Additive Manufacture Development, Applications, & Lessons Learned

Omar Mireles

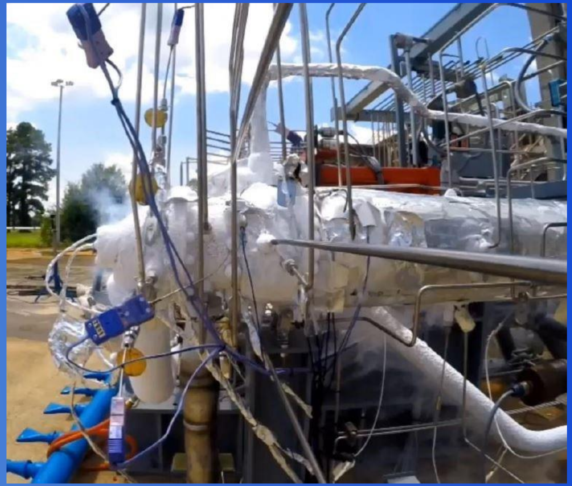
NASA Marshall Space Flight Center

Nuclear & Emerging Technologies for Space, 2019

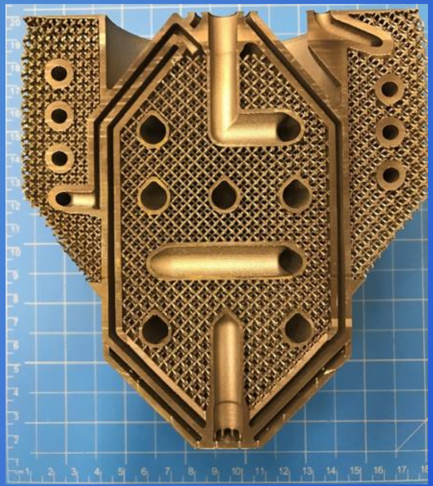
Introduction

- Additive Manufacture (AM)
  - A process of joining materials together to create objects from 3D model data.
  - *Not* the ultimate manufacture solution. Conduct trades.
  - Takes practice (design through in-service).
- Appropriate Application
  - High complexity = difficult to manufacture = long lead times = low production rate = high cost.
- Advantages
  - Increased design freedom and customization
  - Near net-shape complex geometry
  - Part count reduction
  - Performance improvement (i.e. weight reduction)
  - One-off and discontinued parts
  - Shorter lead times
  - Properties better than cast, 10-15% below wrought

AMDE Ox Turbopump Stator. Courtesy Derek O'Neal.



AMDE Fuel Turbopump Test. Courtesy Marty Calvert.



Cryo Heat Exchanger, Injector, Condenser

Disadvantages

- Misconceptions
  - *MORE* expensive than traditional manufacturing (high hourly rates offset by reducing labor costs).
  - Waste generation: spent powder, build plates, failed builds.
  - Substantial touch labor.

Spent build plates and oversized powder

- Disadvantages:
  - Powder Bed Fusion (PBF) limited to weldable alloys
  - Build envelope size limits
  - Design constraints: overhang surfaces, minimum hole size
  - Surface roughness
  - As built microstructure will require post processing

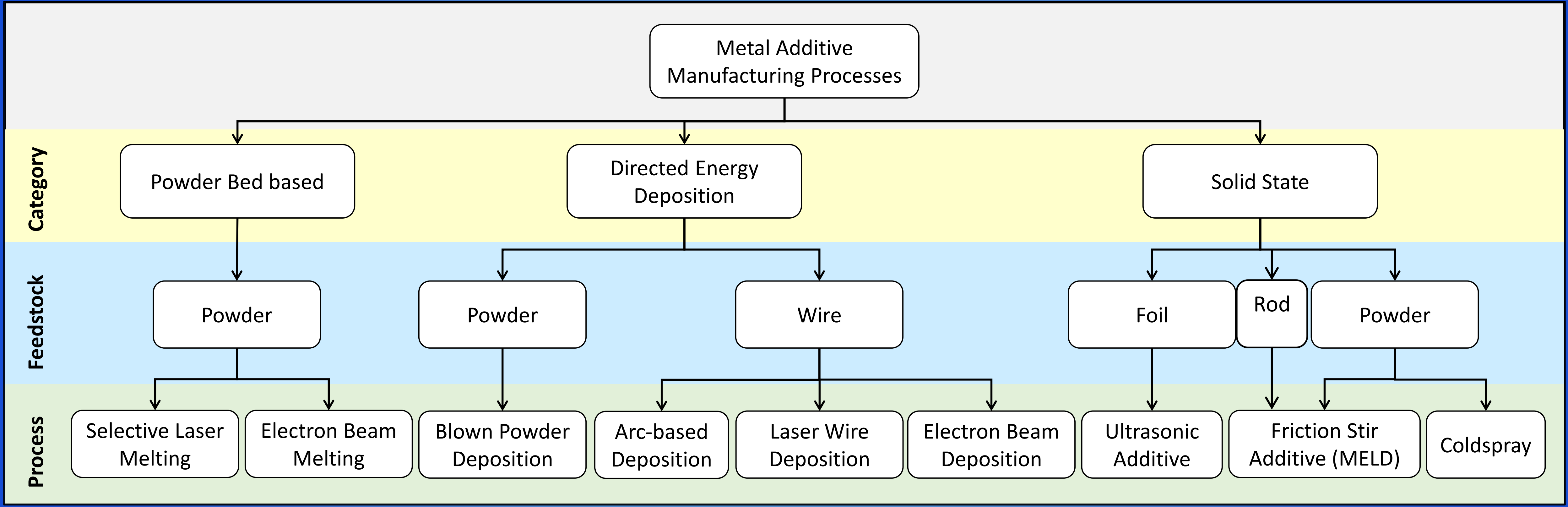
Vacuumed power

- Property Variability
  - Properties dependent on starting powders, parameters, and post-processing
  - Anisotropic properties in the build direction (Z)
  - Size: small-scale vs. full-scale builds
  - Build volume spatial location

COMPLEXITY IS NOT FREE

Think instead: Conservation of Complexity

Overview of Various Metallic AM Techniques



Other metal additive processes are being developed and exist such as binder-jet, material extrusion, material jetting vat photopolymerization, although public data limited at this time.

Based on Ref:

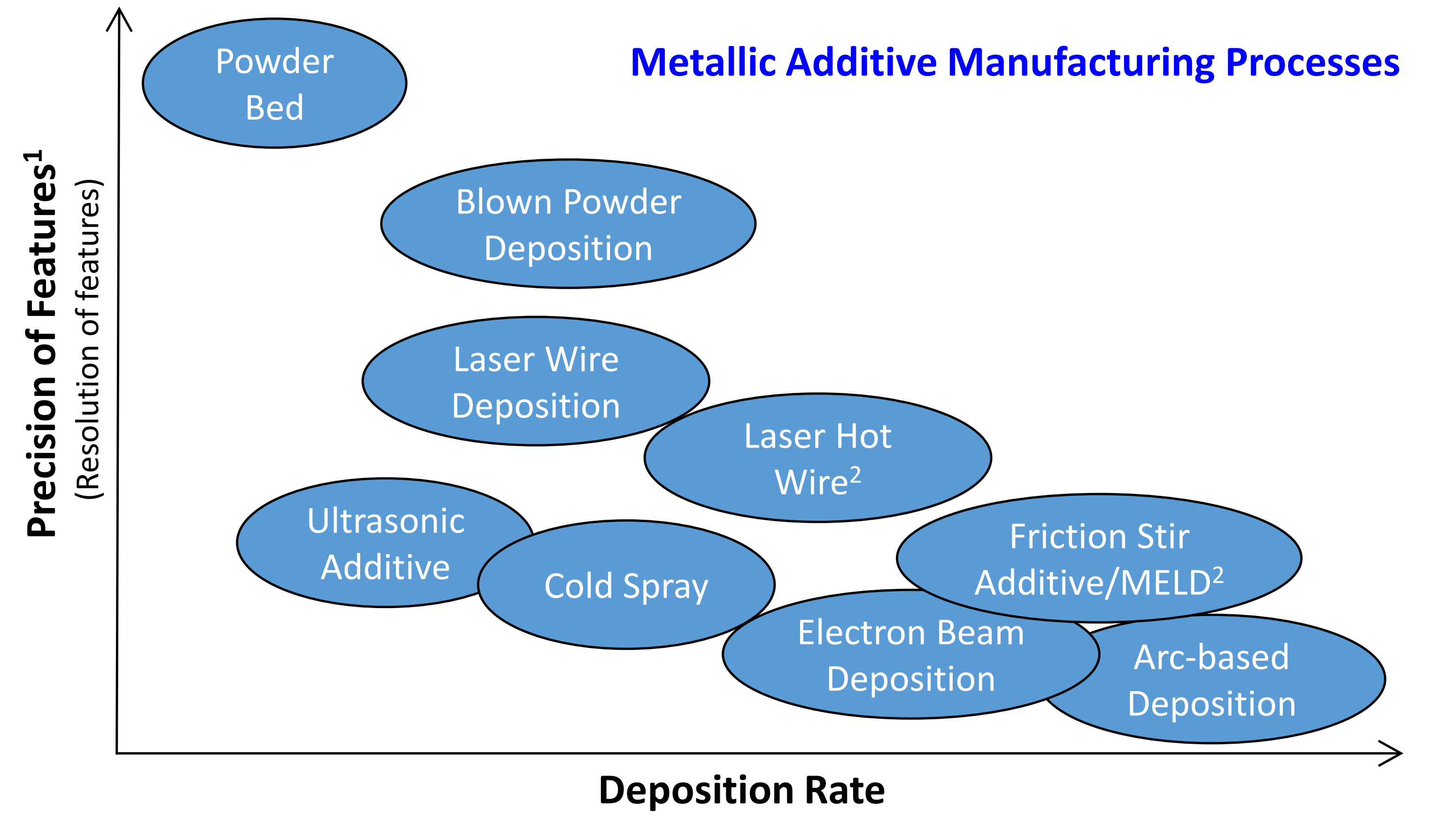
Ek, K., "Additive Manufactured Metals," Master of Science thesis, KTH Royal Institute of Technology (2014).

Gradl, P., Brandsmeier, W., Calvert, M., et al., "Additive Manufacturing Overview: Propulsion Applications, Design for and Lessons Learned. Presentation," M17-6434. 1 December (2017).

ASTM Committee F42 on Additive Manufacturing Technologies. Standard Terminology for Additive Manufacturing Technologies ASTM Standard: F2792-12a. (2012).

Courtesy Paul Gradl, NASA MSFC.

Why choose one AM method over another?



[1] Precision refers to the as-built state and does not encompass hybrid techniques and/or interim machining operations that would increase resolution. There are a lot of other factors not considered in this chart, including heat inputs to limit overall distortion.
[2] Technology still under development

- Complexity of Features
- Scale of Hardware
- Material Physics
- Speed of Process
- Cost/Schedule
- Material Properties
- Internal Geometry
- Availability

Courtesy Paul Gradl, NASA MSFC.

Examples of AM Metallic Alloys

Materials developed for SLM, EBM, and DED processes *(not fully inclusive)*

Ni-Base
Inconel 625
Inconel 718
Hastelloy-X
Haynes 230
Haynes 282
Haynes 188
Monel K-500
C276
Waspalloy

Cu-Base
GRCop-84
GRCop-42
C-18150
C-18200
Glidcop
CU110

Al-Base
AlSi10mg
A205
F357
6061 / 4047

Fe-Base
SS 17-4PH
SS 15-5 GP1
SS 304
SS 316L
SS 420
Tool Steel (4140/4340)
Rene 80
Invar 36
SS347
JBK-75
NASA HR-1

Ti-Base
Ti6Al4V
γ-TiAl
Ti-6-2-4-2

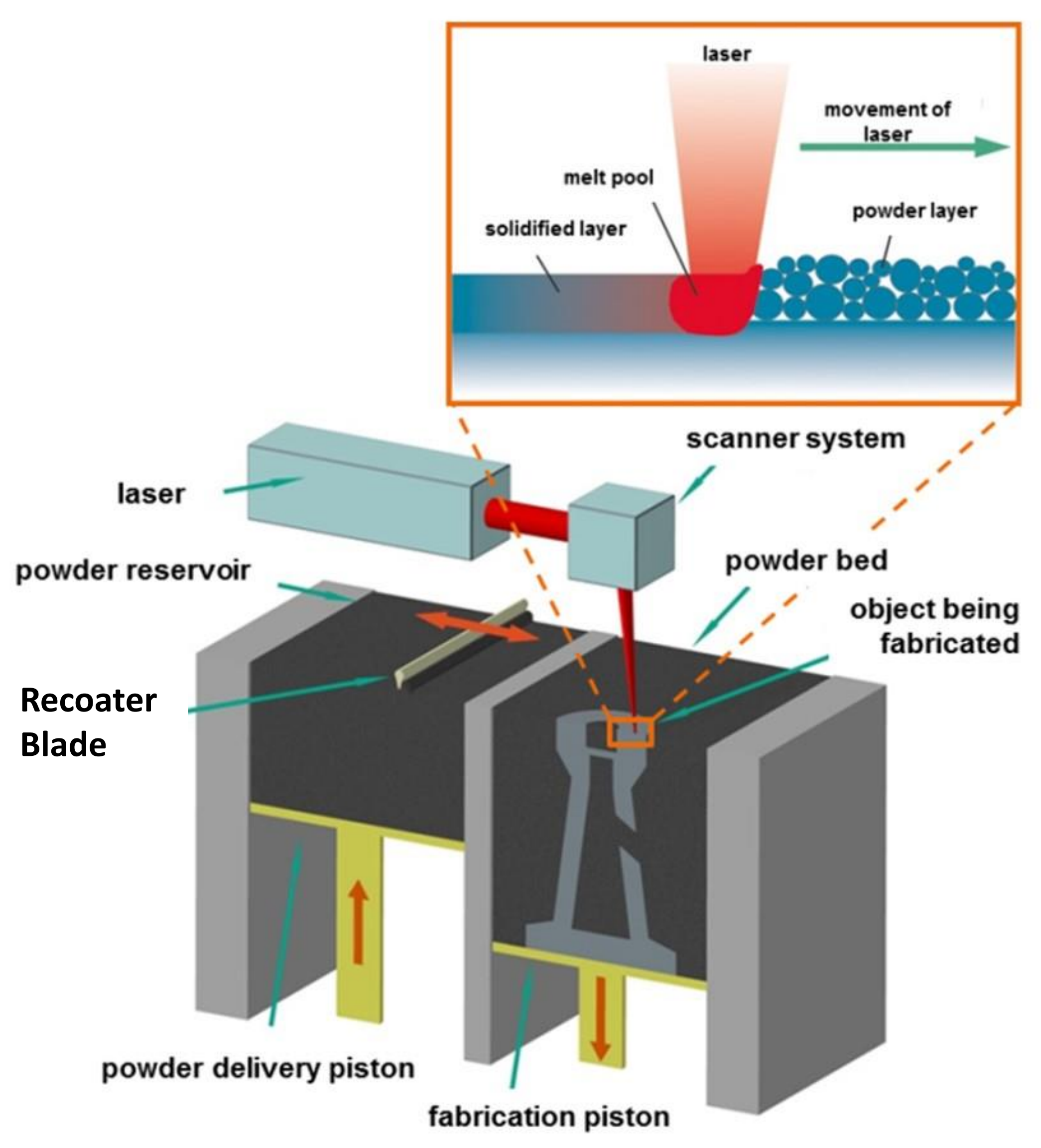
Co-Base
CoCr
Stellite 6, 21, 31

Refractory
W, W-25Re
Mo, Mo-44Re, Mo-47.5Re
C103
Ta

Bi-Metallic
GRCop-84/IN625
C-18150/IN625

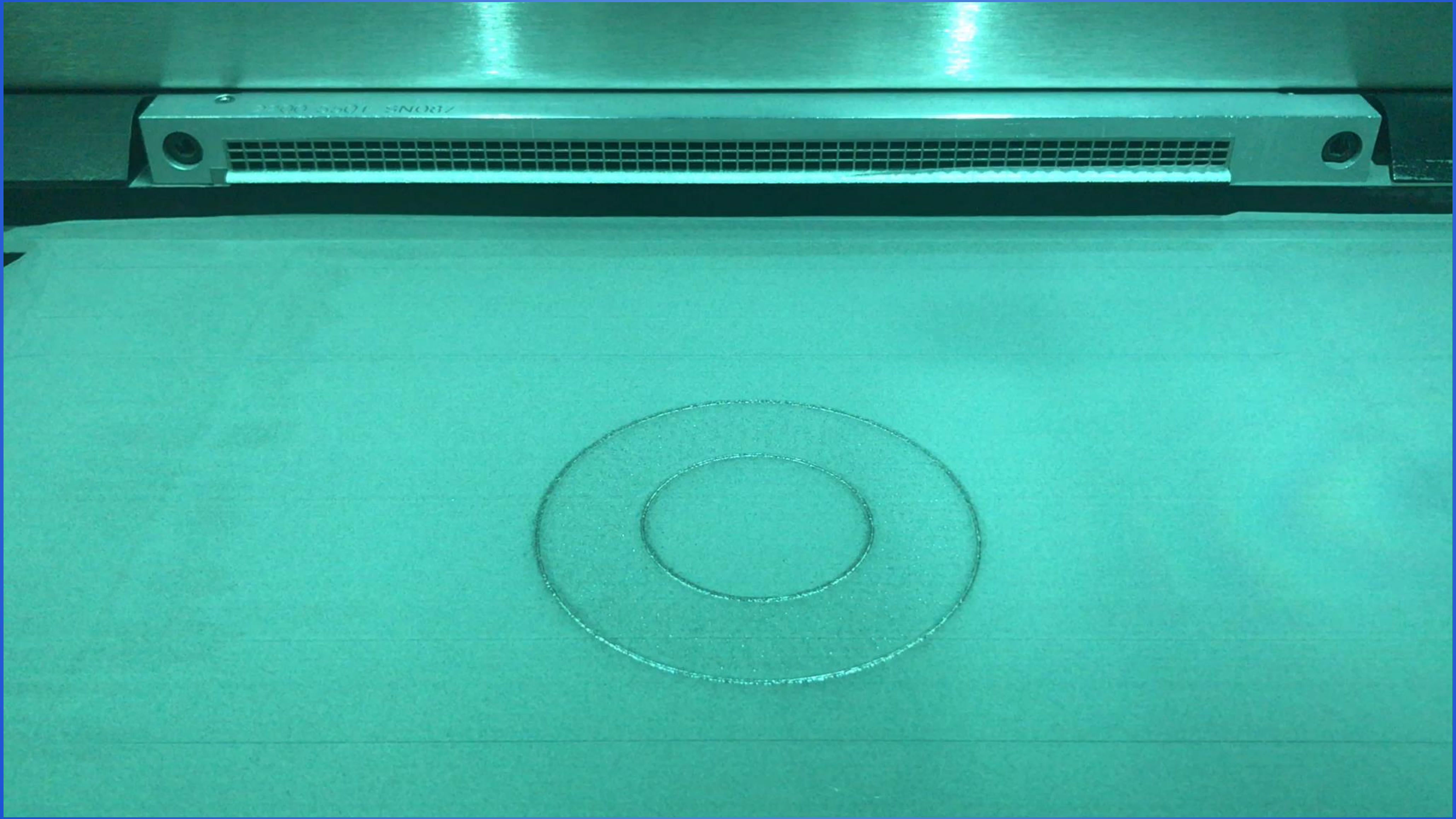
MMC
Al-base
Steel-base
Ni-base

Laser Powder Bed Fusion (L-PBF)



Process Illustration. Image courtesy Simufact.

L-PBF Operational Example

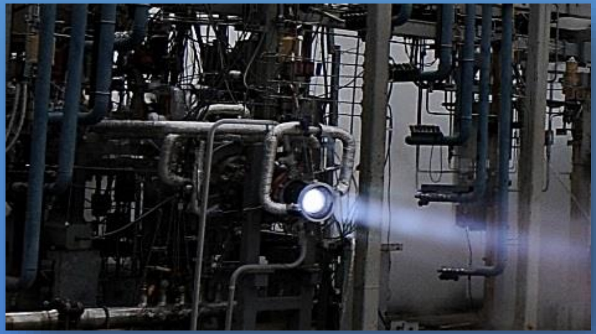


EOS M290, IN718

SLM Combustion Chamber Assembly & Testing

GRCop-84 3D printing process developed at NASA and infused into industry

GRCop-84 AM Chamber Accumulated **2365 sec** hot-fire time at full power with no issues



LOX/Methane Testing of 3D-Printed Chamber Methane Cooled, tested full power

Ox-Rich Staged Combustion Subscale Main Injector Testing of 3D-Printed Faceplate

Morgan, K. L., Gradl, P., “Additive Manufacturing Overview: Recent Propulsion Applications,” Additive Manufacturing for Defense and Government Conference, July 2017

AM IN718 Injectors Hot-fire Tested at NASA MSFC.
Thrust range from 1,200 lb_f to 35,000 lb_f (5.3 kN to 155.7 kN)

Courtesy Paul Gradl, NASA MSFC.

Directed Energy Deposition (DED)

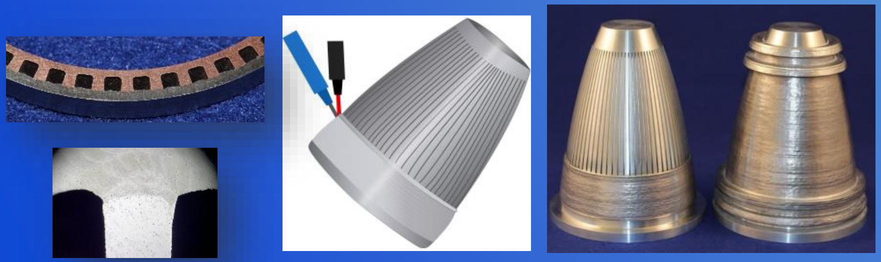
Freeform fabrication technique focused on near net shapes as a forging or casting replacement and also near-final geometry fabrication. Can be implemented using powder or wire as additive medium.

Blown Powder Deposition / Hybrid

Melt pool created by laser and off-axis nozzles inject powder into melt pool; installed on gantry or robotic system

Laser Wire Deposition

A melt pool is created by a laser and uses an off-axis wire-fed deposition to create freeform shapes, attached to robot system



Integrated and Hybrid AM

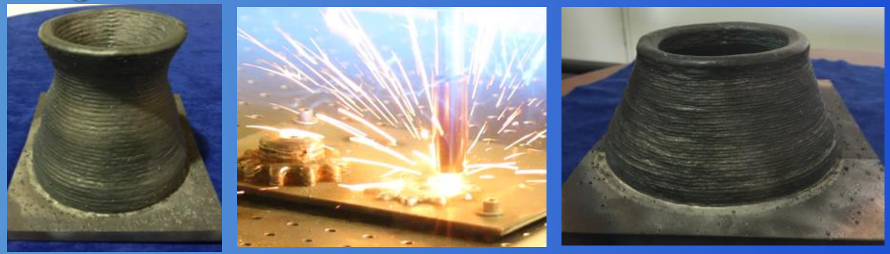
- ➢ Combine SLM/DED
- ➢ Combine AM with subtractive
- ➢ Wrought and DED

NASA SLM/DED

*Photos courtesy DMG Mori Seiki and DM3D

Arc-Based Deposition (wire)

Pulsed-wire metal inert gas (MIG) welding process creates near net shapes with the deposition heat integral to a robot



Electron Beam Deposition (wire)

An off-axis wire-fed deposition technique using electron beam as energy source; completed in a vacuum.

Courtesy Paul Gradl, NASA MSFC.

Large Scale AM Deposition Nozzle

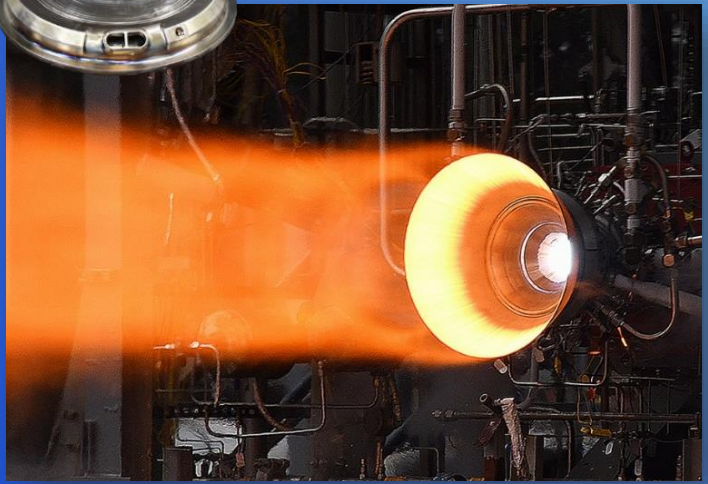
[35] Morgan, K. L., Gradl, P., "Additive Manufacturing Overview: Recent Propulsion Applications," Additive Manufacturing for Defense and Government Conference, July 2017.
[36] Gradl, P. "Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles." AIAA-2016-4771, Paper presented at 52nd AIAA/SAE/ASEE Joint Propulsion Conference, July 27, 2016. Salt Lake City, UT.
[37] Gradl, P.R., Brandsmeier, W. Alberts, D., Walker, B., Schneider, J.A. Manufacturing Process Developments for Large Scale Regeneratively-cooled Channel Wall Rocket Nozzles. Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

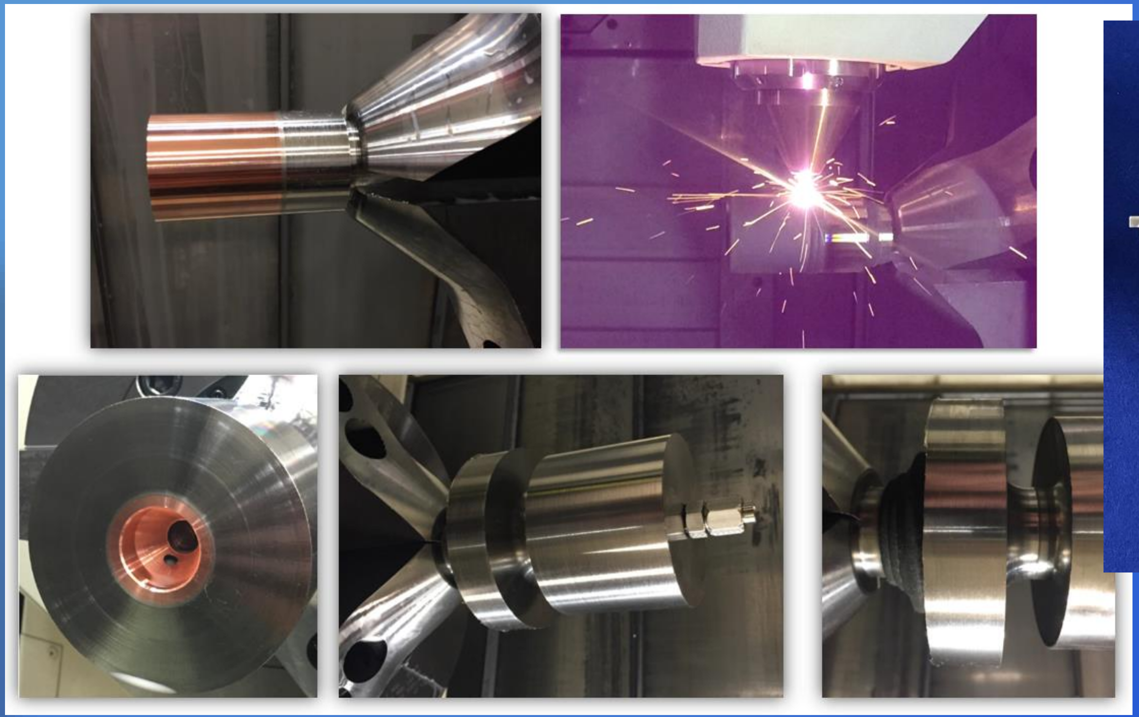
Courtesy Paul Gradl, NASA MSFC.

Bimetallic AM Components

- NASA has developed bimetallic combustion chambers using Cu-alloy liners and Inconel structural jacket (GRCop-84 to IN625)
  - SLM to fabricate the liner and DED for structural support
  - Similar processes used for Spark Ignition Systems with bimetallic but using wrought material and DED (C-18150 to IN625)

IN625-GRCop84 Bimetallic
ASTM E8 Tensile Bar





Courtesy Chris Protz & Robin Osborne, NASA MSFC

Low Cost Upper Stage Propulsion

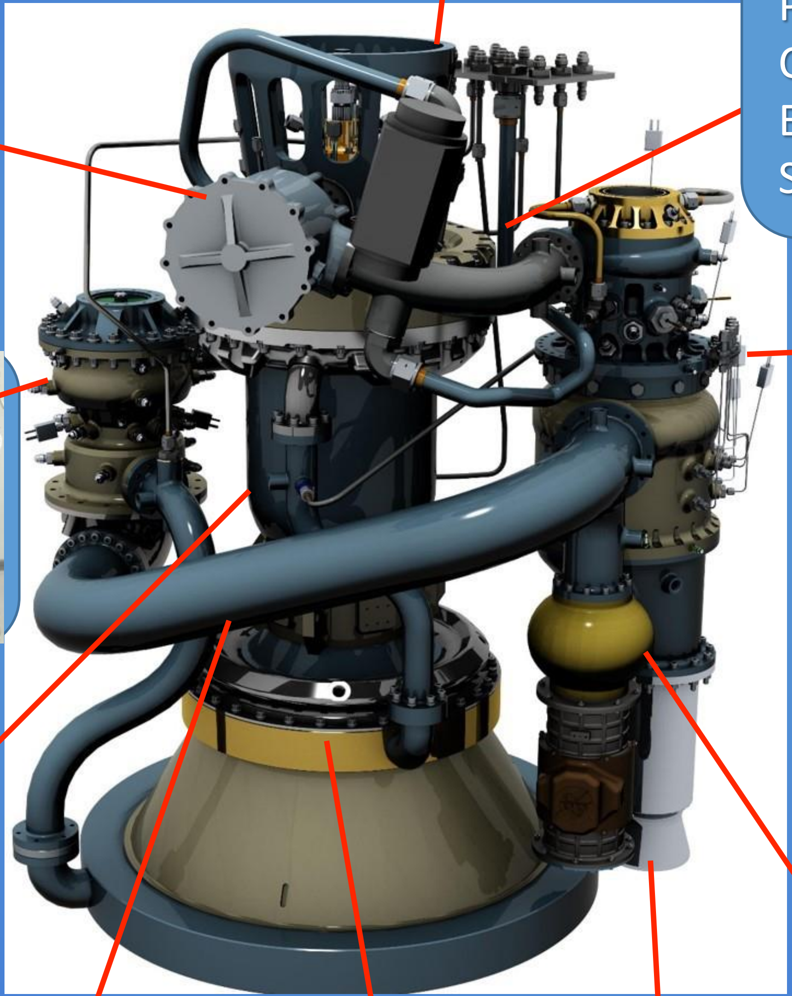
Additive Manufacture Demo Engine (AMDE)

Main Oxidizer Valve
Part Reduction: 6 to 1
Successfully tested

Fuel Turbopump
Part Reduction: 40 to 22
Schedule Reduction: 45%
Successfully tested to 90k rpm

Combustion Chamber
Schedule Reduction: > 50%
Bimetallic SLM/DED
Successfully tested to 100%

Thrust Structure



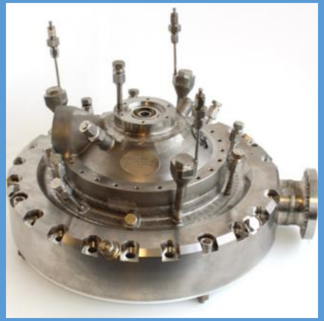
Cross-Over Duct
1 vs. 9 parts.

Regen Nozzle

Turbine Discharge Duct

OTBV
1 vs. 5 parts.

Injector
Part Reduction: 252 to 6
Cost Reduction: 30%
Eliminated braze joints
Successfully tested to 100%



Oxidizer Turbopump
Part Reduction: 80 to 41
Currently being tested

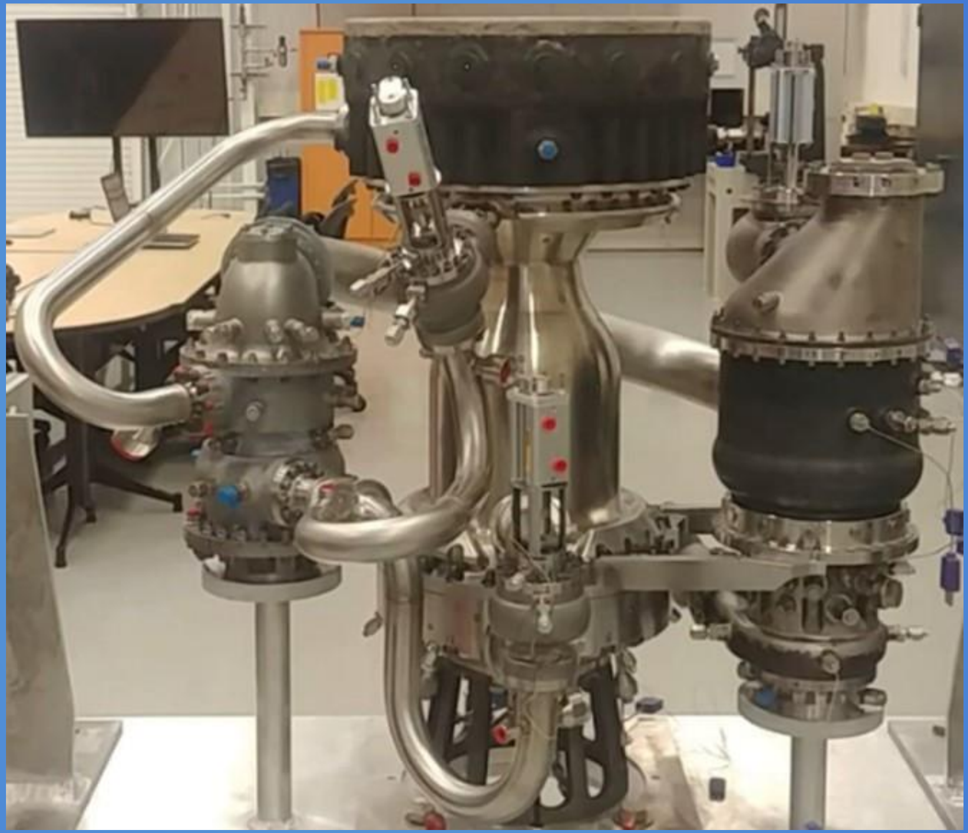
Main Fuel Valve
Part Reduction: 5 to 1
Successfully tested

Mixer (Hidden)
2 vs. 8 parts

CCV (Hidden)
1 vs. 5 parts.

AMDE Main Stage Test (early April 2019)

Assembly, fit check, process mock-up.



AMDE assembly.

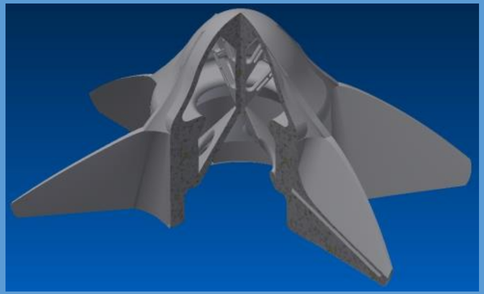
AMDE on the test stand at MSFC.

AM Process Flow

<u>DESIGN & ANALYSIS</u>

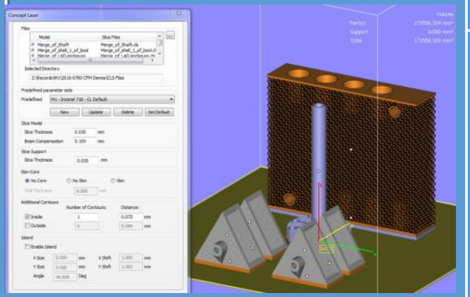
- Performance Requirements

-Design for AM, GD&T, export .stl



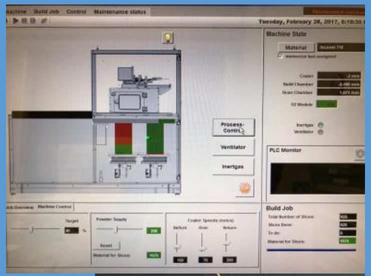
<u>BUILD PREPARATION</u>

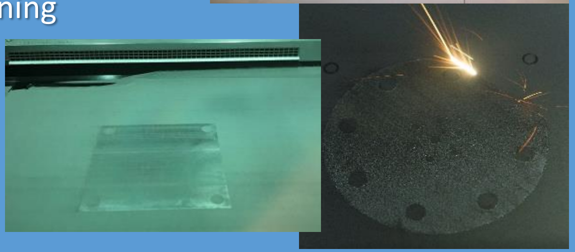
- Repair .stl
- Build placement & orientation
- Thermal stress/distortion prediction
- Support generation
- Slicing
- Scan strategy



<u>BUILD OPERATIONS</u>

- Machine preparation
- Build via parameters
- Process Controls
- Powder refill
- Lens cleaning
- Restarts





<u>POST-PROCESS</u>

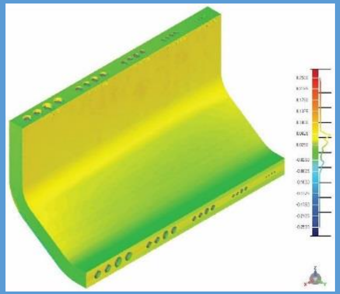
- Powder Removal
- Stress Relieve
- Support Removal
- Plate Separation
- HIP
- Heat Treatments
- Machine/Surface mod
- Mechanical Testing

<u>NONDESTRUCTIVE EVALUATION</u>

- Structured light scanning

- X-ray CT

-Compare inspection models to CAD



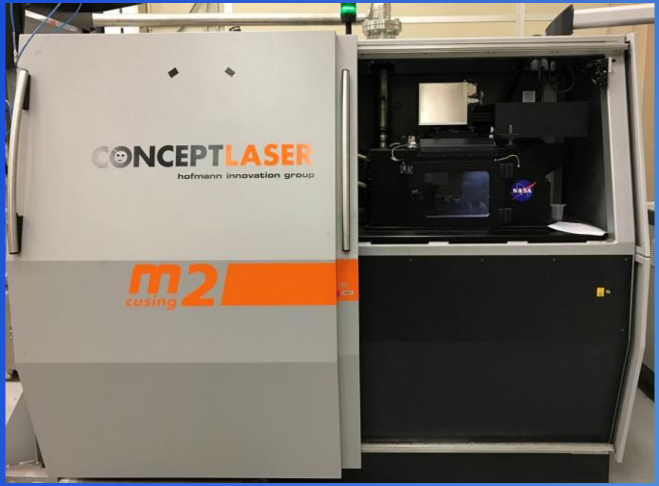
<u>IMPLEMENTATION</u>

- Test & post-ops inspection

- NDE / Destructive evaluation

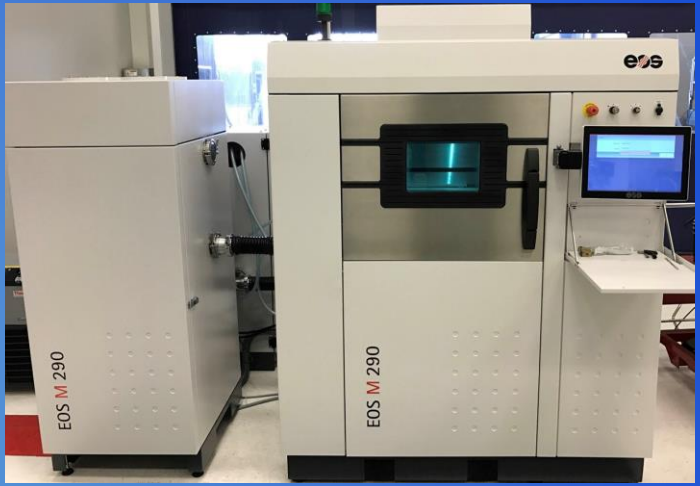

PROPULSION
ER
NASA
NASA MSFC
EM
Materials & Processes Lab

MSFC AM Machines: Metal



Concept Laser M2
250x250x280 mm
Power 400 W
Laser Diameter: 70 µm
Material: GRCop84, GRCop42

Concept Laser M1
250x250x250 mm
Power: 400 W
Laser Diameter: 70 µm
Material: IN718, IN625, Monel K500.



EOS M290
250x250x325 mm
Power: 400 W
Laser Diameter : 80 µm
Materials: IN718, IN625.

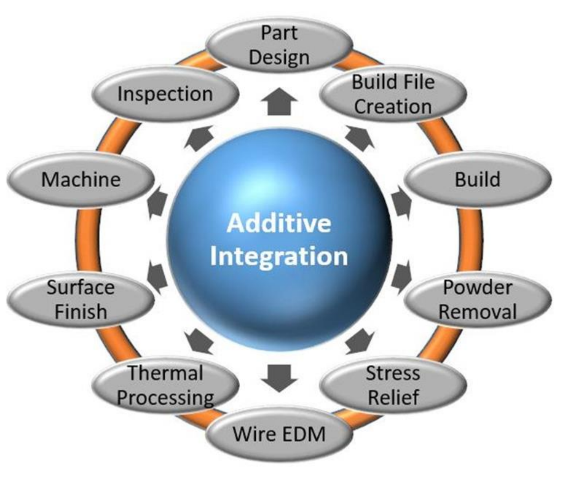
Concept Laser X-Line 1000R
630x400x500 mm
Power 1000 W
Laser Diameter : 70 µm
Material: IN718

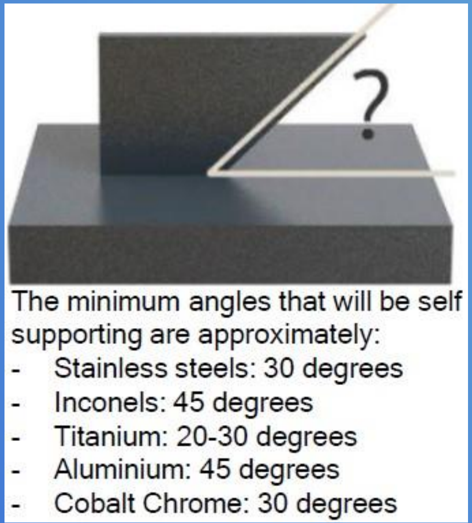
EOS M100
Ø100x95 mm
Power: 200 W
Laser Diameter: 40 µm
Material: Ti64, 316L, CoCr, Haynes 230.
In-development: Haynes 282, JBK-75, HR-1.

Holistic AM Design Flow & Considerations

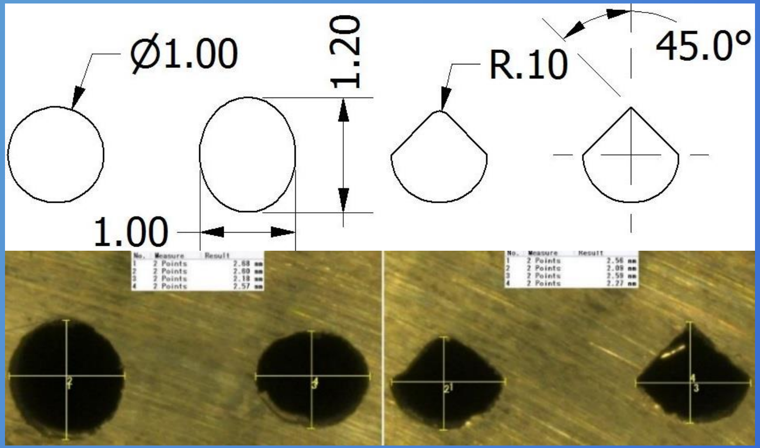
Courtesy Melissa Orme, Morf3D

- Holes & Passages
  - Size limits (Horizontal: Min: 0.4 mm, Max: 8 mm; Vertical: Min: 0.4 mm, Max: unlimited).
  - Channel surface roughness variable on size: powder sintering for smaller OD and overhang angle for larger OD.
  - Hole sag in the Z-axis: circular hole becomes a horizontal ellipse, vertical ellipse becomes near-circular hole.

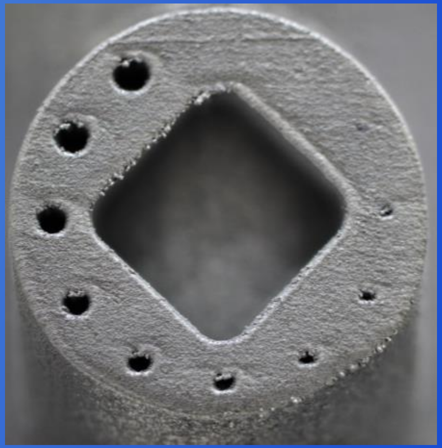




Self-Supporting Angles



1 mm hole array micrographs (45°)

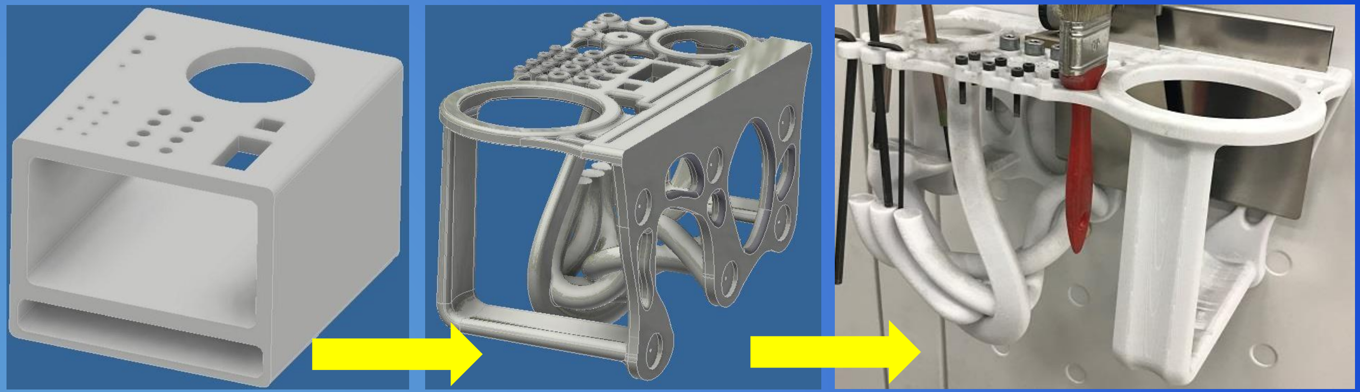


Hole size & surface roughness

The design engineer of the 21st century is successful if parts can be repeatedly and economically manufactured.

Advanced Design for AM

- Topology Optimization
  - Designer provides a design then specifies no-mod zones, constraints, loads, material, and FS.
  - Program generates a design by subtracting unnecessary mass regions.
  - Apply when interface, flow, or thermal features are required but mass reduction is desired.

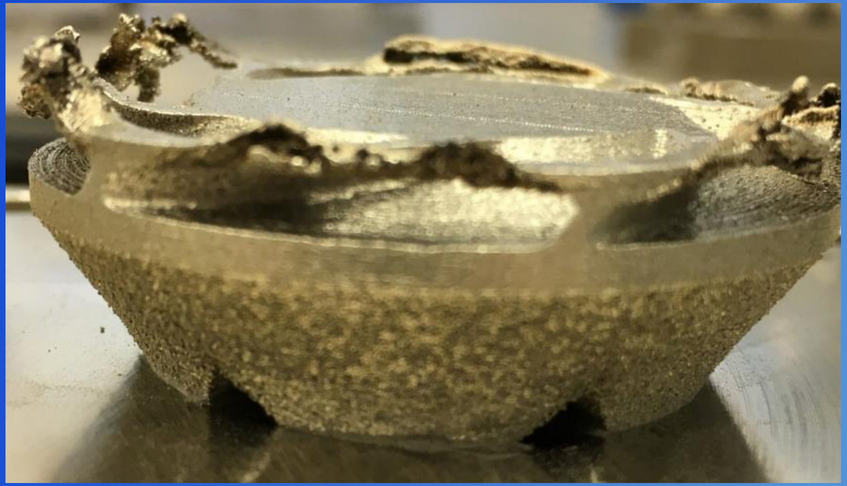


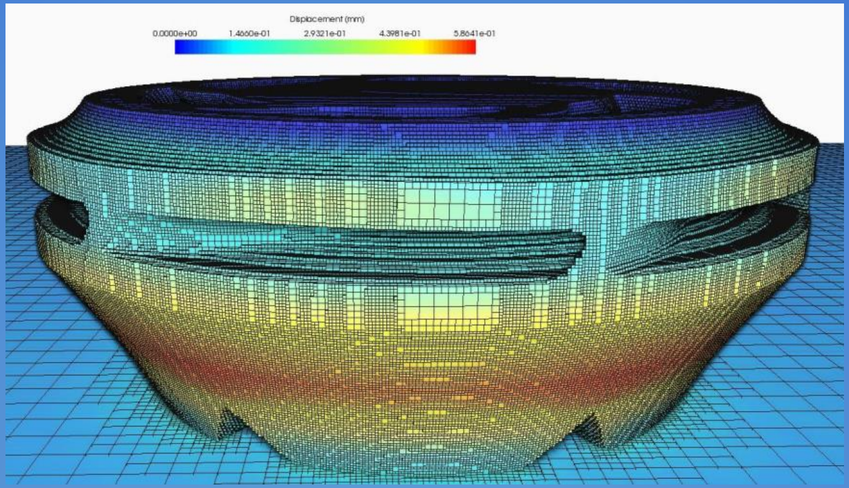
Topology Optimization FDM Tool Rack. Courtesy Zach Jones.

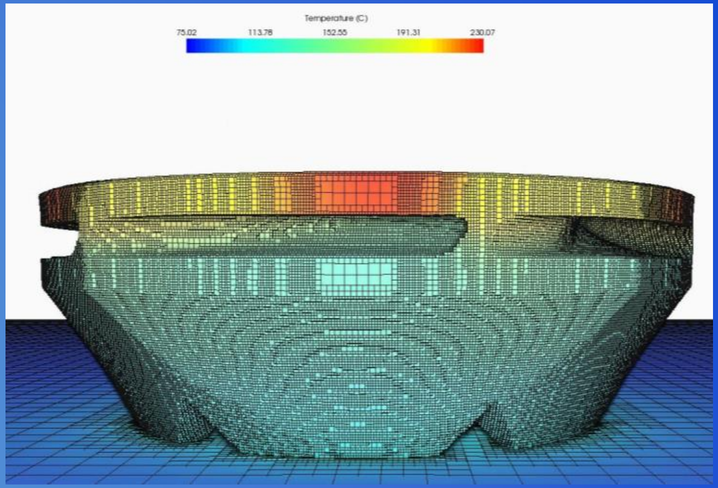
- Generative Design
  - Define interface geometries, enclosure, constraints, loads, material and FS.
  - Software generates numerous point designs and displays an an Ashby chart.
  - Select and prioritize optimized designs: mass, strength, stiffness.
  - Apply when mass and structure dominate.

Generative Design. Courtesy Autodesk.

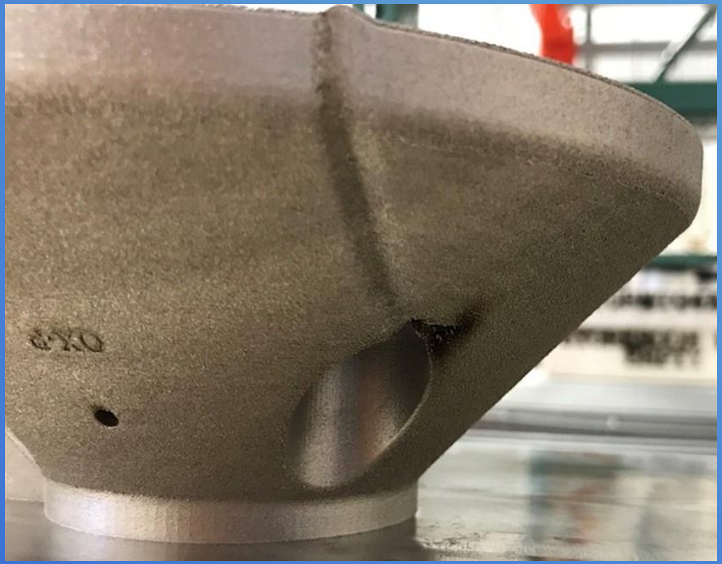
Build Simulation: Residual Stress & Distortion Failure Prediction

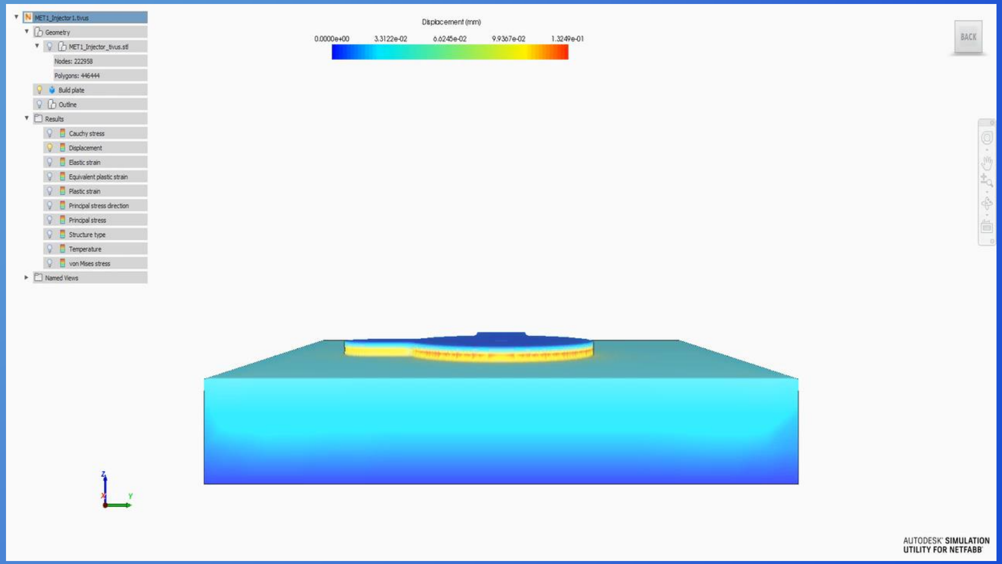






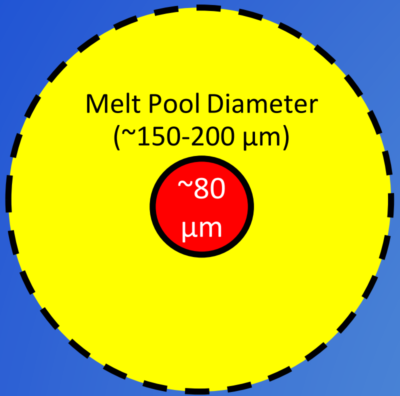
AMPd Engine LOX Impeller (Shrouded) V1 on EOS M290. Build time - $0.3k (3 hrs), Powder - $ 0.01k (0.25 kg), Saw - $0.2k, Plate resurface - $0.2k, Total - $0.71k





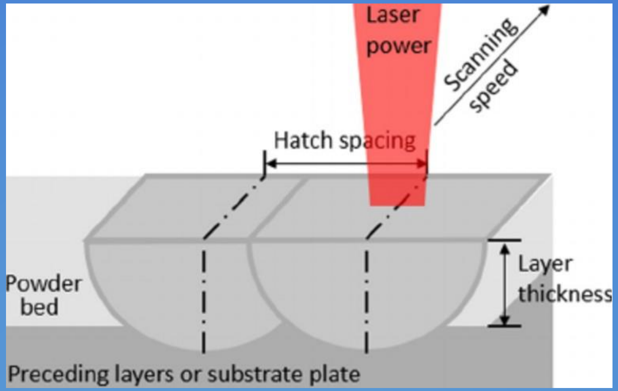
MET1 Injector V1 on EOS M290. Build time - $5.5k (55 hrs), Powder - $ 0.32k (5.82 kg), Saw - $0.2k, Plate resurface - $0.2k, Unsuccessful total - $6.22k. Successful total $6.22k. Total Cost $12.44k. 15 minute long simulation.

Build Process

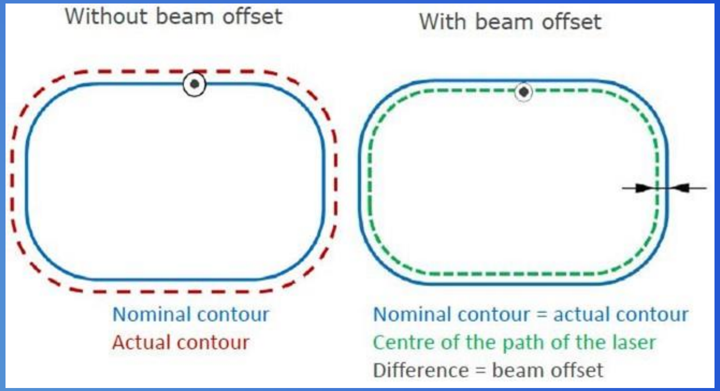


Laser Focus Diameter. Courtesy EOS.

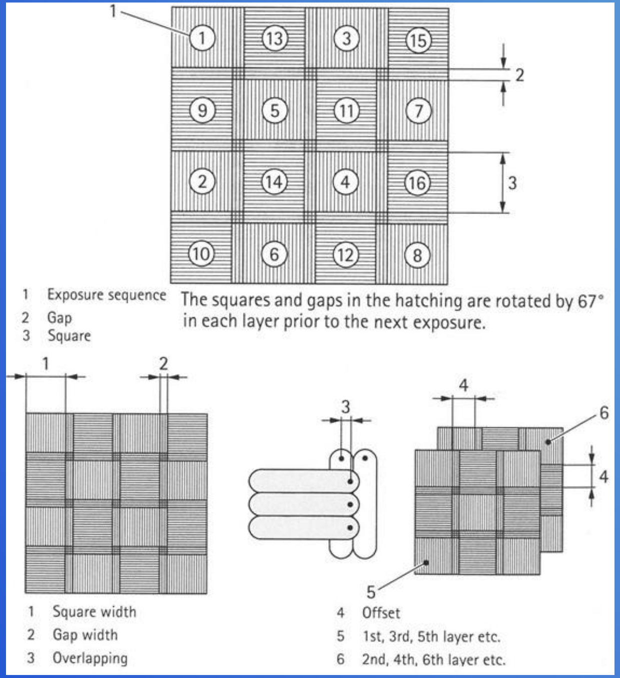

Melt Pool Track



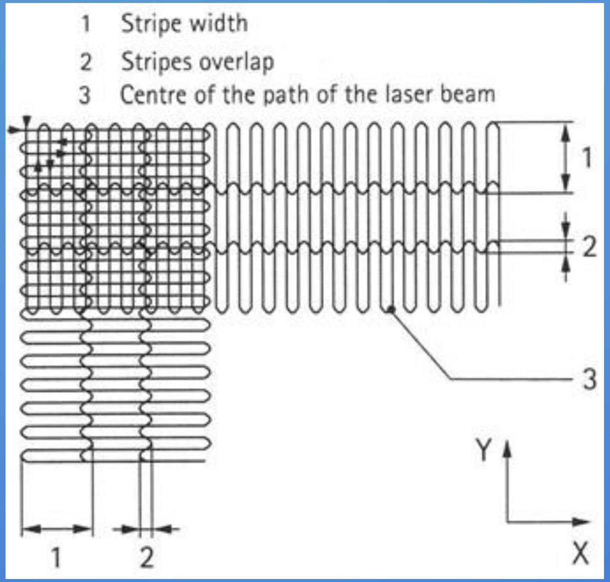
Hatch spacing



Beam Offset. Courtesy EOS.



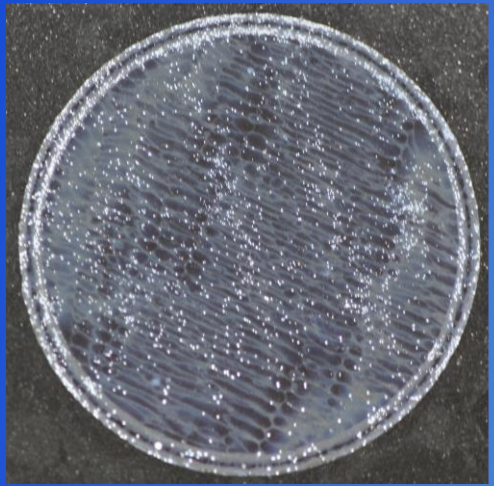
Chess Rotated Exposure Strategy. Courtesy Concept Laser.



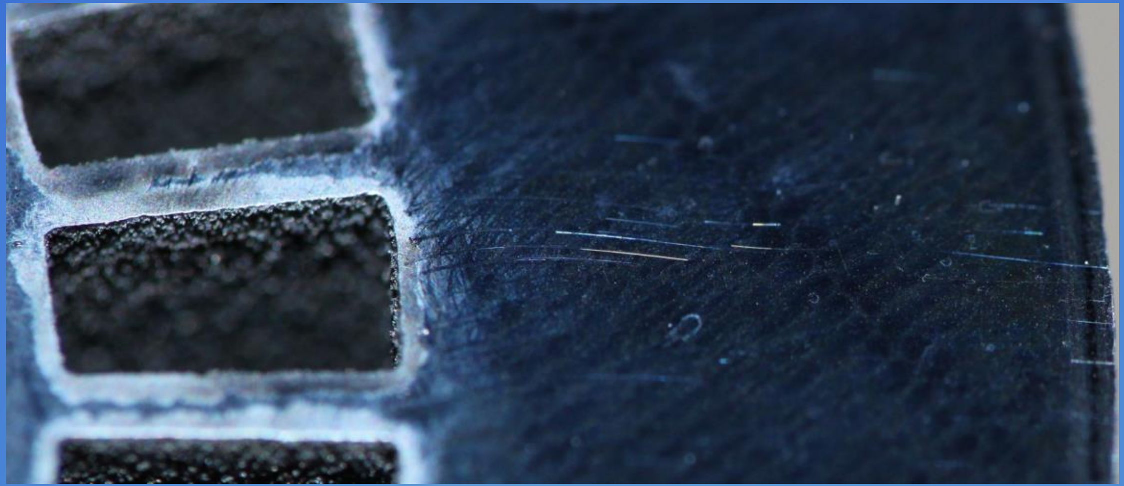
Stripe Exposure Strategy. Courtesy EOS

Parameter	Description
Thickness (t)	Powder layer thickness (mm)
Power (P)	Laser power set-point (W)
Speed (V)	Laser scan speed (mm/s)
Hatch Distance (D)	Distance between centerlines of weld pools (mm)
Overlap	Melt pool overlap (%)
Beam Offset (BO)	Compensates for melt pool size to part (mm)
Scan Pattern	Continuous, Chess, Stripes.

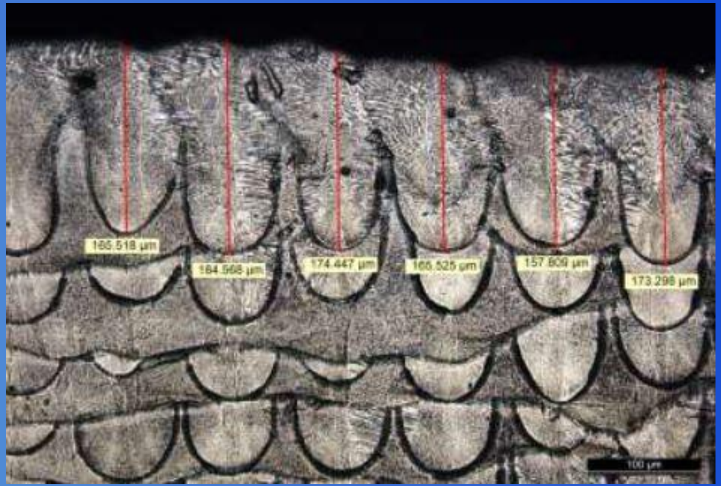
SLM Build Artifacts & Defects



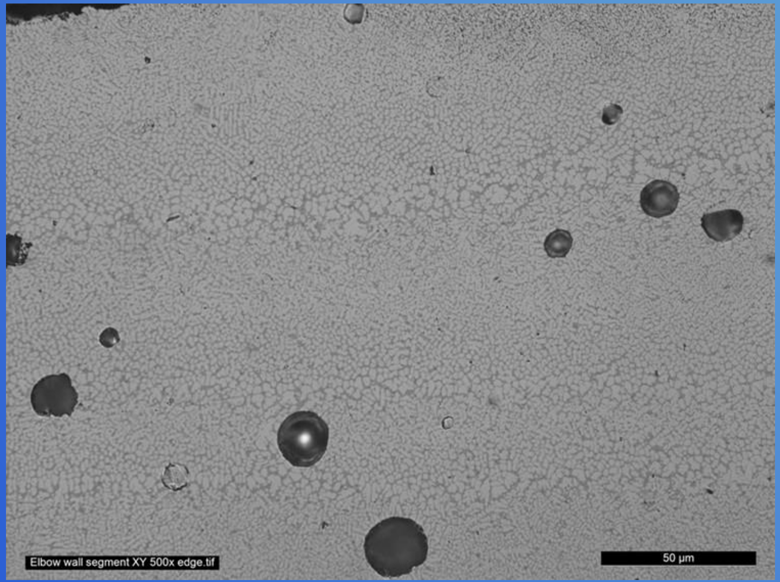
Porosity & weld pool path in AlSi10Mg



Weld pool path in AlSi10Mg



Weld pool depth of IN718

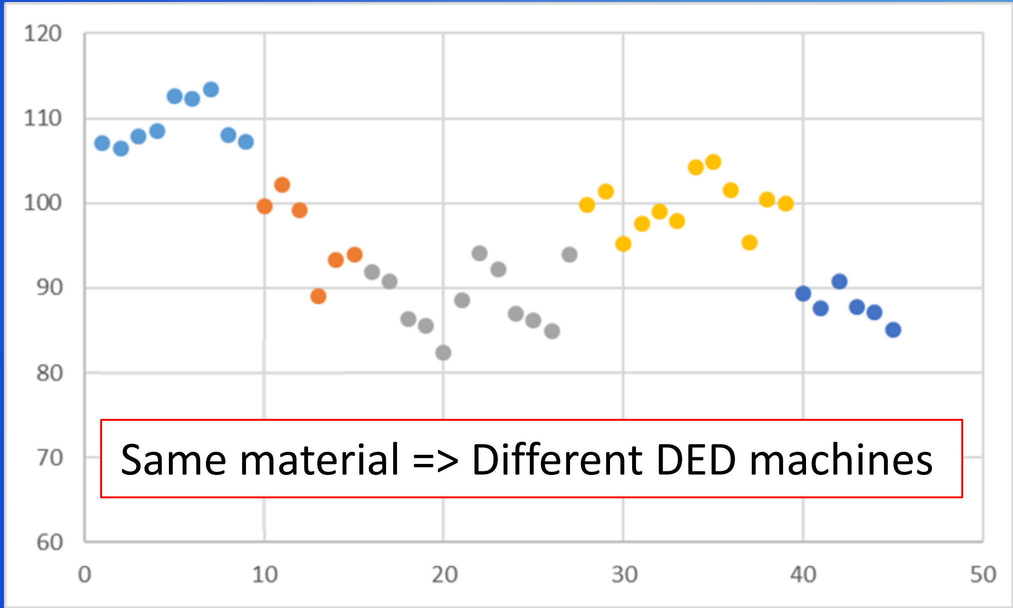


Gas porosity in AlSi10Mg. Trace H_2O reacts with Al to form H_2 bubbles in the melt pool that are trapped upon solidification.

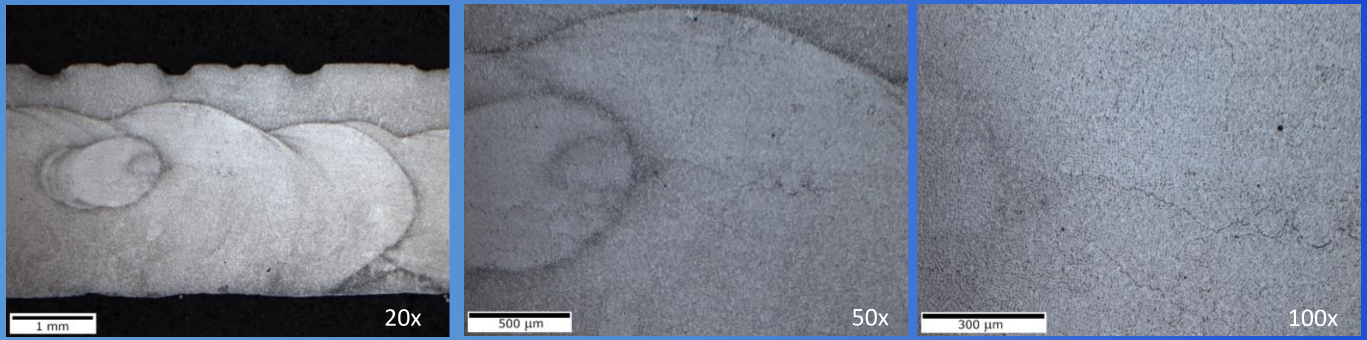
Shrinkage (keyhole) porosity in IN718 results from high laser power or fast scan speed.

DED Microstructure & Properties

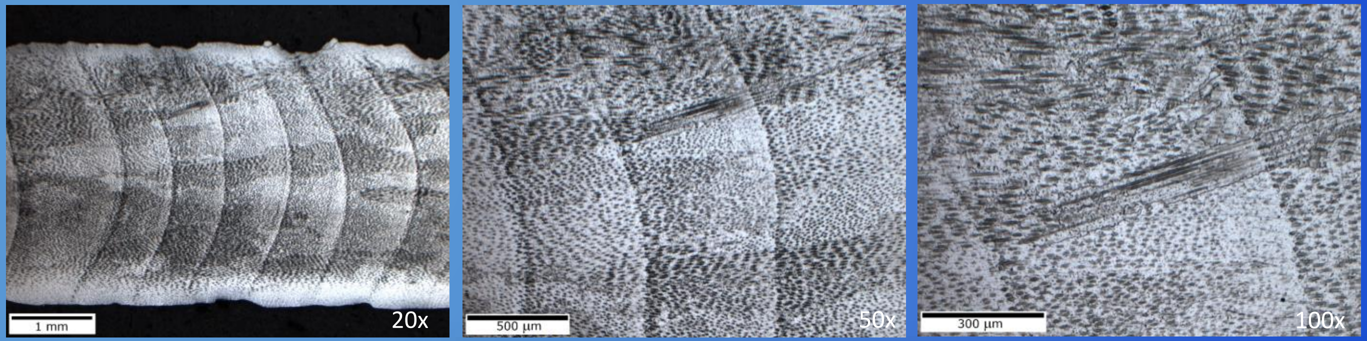
Material properties are dependent on a number of processing parameters (material, build rates, environment, orientation…) => highly variable

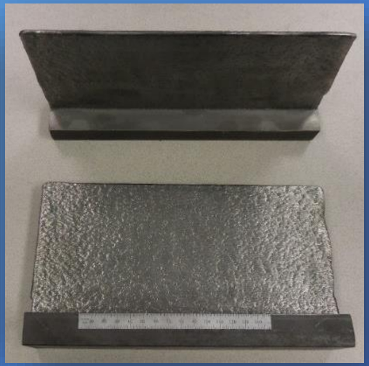


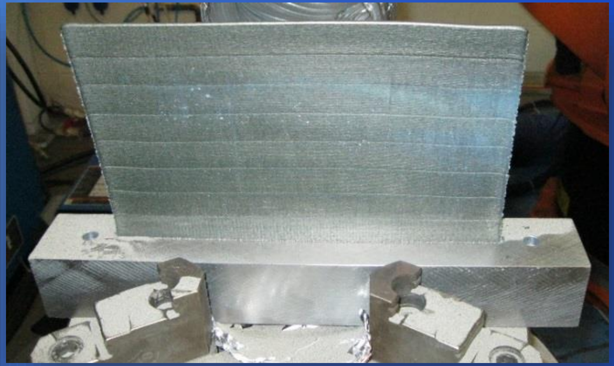
Inco 625 As-Built - Hoop



Inco 625 As-Built - Axial







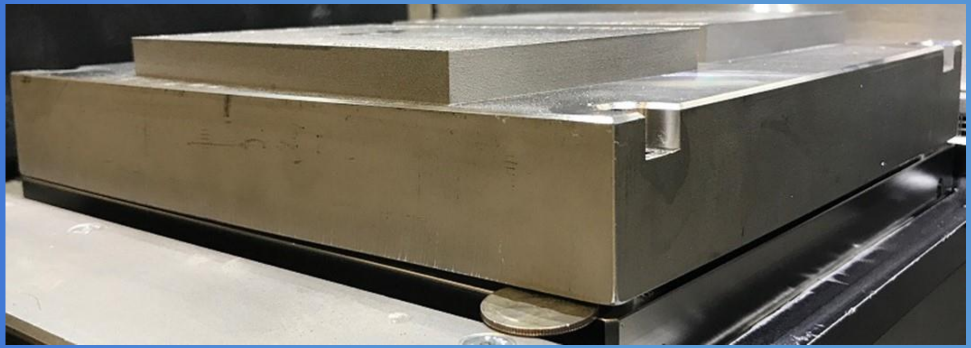
Courtesy Paul Gradl, NASA MSFC.

Stress Relief

- *Stress Relief* – Reduces residual stress as a result of the SLM process.
  - IN718: 1065 ± 14 °C, 1.5 hrs -5/+15 min in argon, furnace cool venting to air as soon as allowable.

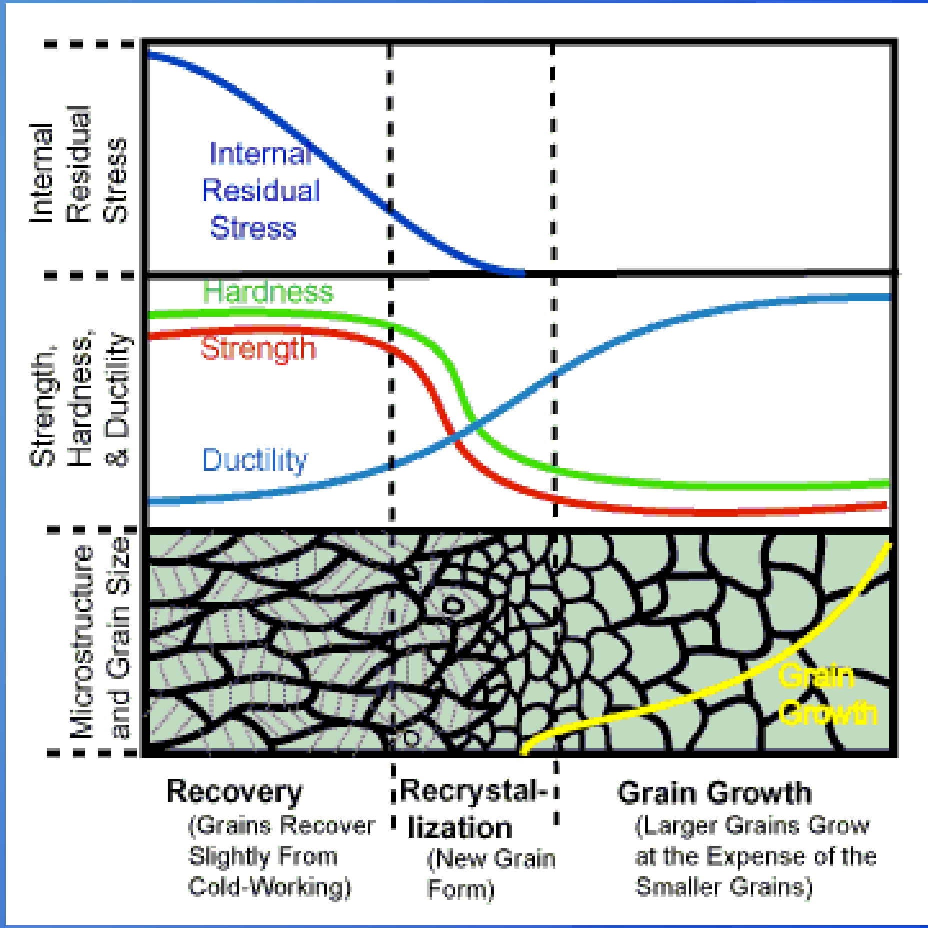
- *Recrystallization* – Microstructure change from dendritic (stressed) to equiaxed grains (stress free).

Cooling shrinkage behavior.



SLM induced residual stress of IN718 distorting 316L build plate.

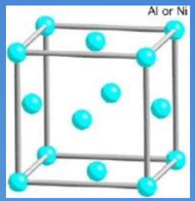
Residual stress induced failure.



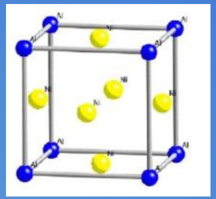
Nucleation, Recrystallization & Grain Growth

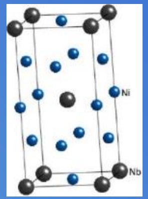
Microstructure of IN718

- IN718 is a precipitation strengthened alloy[1,2]
  - γ matrix solid solution: Ni-Cr, face-centered cubic (FCC).
  - γ′ phase: Ni_3(Al, Ti, Nb), FCC.
  - γ′′ phase: Ni_3Nb, body centered tetragonal (BCT).
  - δ phase: Ni_3Nb, orthorhombic (needle-like).
  - MC-type carbide phase: (Nb,Ti)C, FCC.
  - Laves phase: $(Fe,Ni)_2Nb$, hexagonal close packed (C14). Intermetallic prone to cracking.

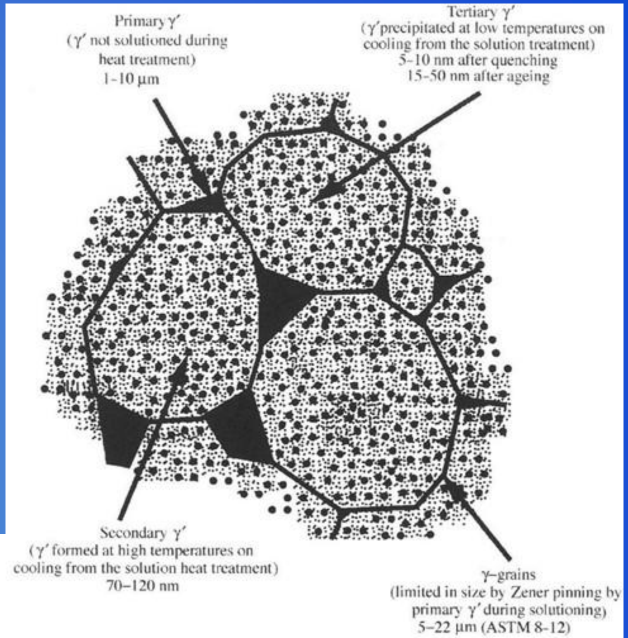


γ FCC structure[3]


γ′ FCC structure[3]

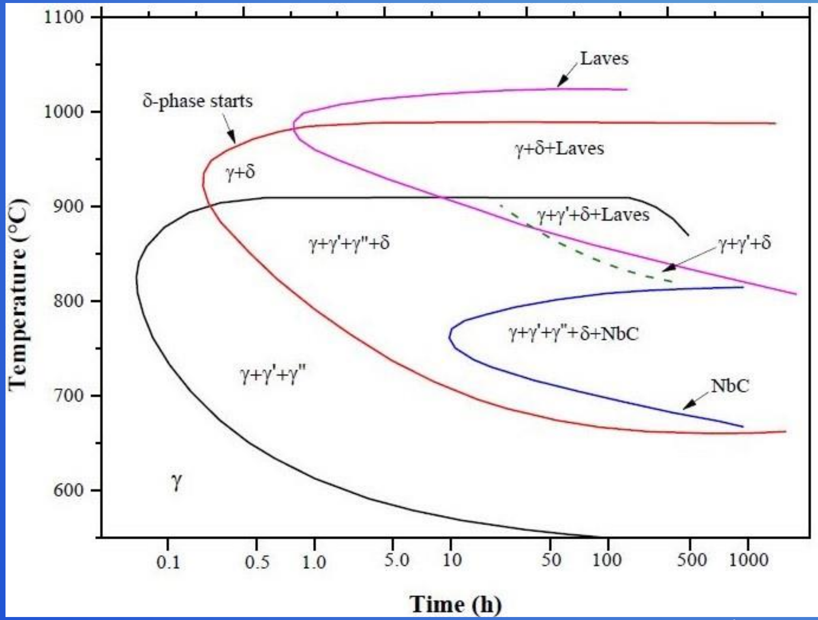


γ′′ BCT structure[3]

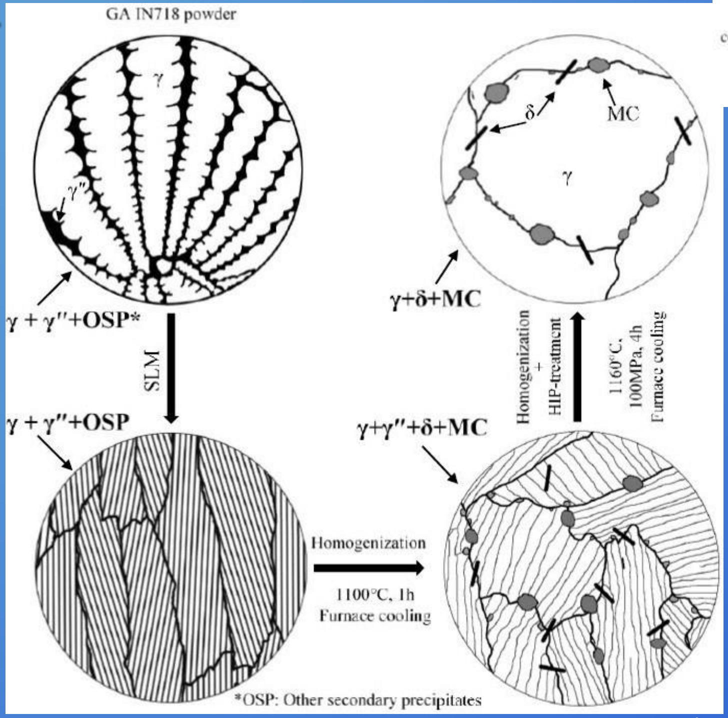


IN718 Microstructure. Courtesy Reed.

- Solidification sequence[1,2]
  - L→ L + γ (1359 °C), L→ γ + MC (1289 °C), L→ γ + Laves (1160 °C).
  - δ phase precipitate (solid state reaction) at 1145 ± 5 °C.
  - γ′ and γ′′ phases precipitate at 1000 ± 20 °C.



Time-Temperature Transformation Diagram-IN718[1].

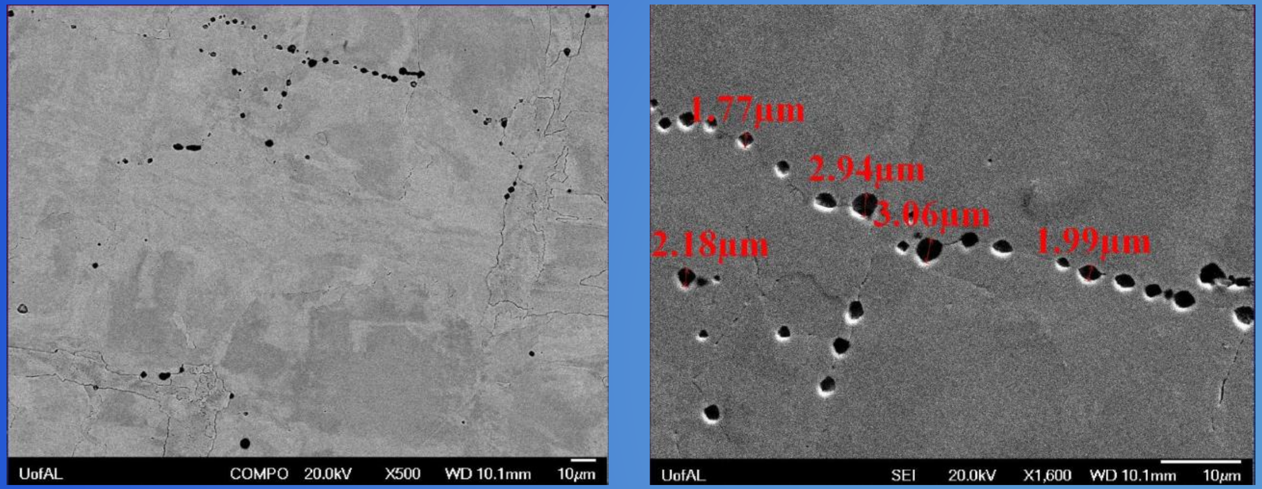


Microstructural change & phase evolution of IN718[1].

[1]Courtesy Mostafa et. al, 2017.
[2]Manikandan, 2015.
[3]Courtesy Bhadeshia, 2018.

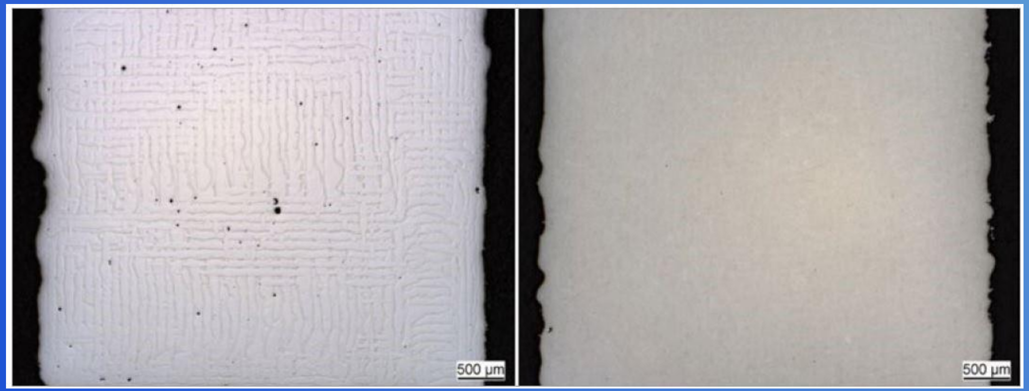
Hot Isostatic Press (HIP)

HIP – Closeout porosity and potential to heal defects.
T = 0.7-0.9T_m , P = 100-207 MPa (15,000-30,000 psig), t = 1-4 hrs.

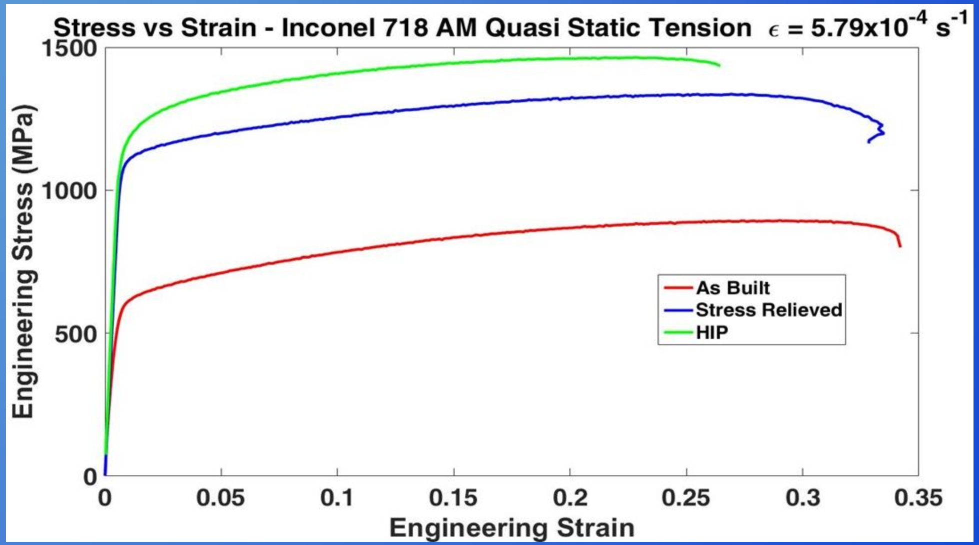


Monel K500 SEM BSE micrographs 500x (L) and 1600x (R) showing porosity along grain boundaries. Courtesy UA Senior Materials Team.


MSFC HIP Furnace



HIP pore close-out. Courtesy Metal AM, Winter 2017.

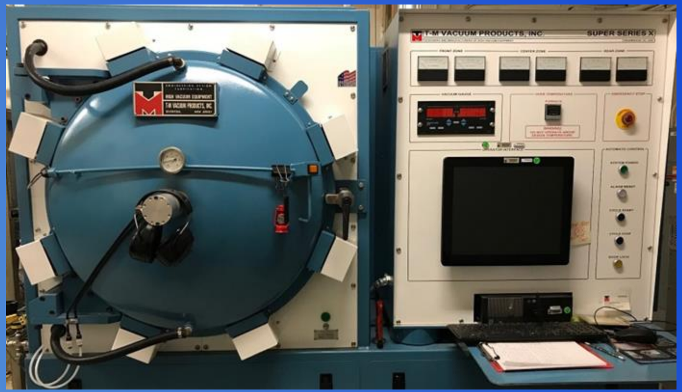


SLM IN718 Tensile Strength vs. Condition. Courtesy Hazeli.

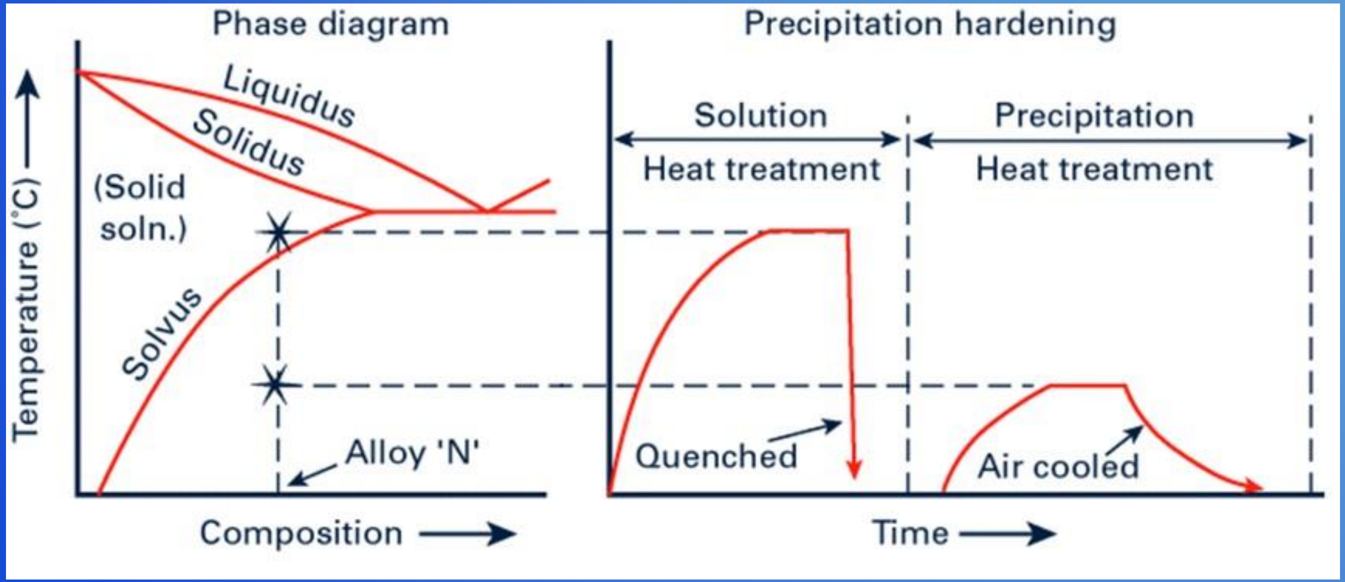
Homogenization: Solutionize & Age

- *Solutionize:* Creates γ as the only stable phase in solution then quench to supersaturate the solution.
  - AMS 5664: 1066 ± 13°C, time thickness dependent, air quench.

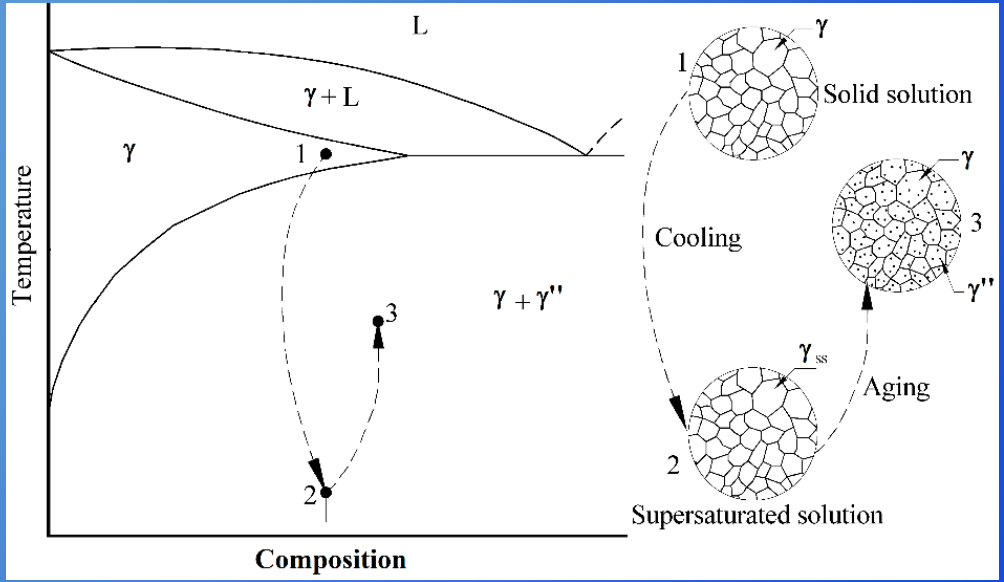
- *Age*: γ'' nucleate uniformly in the microstructure and grown to an optimal size.
  - AMS 5664: 760°C for 8h (γ'' forms), cool to 650°C, hold for 20 h (γ'' grow), air cool.



MSFC Vacuum Furnace



General phase diagram showing heat treatments.



Notional Phase Diagram- IN718

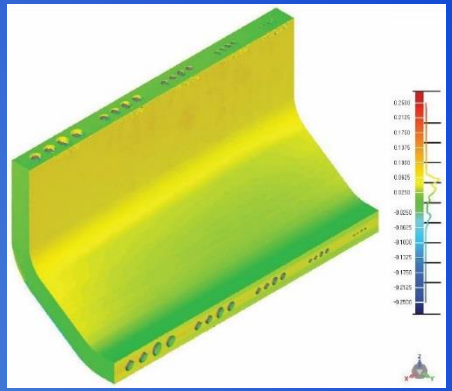
NDE

- Structured Light Scanning
  - Surface mapping
  - Geometric distortion/deviation
  - Limited spatial resolution
  - Equipment expensive but operation relatively inexpensive

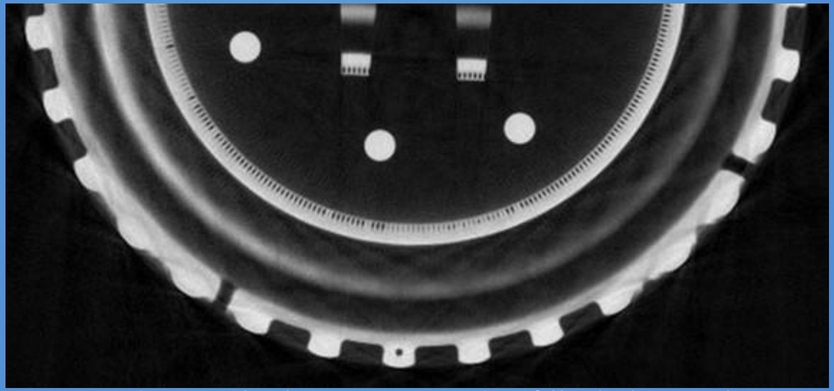
- X-ray radiography & CT
  - Detect trapped powder
  - Large flaws
  - Limited spatial resolution (excludes micro-focus CT)
  - Material determines scan time/resolution
  - Expensive & time consuming

Visual Borescope

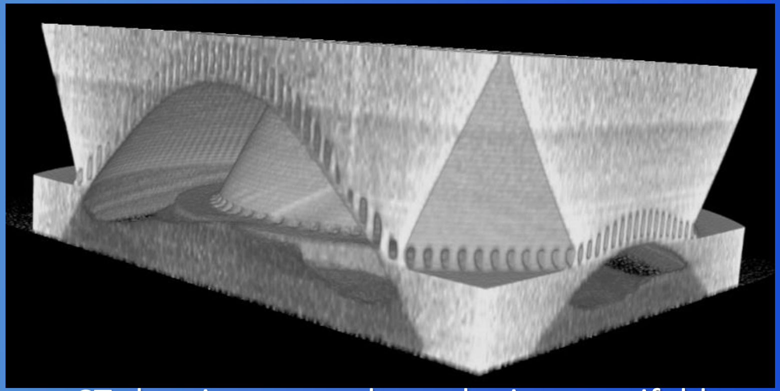
Structured Light Scanning



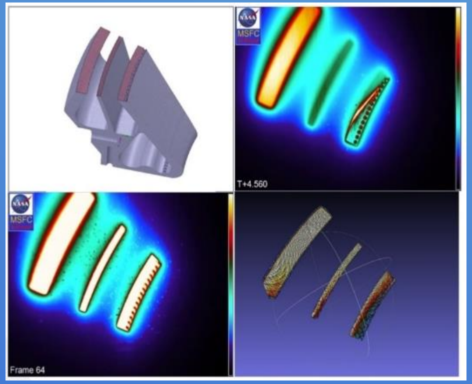
CAD-scan data comparison



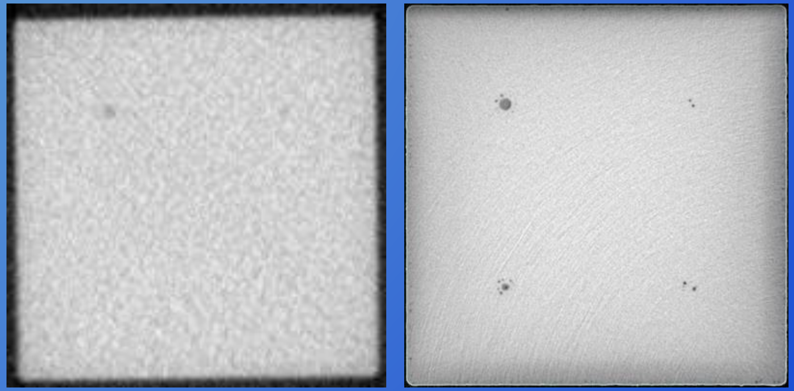
Radiograph showing powder filled channels



CT showing trapped powder in a manifold



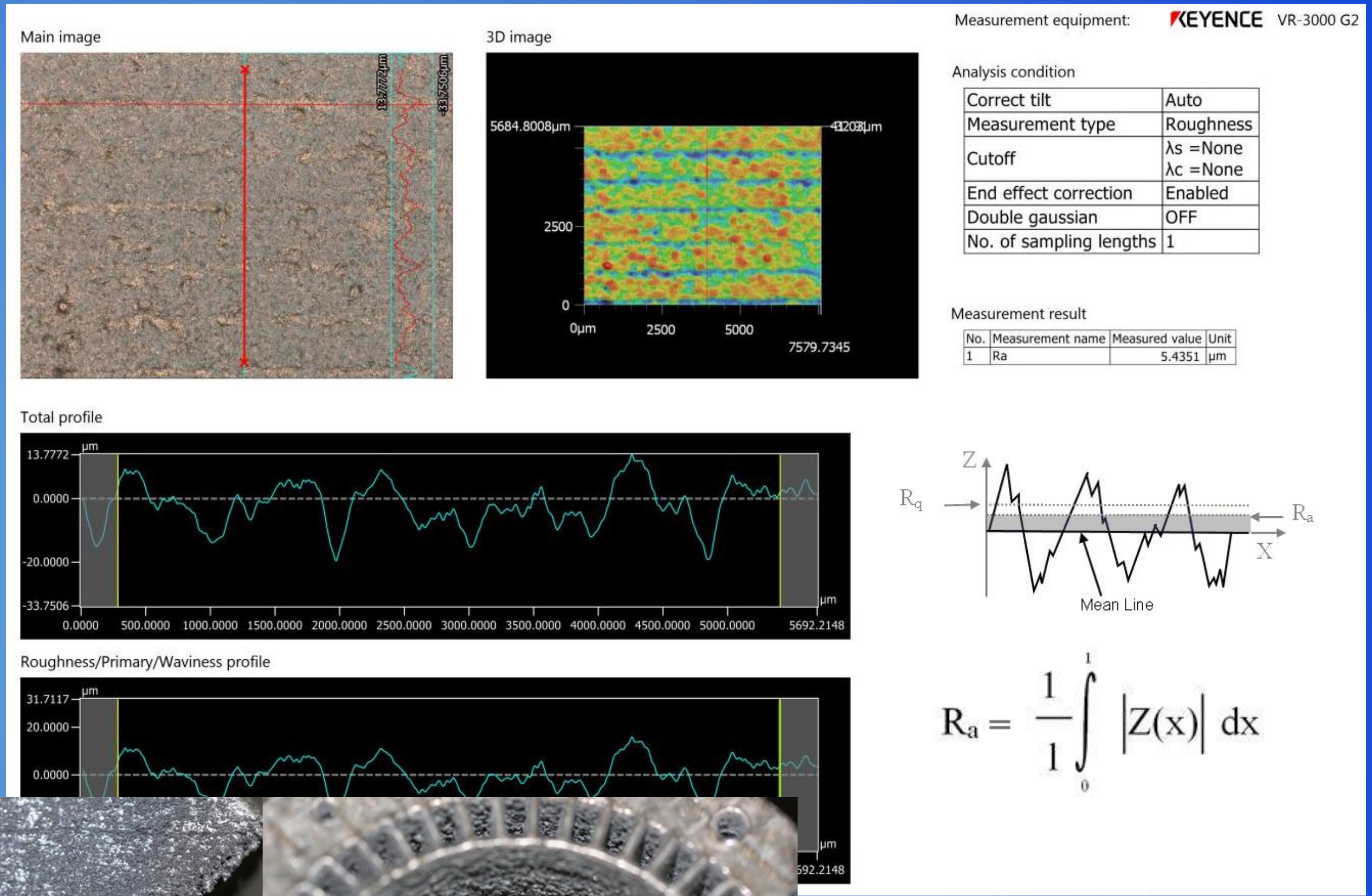
In-situ Inspections

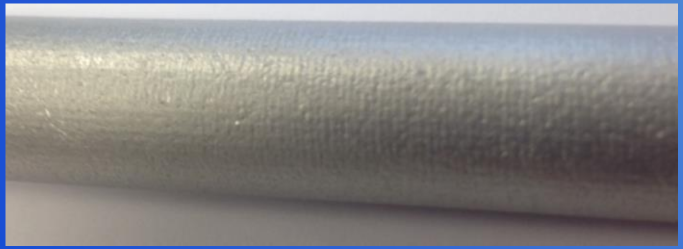


Known flaws in AlSi10Mg block. Left: Regular CT. Right: Micro-CT

Surface Finish Modification

- As built roughness
  - PSD & parameters influence Ra.
  - High cycle fatigue (HCF) knock down due to near-surface porosity.
- Surface finish modification
  - Shot peen
  - Tumble
  - Machine
  - Extrude/slurry hone
  - MicroTek (removes 0.05 mm)
  - Electro-polish





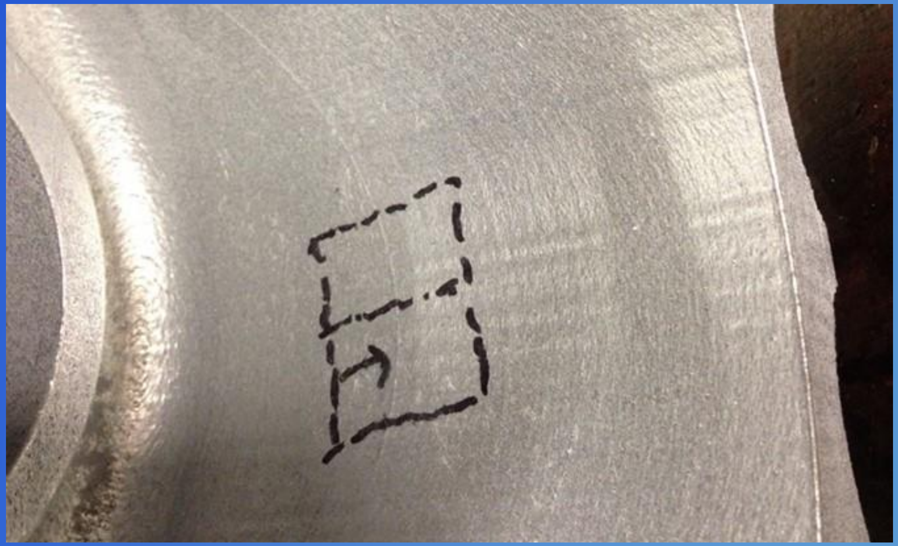
Software induced tesselation

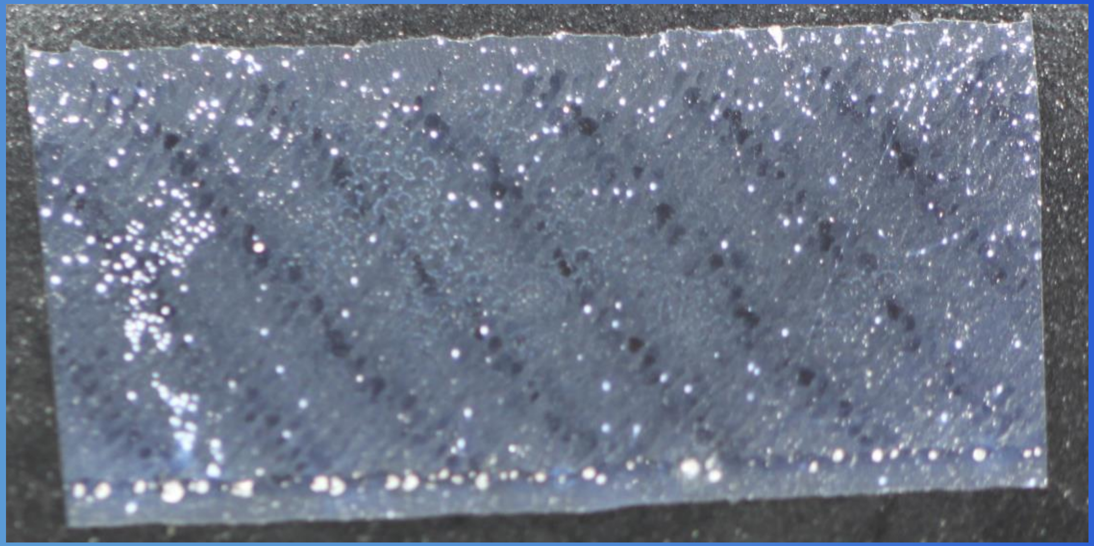
As-built surfaces of AlSi10Mg on Concept Laser X-Line.

Material	R_a (μm)
Inconel 718	5.05
GRCop-84	5.44
AlSi10Mg	3.29
Ti-6Al-4V	?

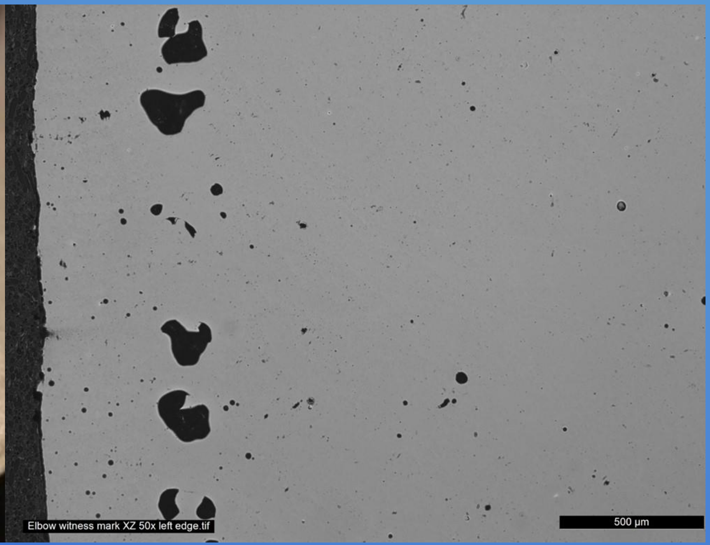
Typical as-built surface roughness (SLM)

Build Artifacts & Defects

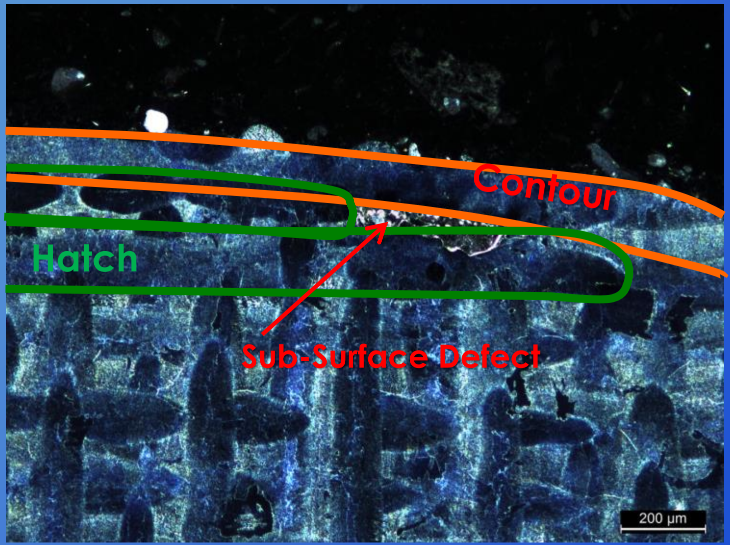




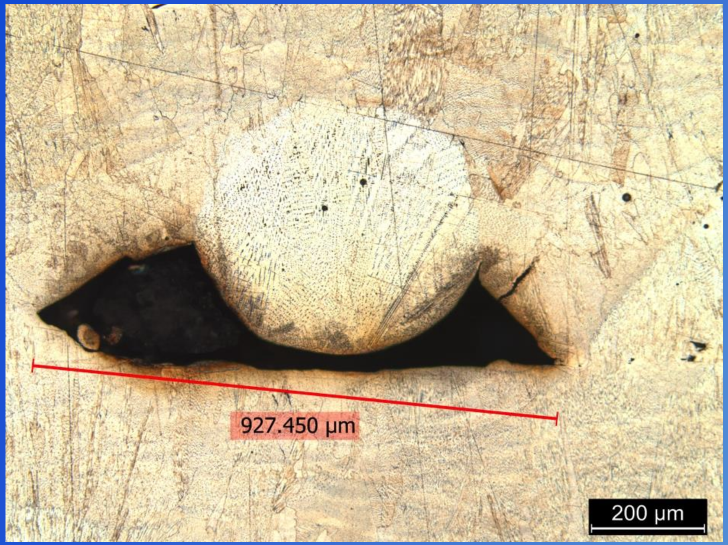
Witness marks on the surface and interior



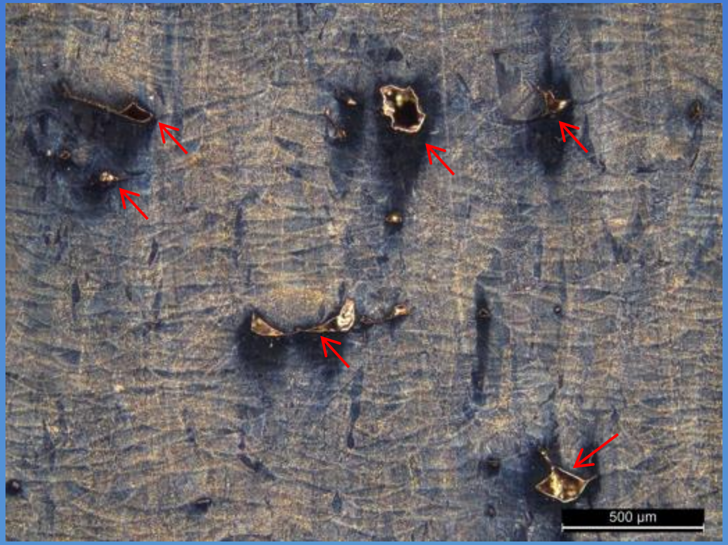
Edge Porosity



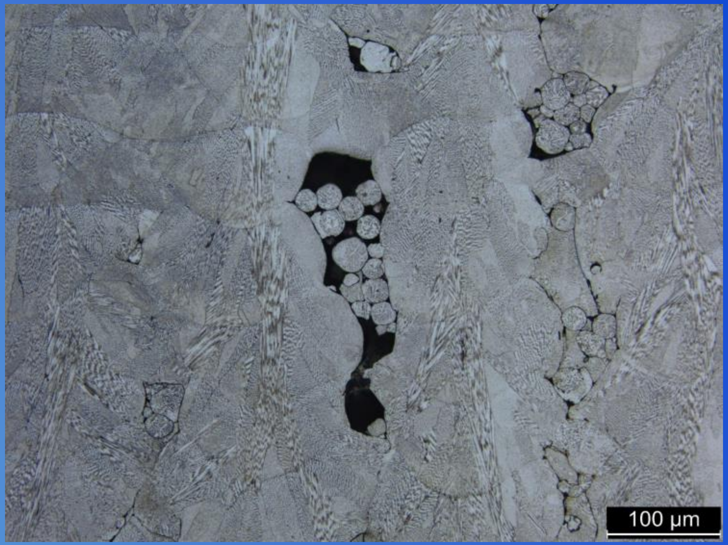
Edge Porosity can result from an excessive beam offset.



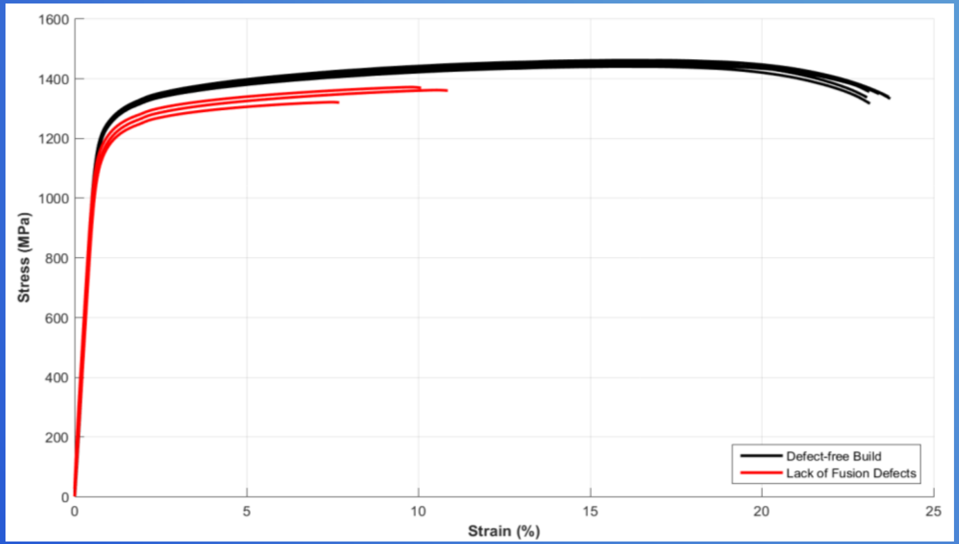
Horizontal Lack of Fusion (LOF) defect from ejecta.

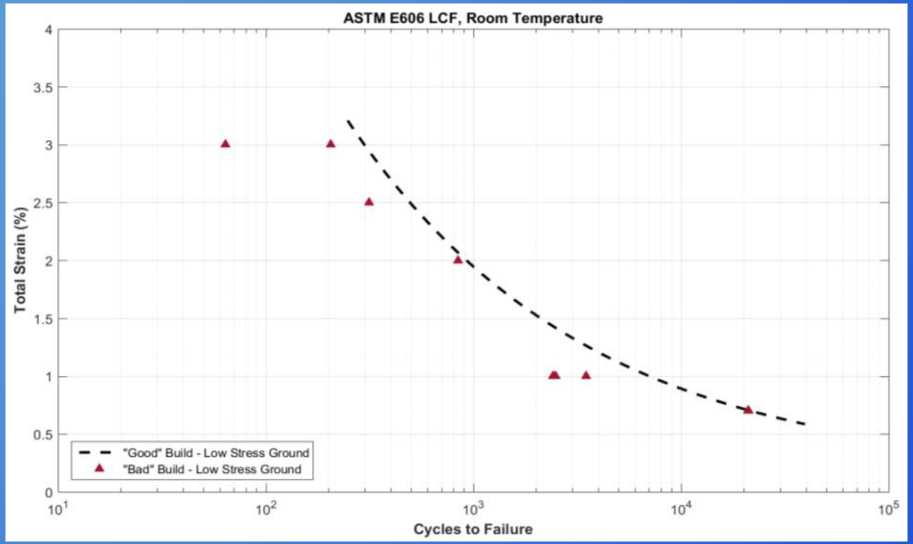


H-LOF defect from insufficient laser power (set point or attenuation).



Vertical-LOF defect from wide hatch spacing.



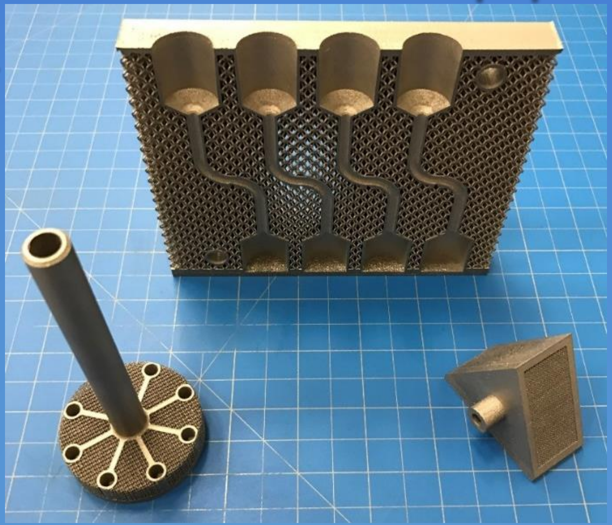


LOF defects decrease mechanical properties such as tensile strength, elongation, high cycle fatigue.

Courtesy Arthur Brown

Lattice Structure Applications

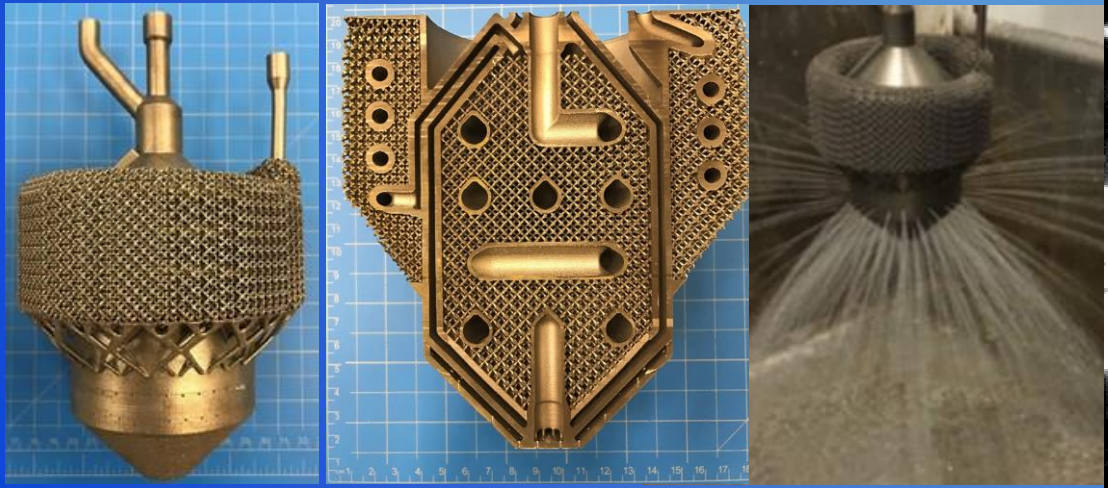
- Relative density & surface area gradients.
- Reduce weight, retain stiffness.
- Gas/liquid permeable solid: porous foam & Regimesh replacement.
- Metal Matrix Composite (infiltrate).
- Custom property potential: mimic properties of different materials in the same part using the same material in adjacent regions.
- Computationally expensive.



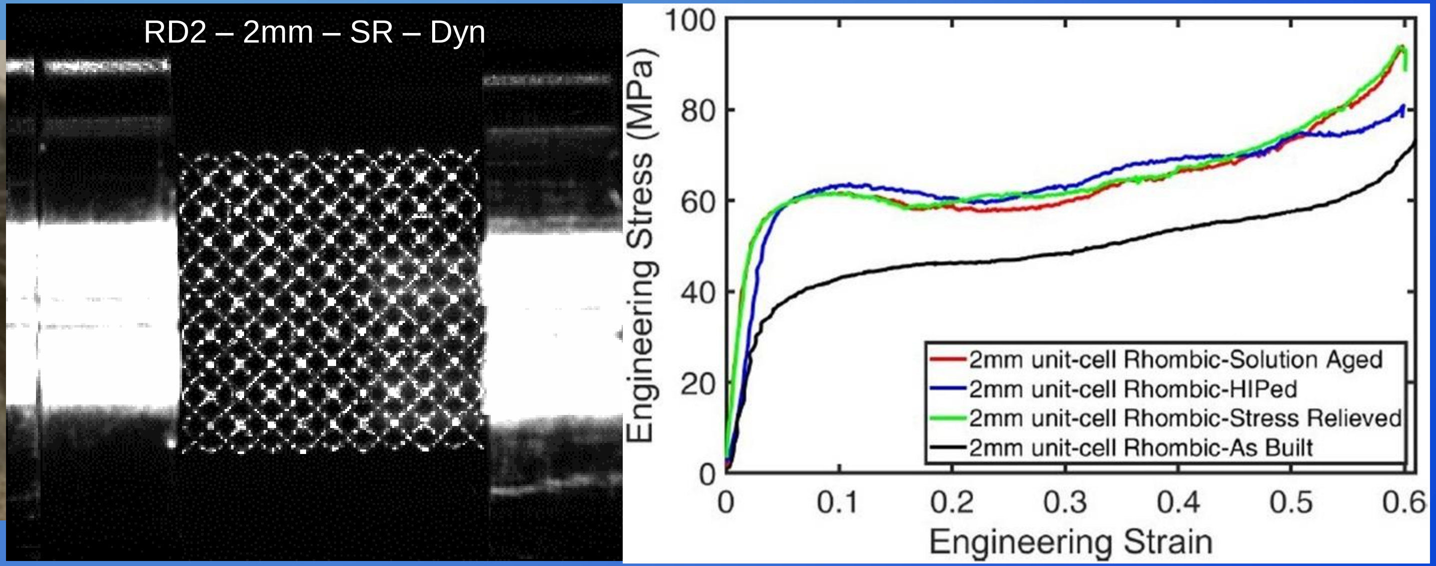
CFM Magnetically Coupled Rotor, Heat Exchanger, LAD demos

ECLSS 4-Bed Molucular Sieve (4BMS-X) Heater Plate

KSC O_2 Generator Cold-Head



Cryo Heat Exchanger-Injector-Condenser Demo



Dynamic mechanical testing. Courtesy Kavan Hazeli, UAH.

MSFC AM Flight Certification Standard

- Standardization is essential for consistent and reliable production of flight critical AM components.
- NASA cannot wait for organizations to issue standards since human spaceflight programs already rely on AM:
  - Commercial Crew
  - SLS
  - Orion
- Objective: Develop an appropriate AM standard
  - MSFC-STD3716 & MSFC-STD-3717.
  - Draft released in 2015 for peer review.
  - Final revision released October 2017.
  - Iterative (living) document.


NOT MEASUREMENT SENSITIVE

National Aeronautics and Space Administration

MSFC-STD-3716
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20
MSFC TECHNICAL STANDARD

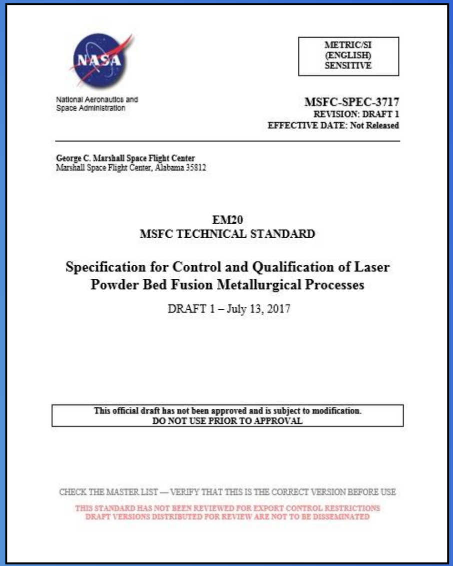
Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals

DRAFT 1 – April 10, 2017

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST — VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED


METRIC/SI (ENGLISH) SENSITIVE

National Aeronautics and Space Administration

MSFC-SPEC-3717
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20
MSFC TECHNICAL STANDARD

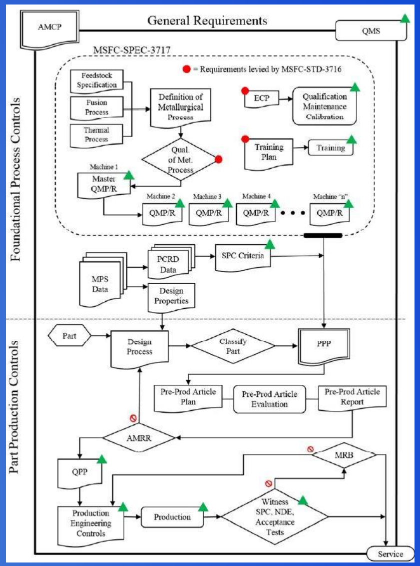
Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

DRAFT 1 – July 13, 2017

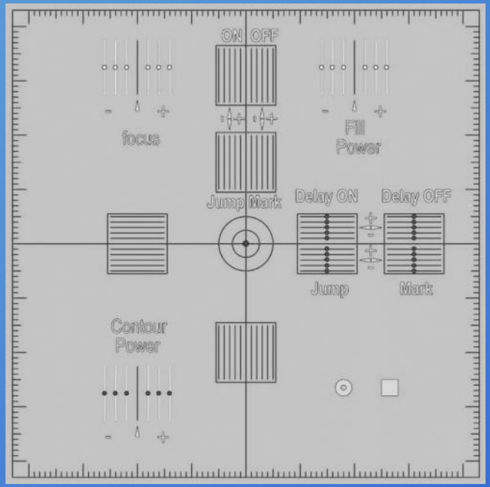
This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST — VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED



Process specification: From powder to acceptance



Machine repeatability

MSFC-STD-3716 & -3717

Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals.

AMCP	Additive Manufacturing Control Plan
AMRR	Additive Manufacturing Readiness Review
MPS	Material Property Suite
MRB	Material Review Board
NDE	Non Destructive Evaluation
PCRD	Process Control Reference Distribution
PPP	Part Production Plan
QMP	Qualified Metallurgical Process
QMS	Quality Management System
QPP	Qualified Part Process
SPC	Statistical Process Control