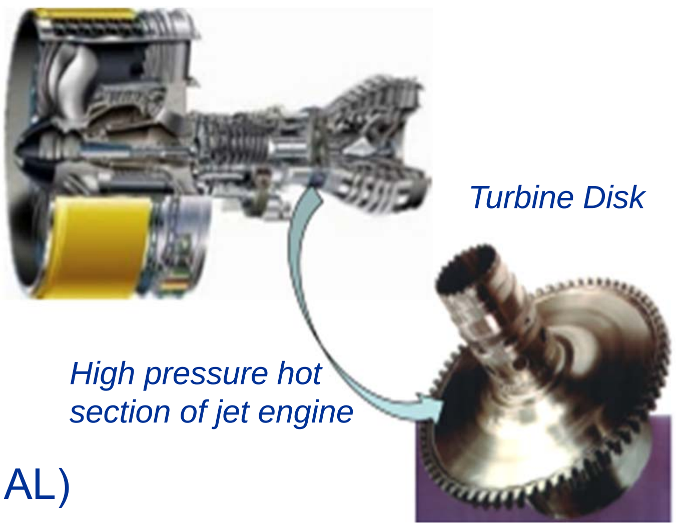
The material properties comply with chemical requirements of UNS N07718 and properties of ASTM F3055-14 specification.

INCONEL® is a registered trademark of Special Metals Corporation.

Inconel 718 Electron Beam Powder Bed Components

TMS 2015: 144th Annual Meeting & Exhibition
Symposium – Additive Manufacturing: Interrelationships of Fabrication, Constitutive Relationships Targeting Performance, and Feedback to Process Control
Session – Electron Beam Techniques for Additive Manufacturing

Fabrication of Turbine Disk Materials by Additive Manufacturing: Post Heat Treatment Study



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3. Air Force Research Laboratory (Dayton, OH)

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Motivation

Today's turbine disks are fabricated from 3rd generation powder metallurgy (PM) nickel-based superalloys (e.g. **GE**: René 104 (ME3), **Rolls Royce**: RR1000).

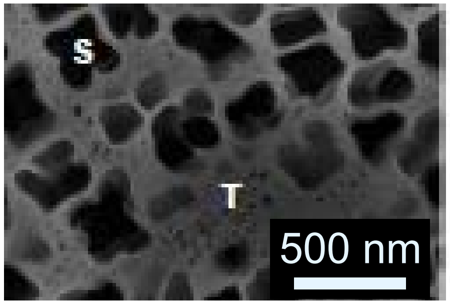
Conventional γ'/γ LSHR disk alloy compared to $\gamma'' \rightarrow \delta/\gamma'/\gamma$ Inconel 718 alloy has:

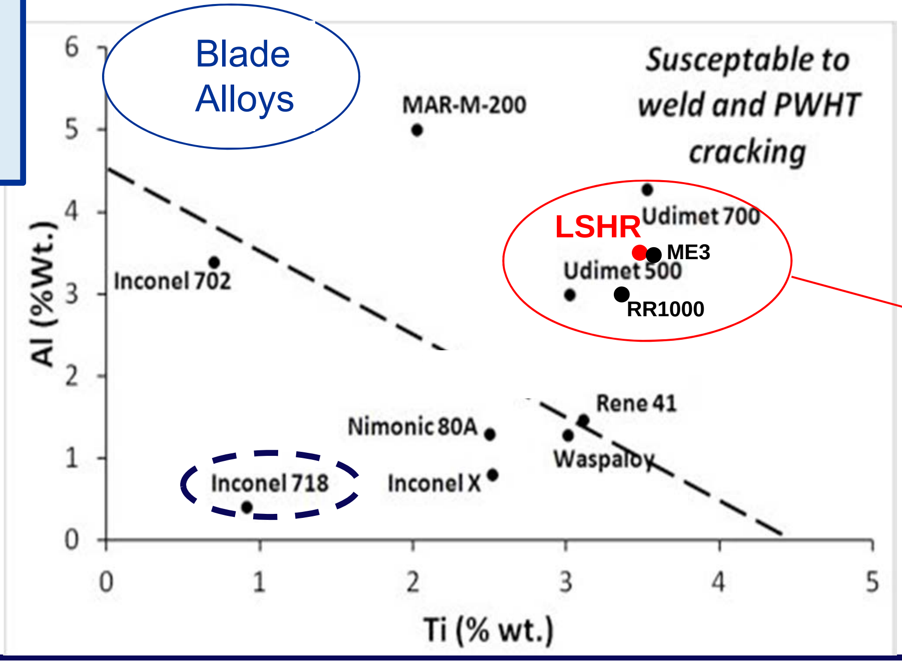
- Higher temperature long-term stability and durability
- Simpler microstructure that is well-understood
- Poorer weldability → Powder-bed fabrication at high temperatures is attractive

wt.%	Cr	Co	Al	Ti	Nb	Ta	Mo	W	Zr	C	B	trace	Ni
NASA LSHR	12.5	20.5	3.5	3.5	1.5	1.5	2.7	4.3	0.05	0.05	0.03	Si, Fe, N, O, S	bal

Weldability of Ni-based superalloys

γ'-precipitates

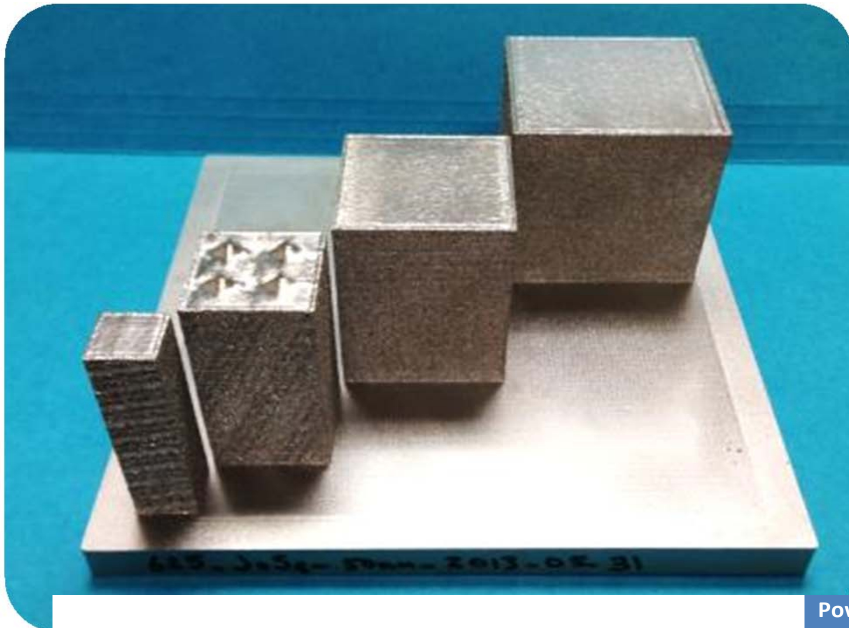




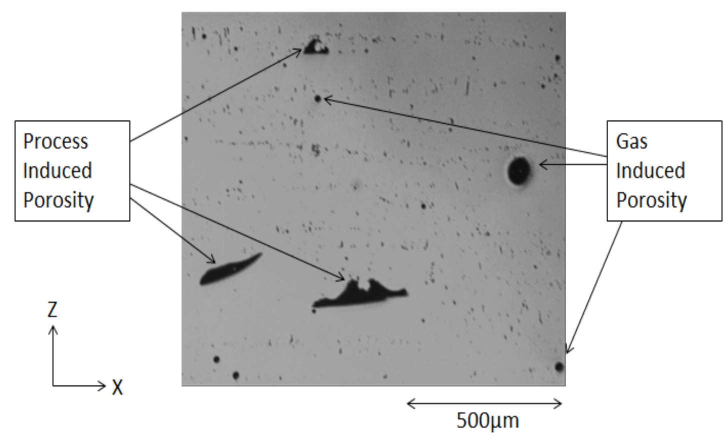
Adapted from: LN Carter, MM Attallah, RC Reed, Superalloys 2012 (2012) pp. 577-608

NASA-patented Low Solvus High Refactory (LSHR) disk alloy, **US 6974508 B1, Gabb et al (2005)**

Understanding E-Beam Parameters Can Lead to Geometry Control and Microstructure



Systematic studies in geometry control for nickel alloys have identified a) the causes for swelling and b) the properties of builds that exhibit swelling.

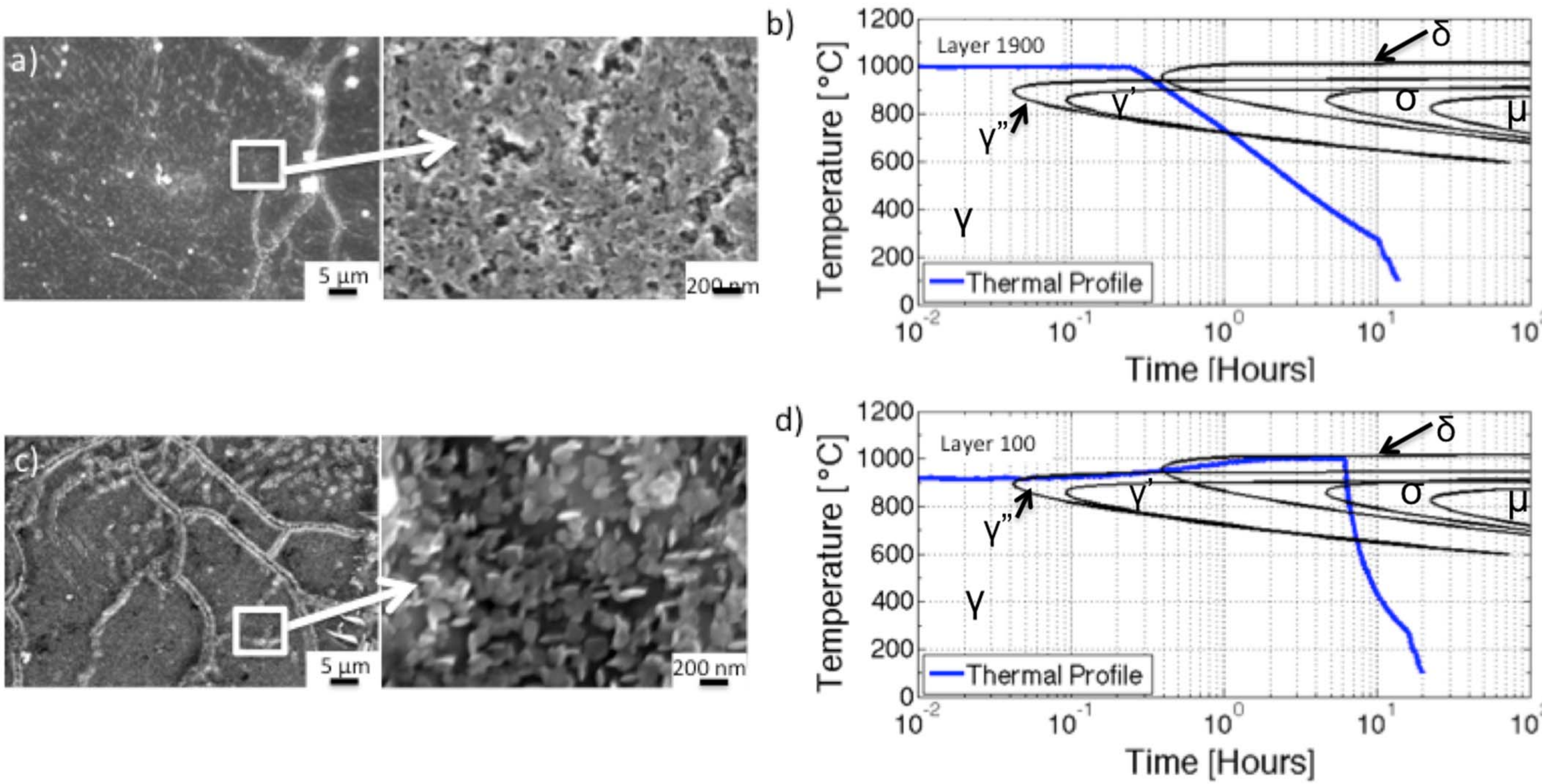


Process induced porosity vs. gas induced porosity for Vertical GA powder Sample E, 50x. XZ plane, parallel to build direction.

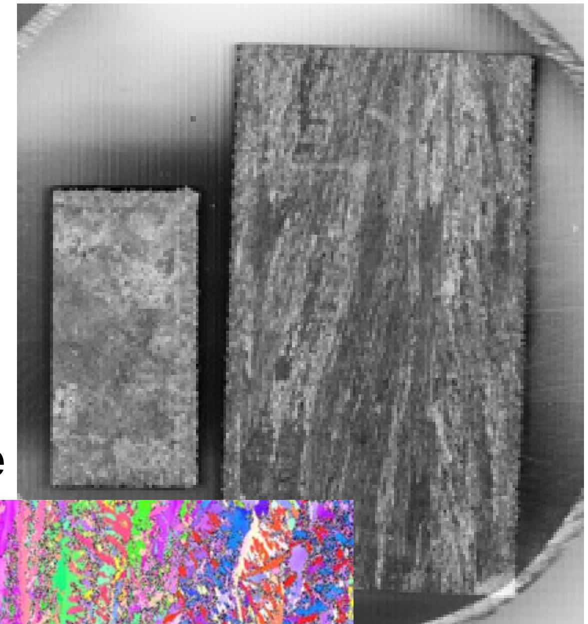
Powder	Relative Cooling Rate	Orientation	Layer Thickness [µm]	UTS [MPa]	YS(0.2) [MPa]	Elongation [%]
Gas Atomized	Fast	Horizontal	50	941.76	590.13	34.28
Gas Atomized	Slow	Horizontal	50	1108.37	868.87	22.08
Gas Atomized	Fast*	Vertical	50	1002.91	887.32	5.43
Gas Atomized	Fast	Vertical	50	1081.72	821.88	19.61
Rotary Atomized	Slow	Horizontal	70	1142.32	957.06	19.48
Rotary Atomized	Slow	Horizontal	50	1185.94	974.04	20.05
Plasma Rotated Electrode	Fast	Horizontal	50	1185.89	967.15	20.03
Plasma Rotated Electrode	Fast	Vertical	50	1069.17	631.62	16.79

Microstructure and Mechanical Properties Are Linked to Thermal History

- Inconel 718 is a complex alloy with multiple constituent phases and a complex microstructure
- Arcam EBM Inconel 718 builds occur at temperatures in excess of 800C
- Thermal gradients exist top to bottom of a build
  - Gives rise to microstructure gradients

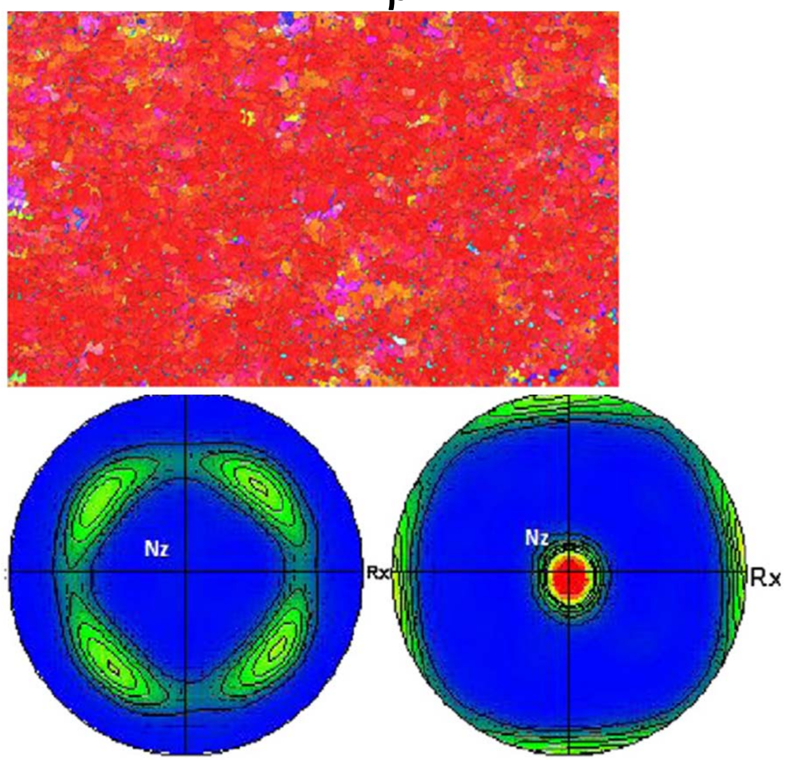


Columnar Grain Growth of Powder Bed Technologies



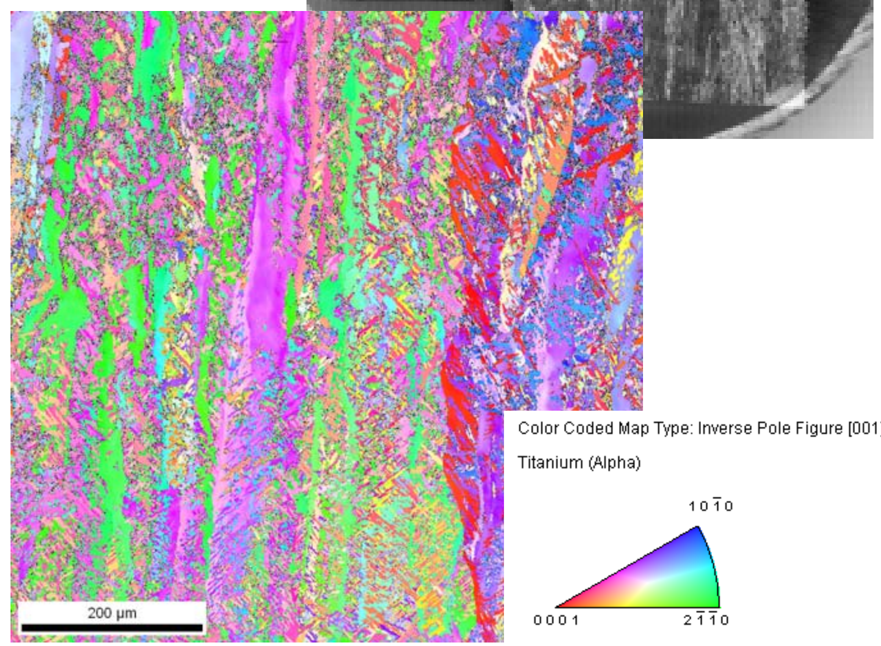
- Beta grains are all elongated in the build direction – due to thermal gradient
- Independent of Build Geometry
- Independent of material

Reconstructed β Phase



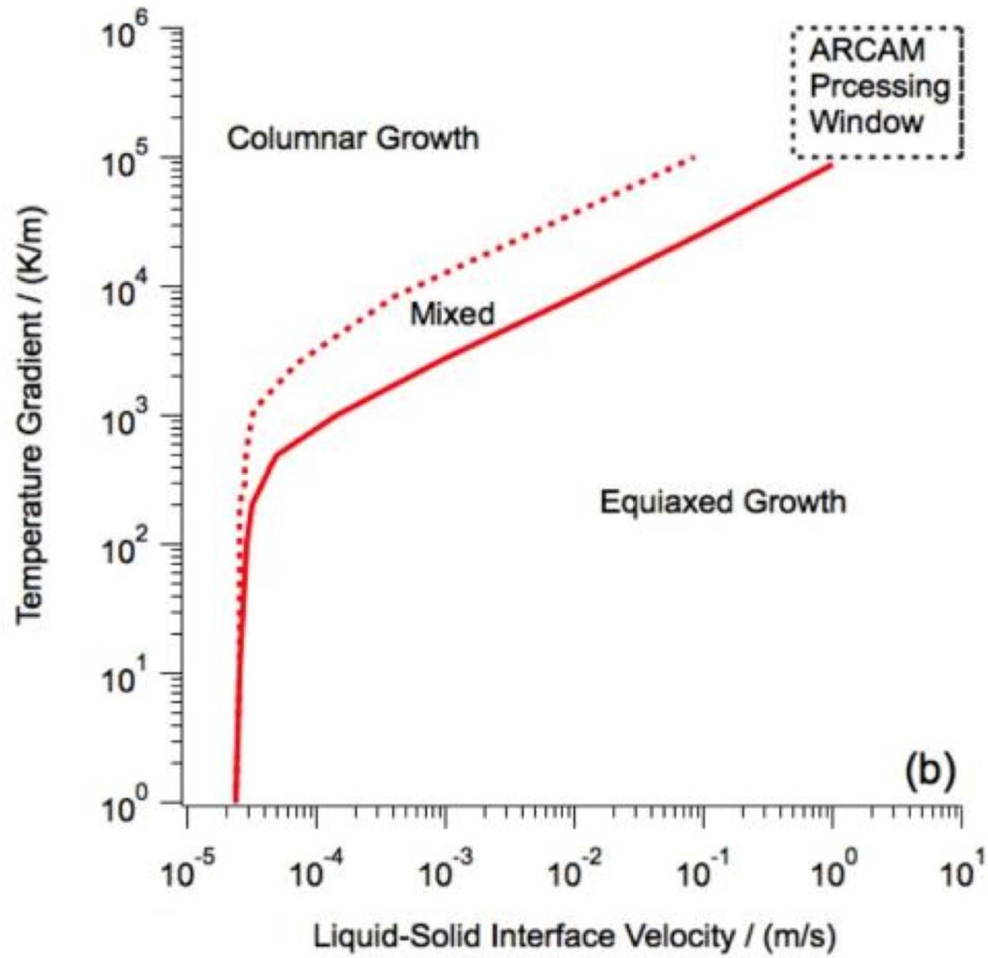
Antonysamy *et. al. 2013*

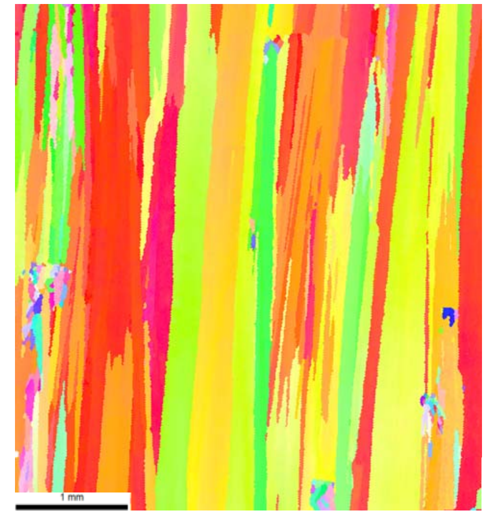
For α phase

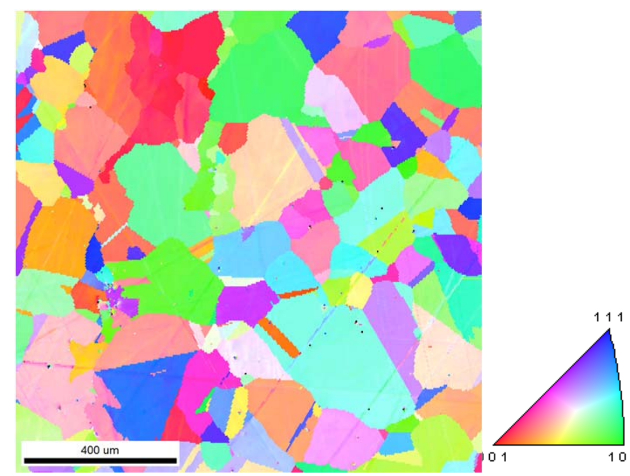


Unocic, *ORNL Data*

We can alter solidification texture by accurately controlling processing parameters

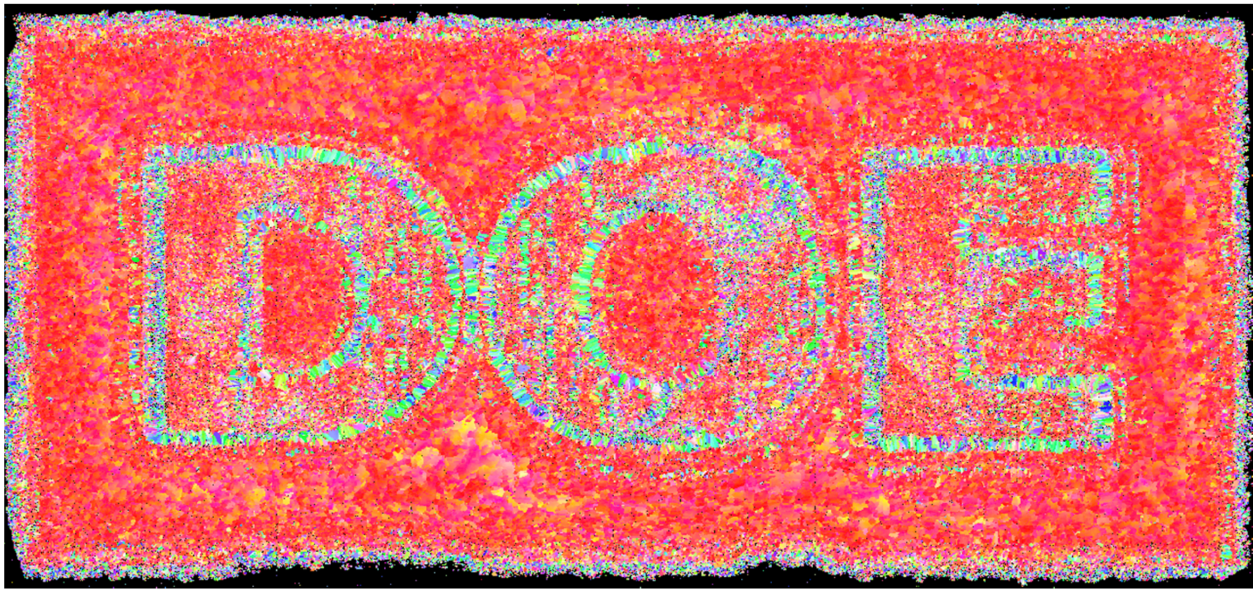


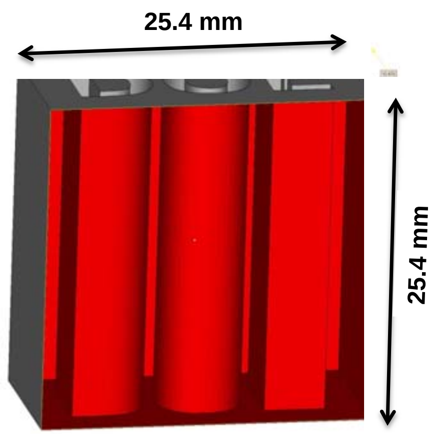




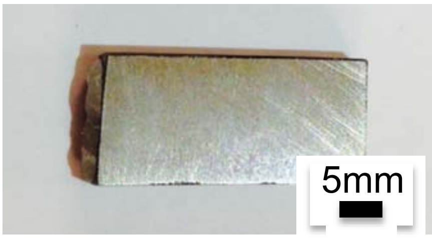
Demonstrate Site-Specific Microstructure Manipulation

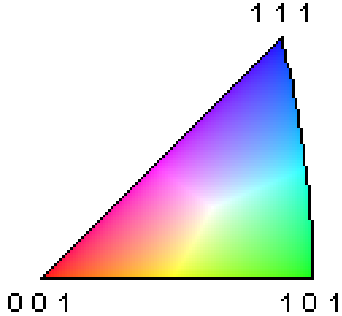
- Fabricated by 1.0” x 0.5” x 1.0” sample with vertical lettering
- Advanced beam controls and unique processing parameters used to control crystallographic orientation





- Color Coded Grain Orientation Map for Inconel 718
  – Red area is [001] orientation



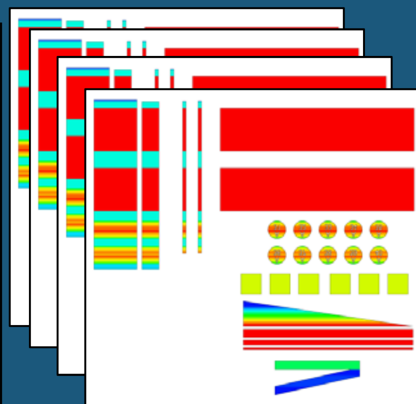


Data-Streams

Planning

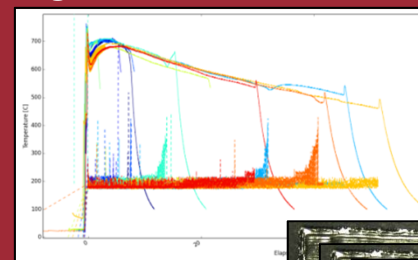
Geometry (CAD)

Process Parameters

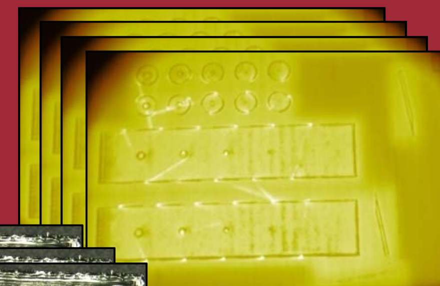


Execution

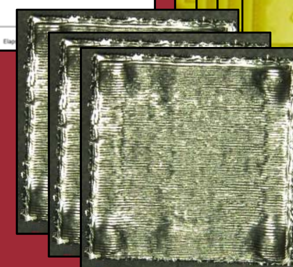
Log-files, environment



IR videos



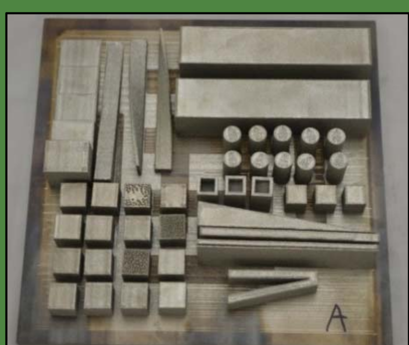
Optical



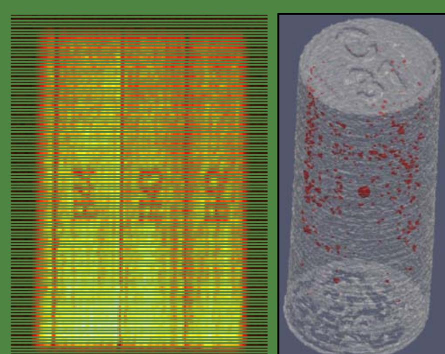
Outcome

← Non-destructive →

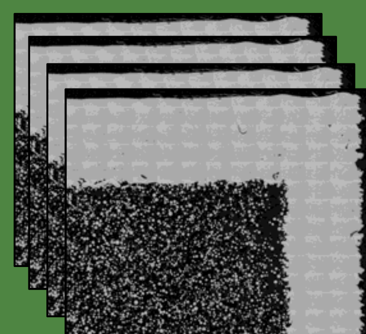
← Destructive →



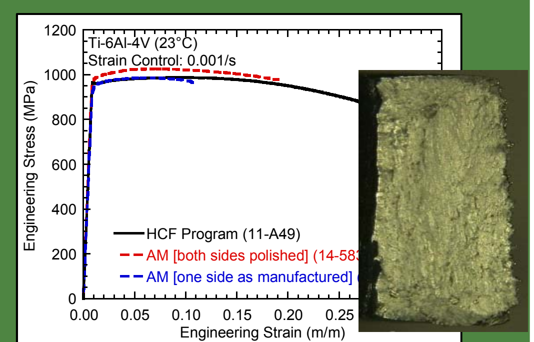
Macroscopic



Ultrasonic, X-ray CT

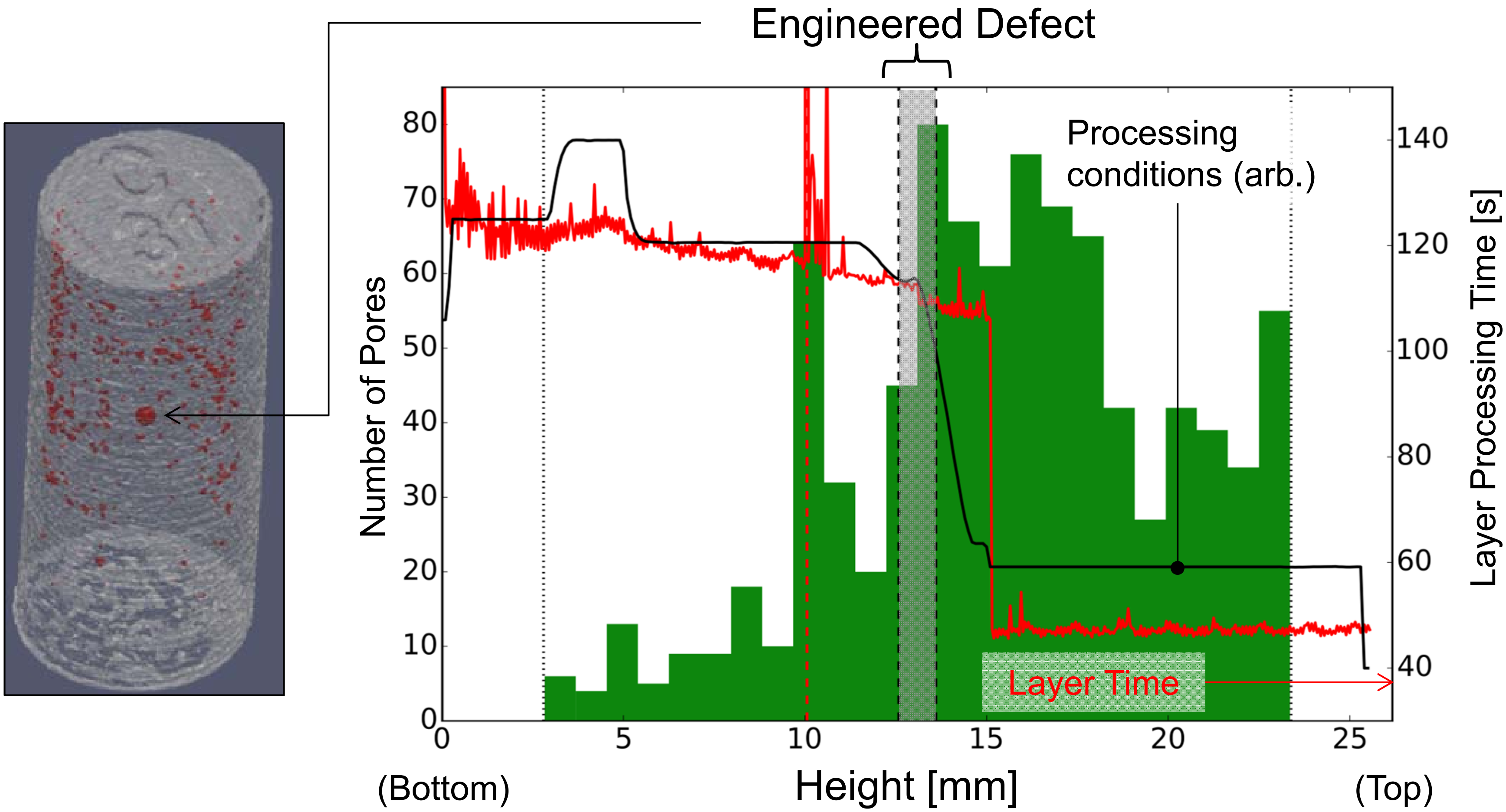


(Serial) sectioning



Performance & Properties

Data Fusion Example



Anomaly/interruption: Execution ↔ Outcome correlation
Late stage porosity: Planning ↔ Outcome

AM Metals Lead: Ryan Dehoff

Thanks to:

M. Kirka[1], K. Unocic[1], W. Sames[1,2], F. List[1], M. Goin[1], M Pearce[1], T. Watkins, E. Cakmak, S. Babu[1,3], H. Bilheux[1], V. Paquit[1], B. Compton[1], R. Dinwiddie[1] D. Erdman[1], B. Peter[1], C. Blue[1], G. Helmrich[3] A. Tremsin[4], F. Medina[5], I. Elfstrom[5], U. Ackelid[5], D. Lados[6], H. Galarraga[6], T. Lolla[7], C. Sudbrack[8], E. Schwalbach[9], M. Groeber[9], Amy Elliott[1], Phil Lane[10], Rick Lucas[10]

Questions

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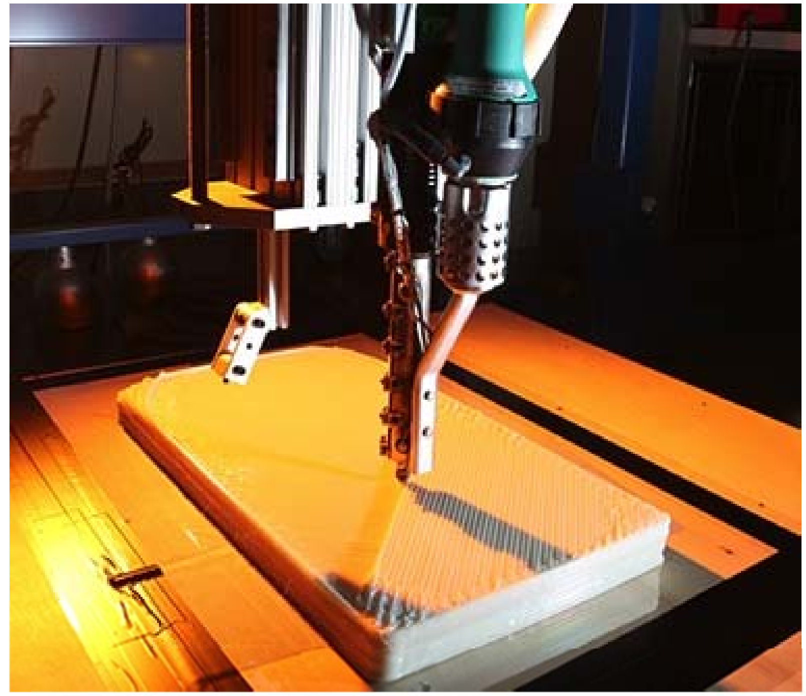
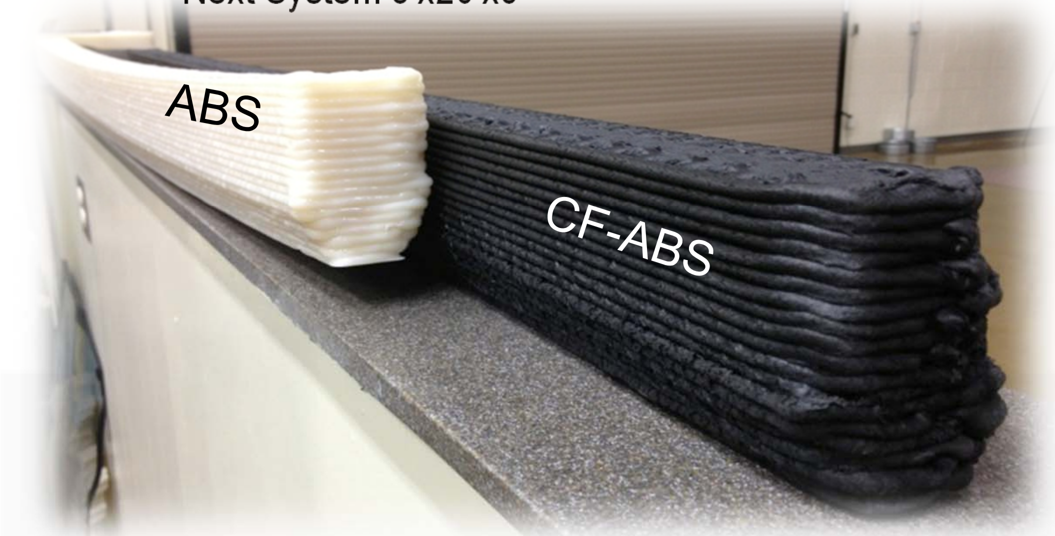
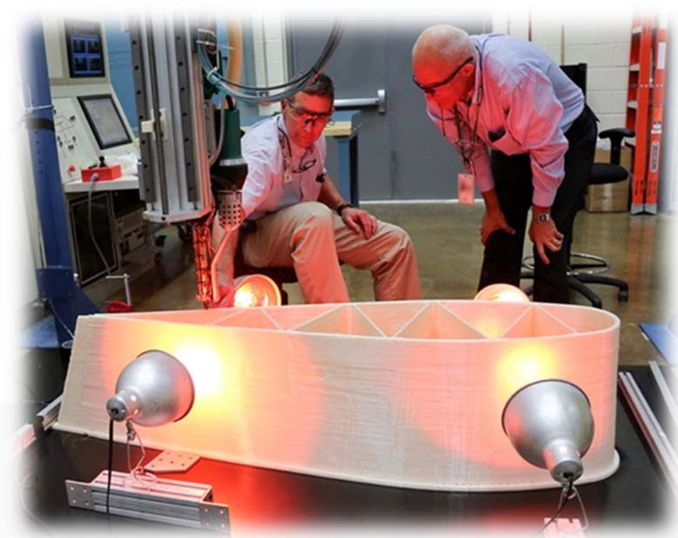
[5]Arcam AB, Goteburg, Sweden
[6] Worcester Polytechnic Institute, Worcester, MA
[7]The Ohio State University
[8]NASA Glen Research Center
[9]Air Force Research Laboratory
[10]ExOne, Irwin, PA

Big Area Additive Manufacturing (BAAM)

- Pellet-to-Part
  - Pelletized feed replaces filament to enable 50x reduction in material cost
- High Deposition Rates (~45 lbs/h)
  - 100X to 1000X commercial systems
  - FDM is 1 to 4 ci/hr
  - BAAM is 400 to 1,000 ci/hr
- Large Scale
  - Prototype system 8'x8'x8' build volume
  - Cincinnati System 6'x12'x1.5' build volume
  - Next System 8'x20'x5'







Direct Fabrication
3D Printed Electric Shelby Cobra

- 6 People – 6 Weeks
- Printed parts
  - ABS with 20% carbon fiber
  - Finish: Sand, filler, primer automotive paint
  - 1400-1500 lbs (body 500, front 300, battery 250, motor 130
  - $2500 in printed material (~$5/lb)
  - Print time: 24 hrs.
- Electric Motor
  - Horsepower: 135
  - Range: 30 miles
  - 0-60 mph: ~5
  - Top Speed: 70-85 mph
  - Battery: Li ion