Intro to Additive Manufacturing for Propulsion Systems

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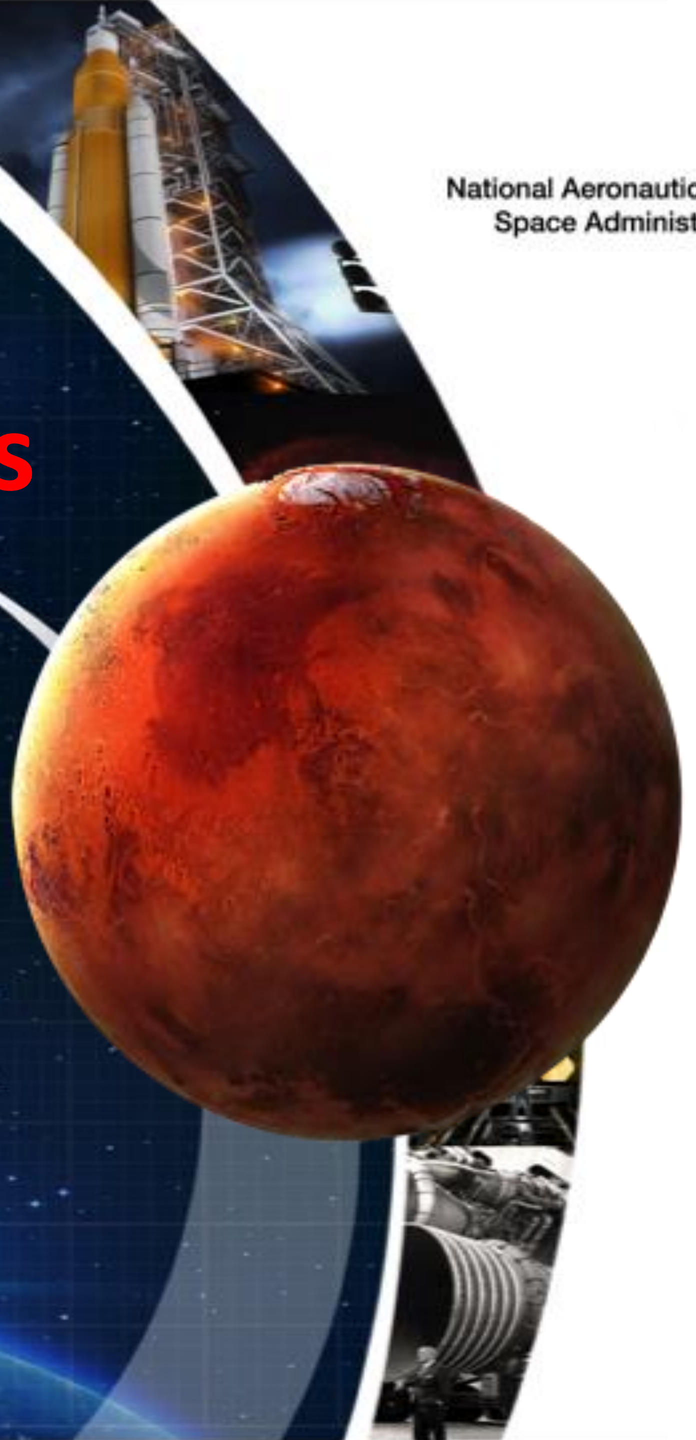

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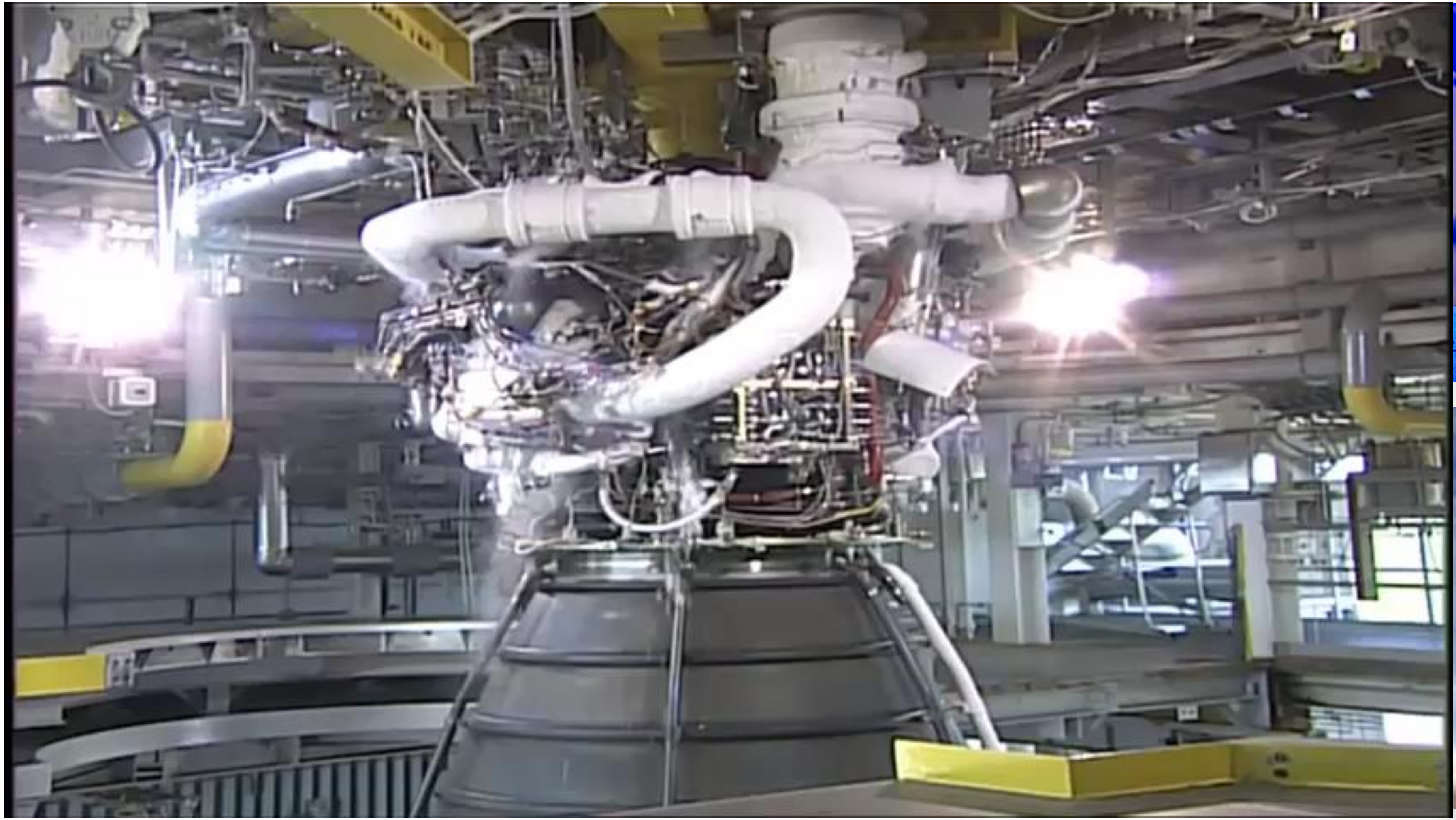
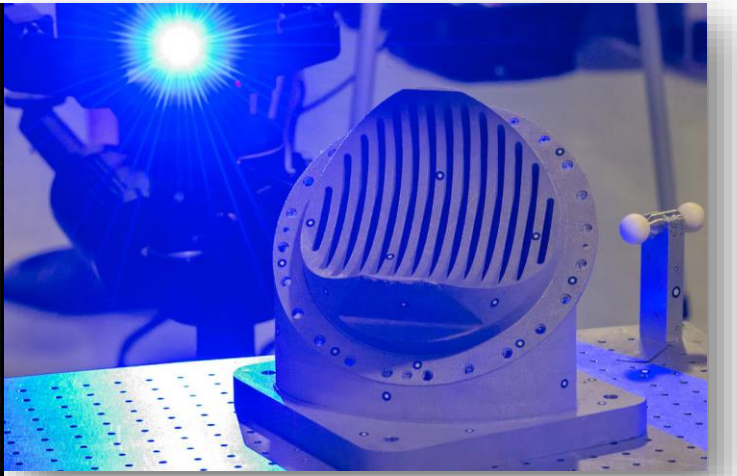
AIAA
Propulsion Energy and Forum 2018

Additive Manufacturing is real…

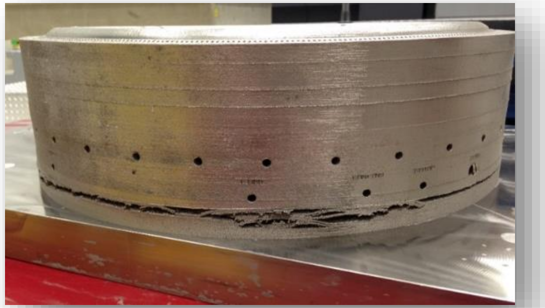




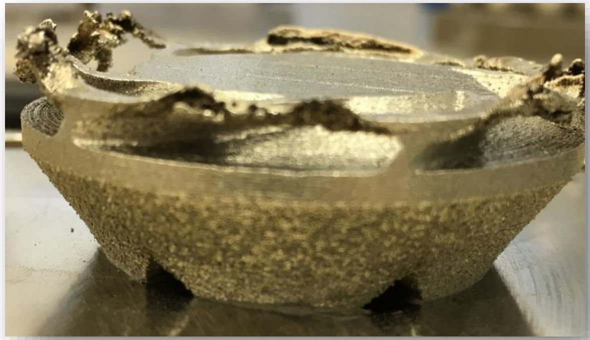
Successful hot-fire testing of full-scale Additive Manufacturing Part to be flown on NASA's Space Launch System (SLS) RS-25 Pogo Z-Baffle – Used existing design with additive manufacturing to reduce complexity from 127 welds to 4 welds

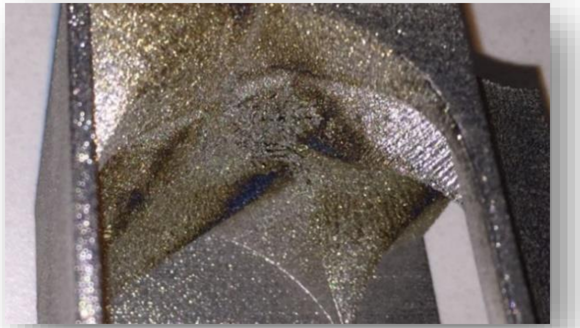
Ref: Andy Hardin, Steve Wofford/ NASA MSFC

Intro to Additive Manufacturing



But…don’t say we didn’t warn you!





Overview and Agenda

General Overview and Applications

- Intro / What is AM (focus on metals)?
- Different Techniques/Comparison and Overview
- Intro of Materials
- Applications of Techniques
- Hot Fire Testing and Flight Examples
- Intro on design for AM

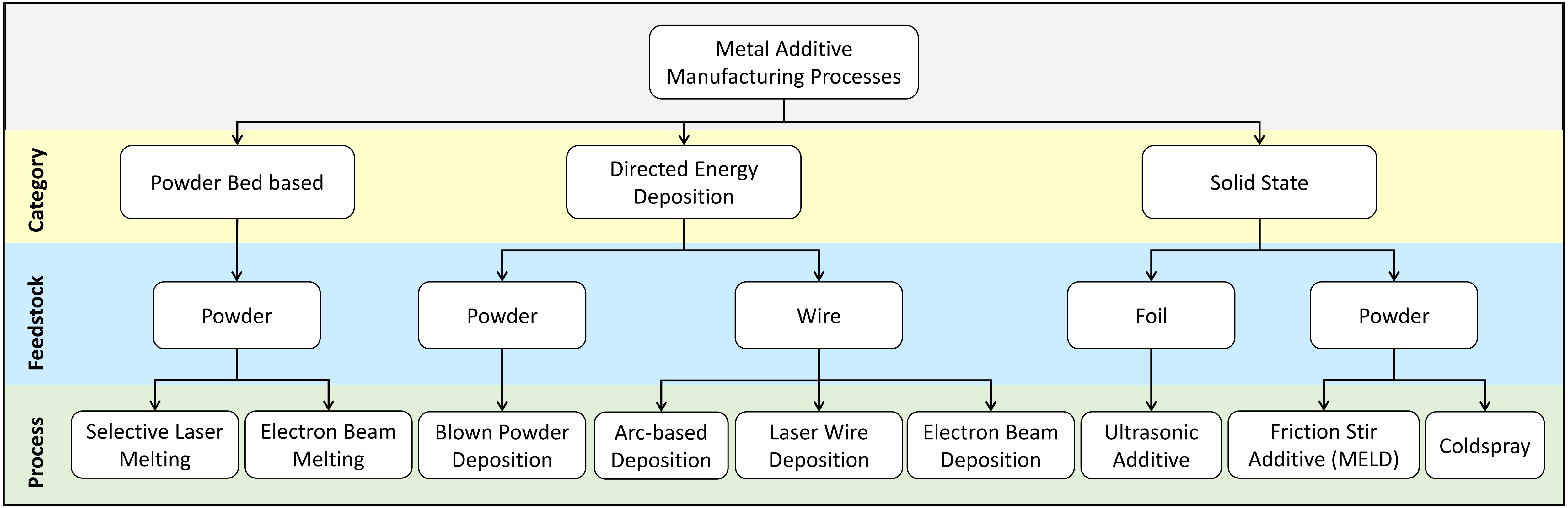
Design for AM and Detailed Fabrication Cases

- Details of Fab Process and Development – SLM
- Material Development
- How to Design for AM
- Analysis Techniques for Builds
- Build Failures
- Overview of Certification for AM

Introduction to Additive Manufacturing

- **Additive Manufacturing** – process of joining materials to create objects from 3D model data
- This presentation will focus exclusively on metals
- Additive Manufacturing = AM
- Additive manufacturing is not a solve-all; consider trading with other manufacturing technologies and use only when it makes sense
- Complete understanding of design process, build-process, and post-processing critical to take full advantage of AM
- Additive manufacturing takes practice!

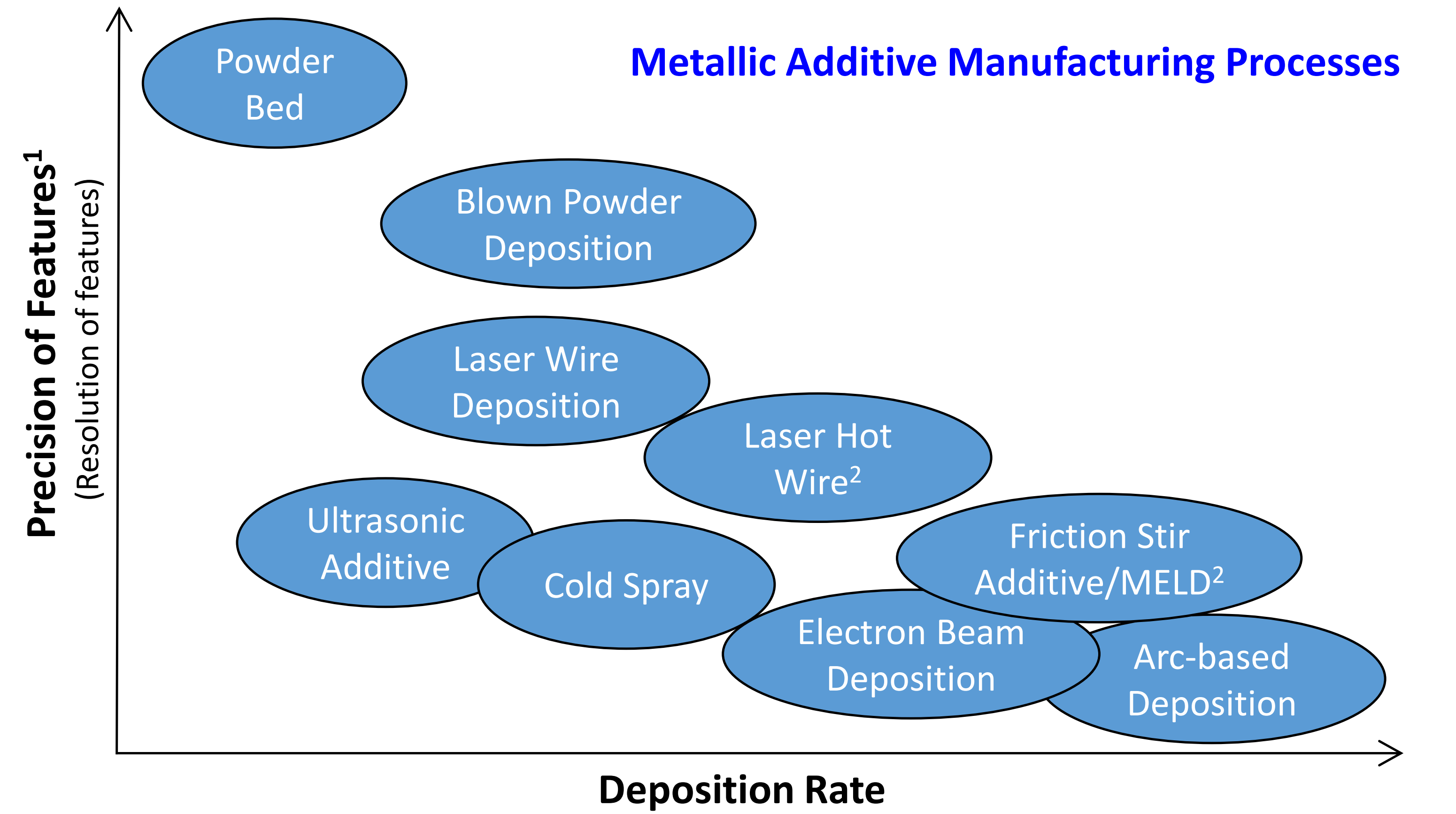
Overview of Various Metallic Additive Techniques



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).

Why use one AM technique over another?

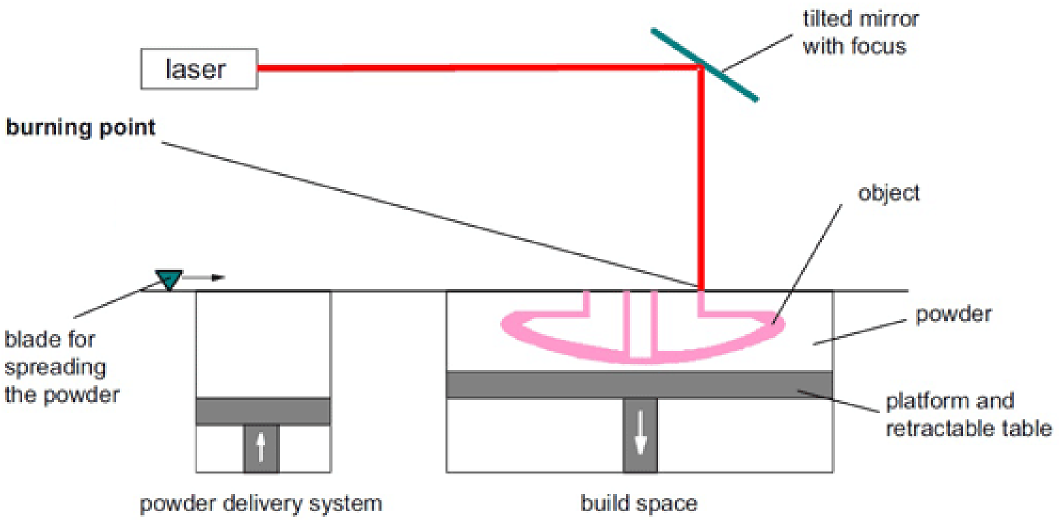


[1] Precision refers to the as-built state and does not encompass hybrid techniques and/or interim machining operations that would increase resolution. There are a lot of other factors not considered in this chart, including heat inputs to limit overall distortion.
[2] Technology still under development

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

Powder-bed based Processes

VDI-Guideline 3404 (2009) Additive Fabrication-Rapid Technologies (Rapid Prototyping) – Fundamentals, Terms and Definitions, Quality Parameter, Supply Agreements. (2014).

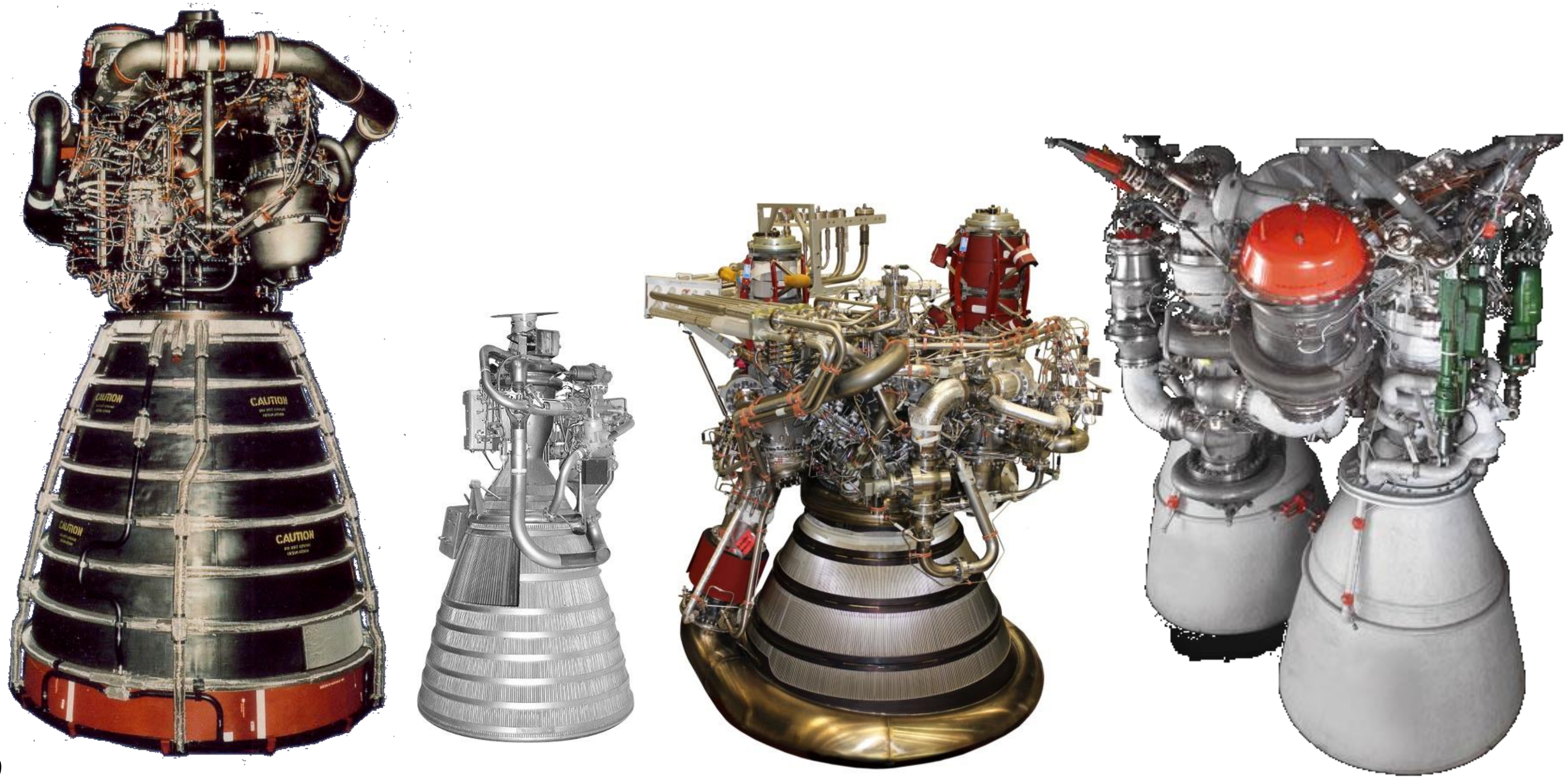


- **Selective Laser Melting (SLM)**
  - <u>Basic Process</u>: Uses a layer-by-layer powder-bed approach in which the desired component features are sintered and subsequently solidified using a laser. Used widely in combustion devices applications.
  - <u>Advantages</u>: Allows for high resolution, fine features, including complex internal designs to be fabricated, such as cooling channels
  - <u>Disadvantages</u>: The scale for SLM is limited and does not provide a solution for all components
- **Electron Beam Melting**
  - <u>Basic Process</u>: Similar to SLM, but uses an electron beam instead of a laser. Not frequently used in combustion devices applications.
  - <u>Advantages</u>: Build is performed under vacuum, which can be useful for reactive materials such as titanium

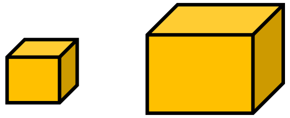
What about scale of SLM?

Engine

SSME/RS-25 **RL-10A-4** **J-2X, Regen Only** **RD-180**



SLM Build Boxes



10x10x10 15.5x24x19
(inches)

90″ 46″ 70″ 56″

Nozzle Exit Dia.

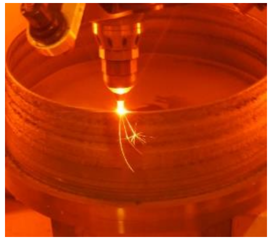
Gradl, P.R., Brandsmeier, W. Alberts, D., Walker, B., Schneider, J.A. **Manufacturing Process Developments for Large Scale Regeneratively-cooled Channel Wall Rocket Nozzles**
Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

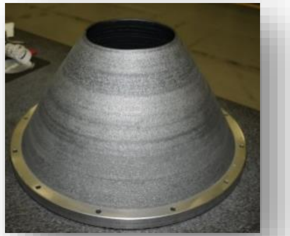
Directed Energy Deposition (DED)

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

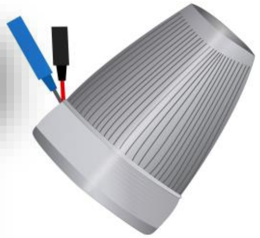




Laser Wire Deposition

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

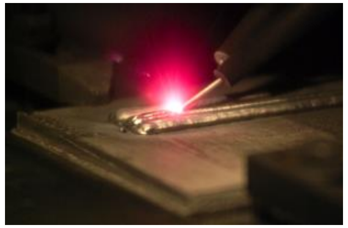
Arc-Based Deposition (wire)

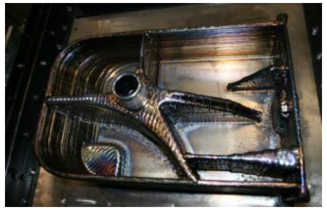
Pulsed-wire metal inert gas (MIG) welding process creates near net shapes with the deposition heat integral to a robot



Electron Beam Deposition (wire)

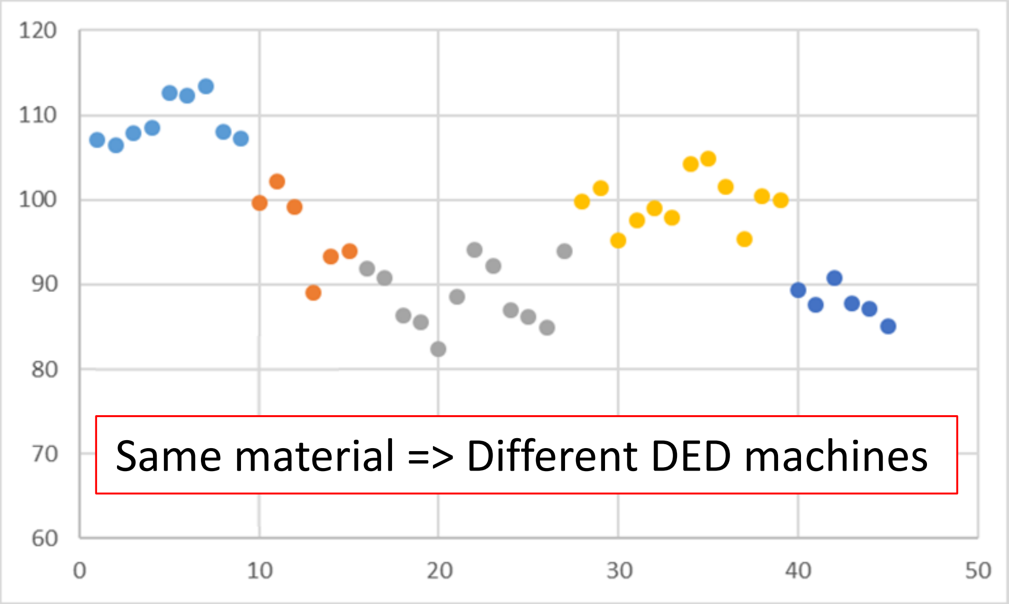
An off-axis wire-fed deposition technique using electron beam as energy source; completed in a vacuum.



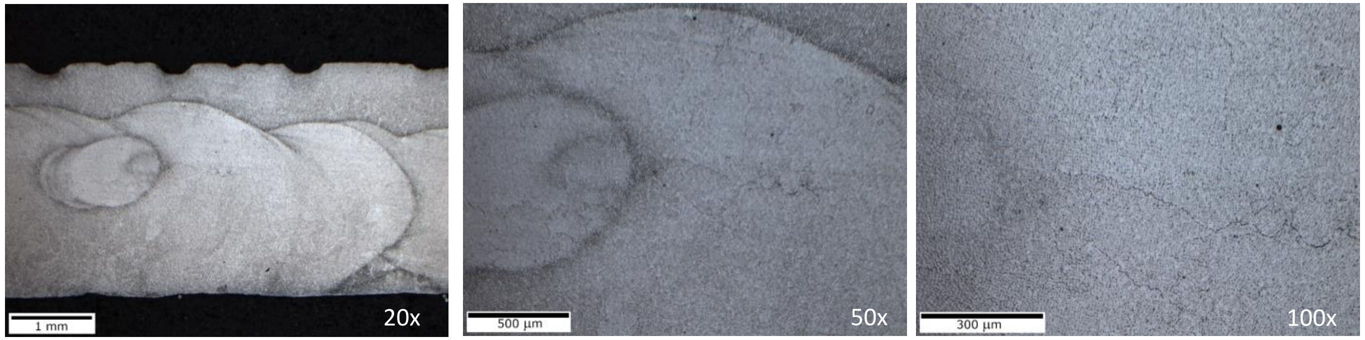


Directed Energy Deposition

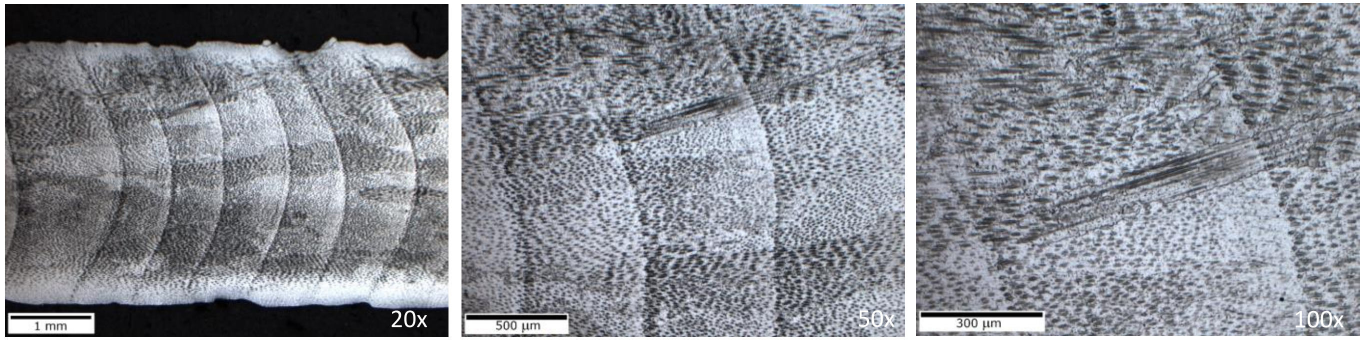
Material properties are dependent on a number of processing parameters (material, build rates, environment, orientation…) => highly variable

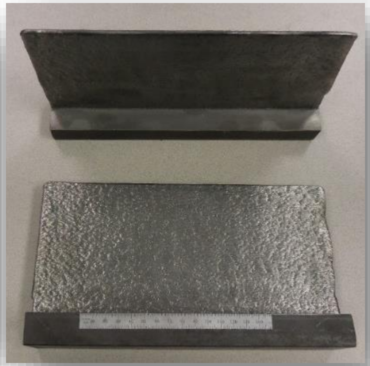


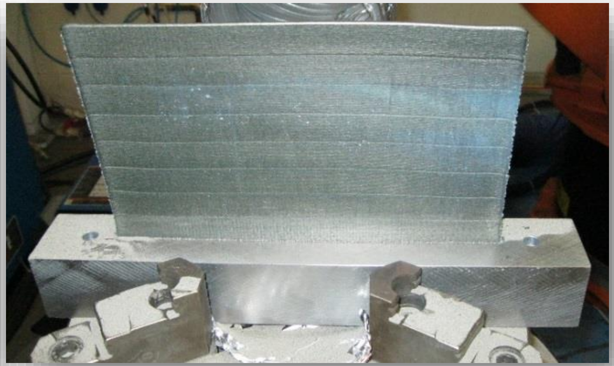
Inco 625 As-Built - Hoop



Inco 625 As-Built - Axial







Materials continually being evolved

*Materials developed for SLM and DED processes**

Superalloys
Inconel 625
Inconel 718
Haynes 230
Monel K-500
Haynes 282
Hastelloy-X
Haynes 188
Stellite 6, 21, 31
C-276
Waspalloy

Refractory
Tungsten
C-103
Tantalum

Aluminum
AlSi10mg
A205
F357
6061 / 4047

Stainless and Steel
SS 17-4PH
SS 15-5 GP1
SS 304
SS316L
SS 420
CoCr
Tool Steel (4140/4340)
Rene80
Invar
SS347

Copper-Alloys
GRCop-84
C-18150
Pure Cu
C-18200
GRCop-42
Glidcop

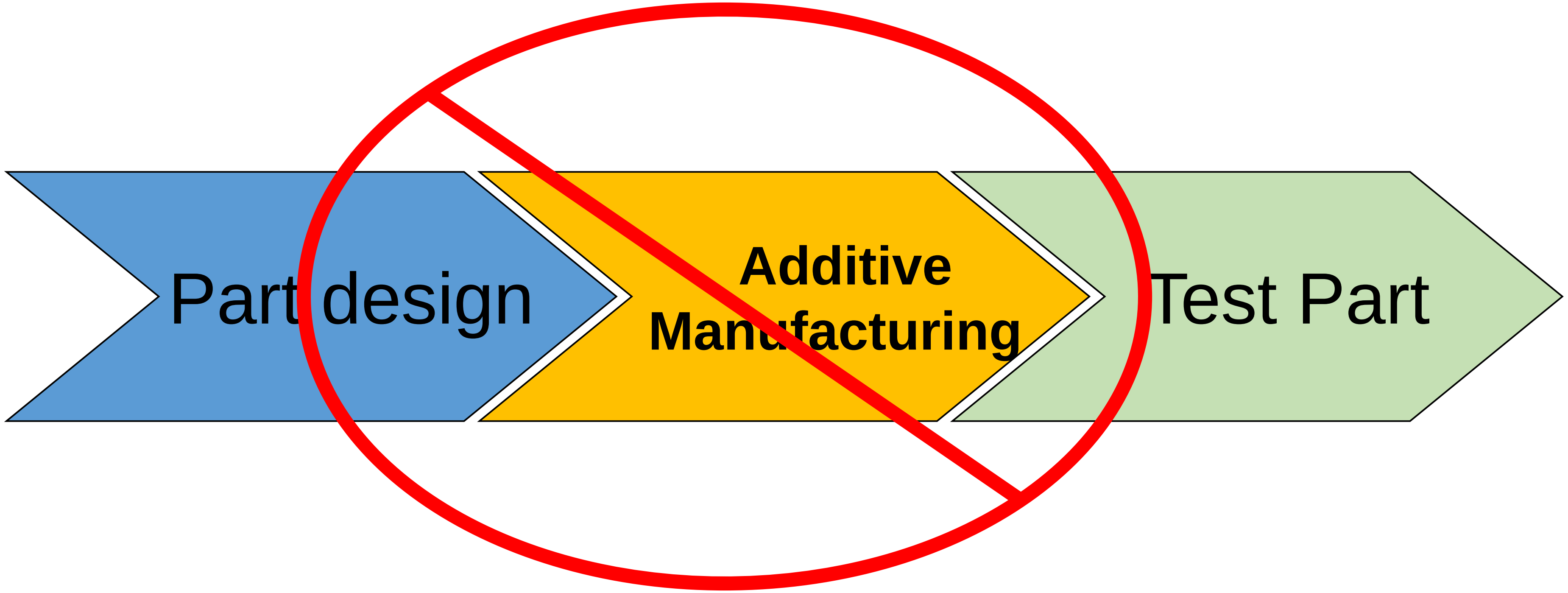
Developmental
Al-MMC
Steel-MMC
Ni-MMC

Titanium
Ti-64Al-4V
Gamm-Ti-Al
Ti-6-2-4-2

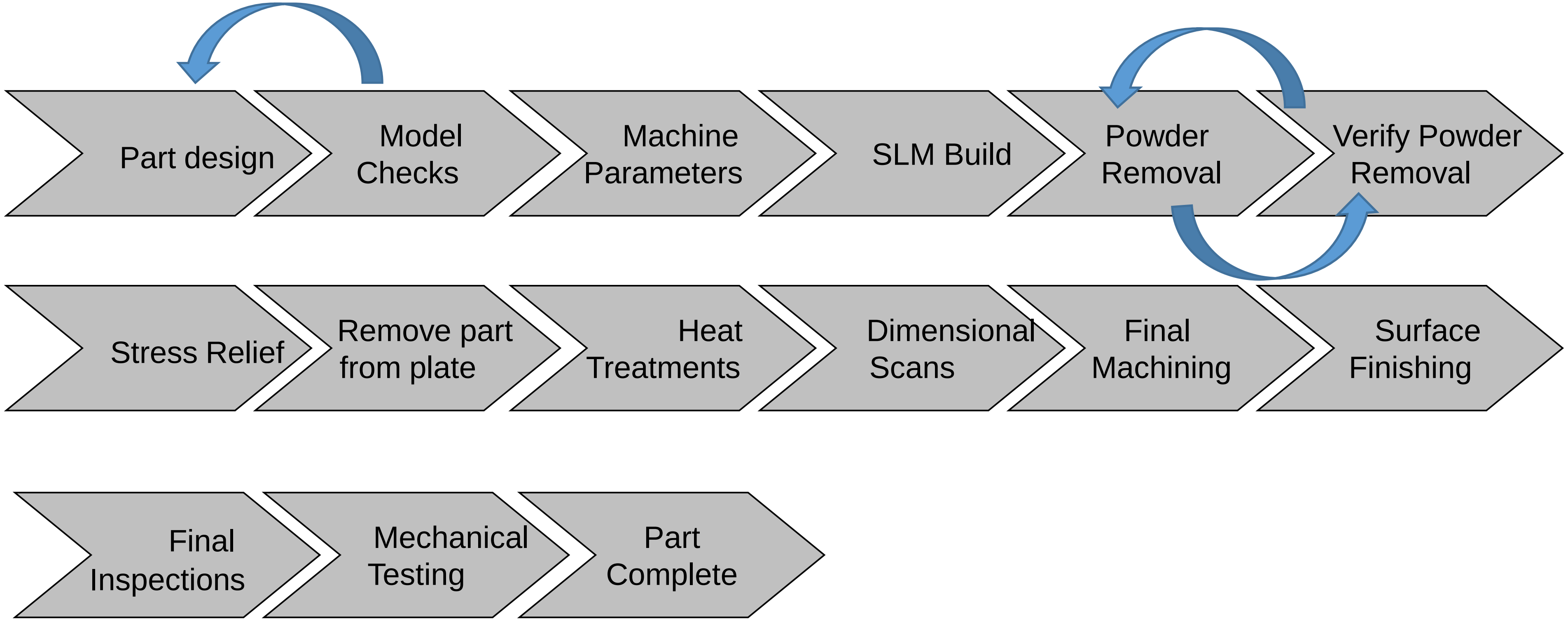
Bimetallic and Multi-metallic
GRCop-84/Inco 625
C-18150/Inco 625

*Not an inclusive list

Perceived Process Flow for AM



Actual Process Flow



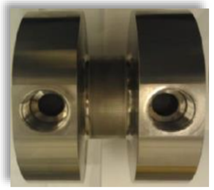
Each process step also includes a series of additional tasks in order to properly design, build, or complete post-processing

Additively-Manufactured combustion chambers

- MSFC has developed over 10 unique AM chambers between 2013-2018
  - Materials: Inco 625, Inco 718, GRCop-84, C-18150, Monel K-500
  - Propellants: LOX/GH2, LOX/LCH4, LOX/RP-1
  - Additive Process: SLM and SLM/DED
  - Over 110 starts and 6100+ seconds of hot fire test .
- Chambers have been fabricated using SLM powder bed AM technique, with a few test articles incorporating DED techniques for a bimetallic end product.

2013 – 2015 | 2016 | 2017 | 2018

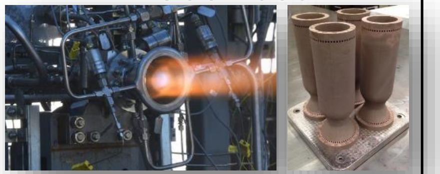
Feasibility Hardware



1.2K Workhorse
2365 sec

META4
26 sec

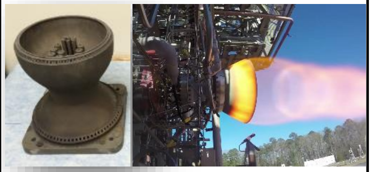
1.2K Commercial Liners
2500+ sec



MET1
25 sec

LOX/RP1 Faceplate
25 sec

LCUSP 2.2
102 sec



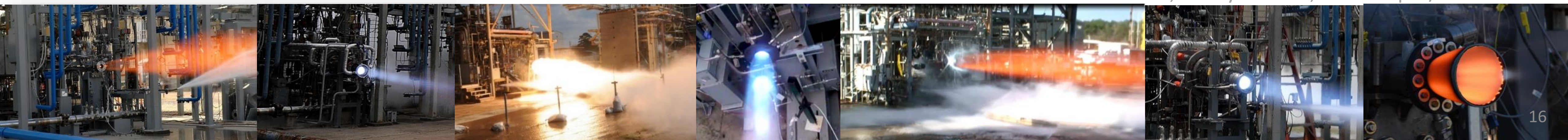
LCUSP 3.0
45 sec

META4 #2
134+ sec

Examples of Chambers

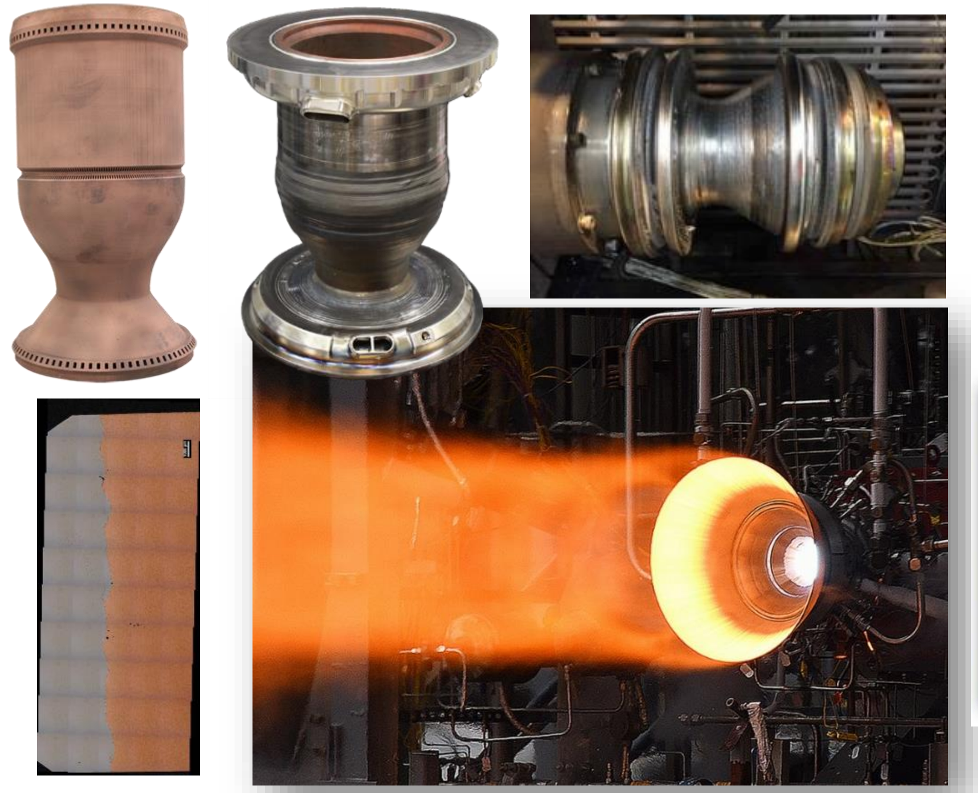
- Additive manufacturing is enabling materials that were historically difficult to process or expensive
  - GRCop-84 (currently working with GRCop-42, C-18150)

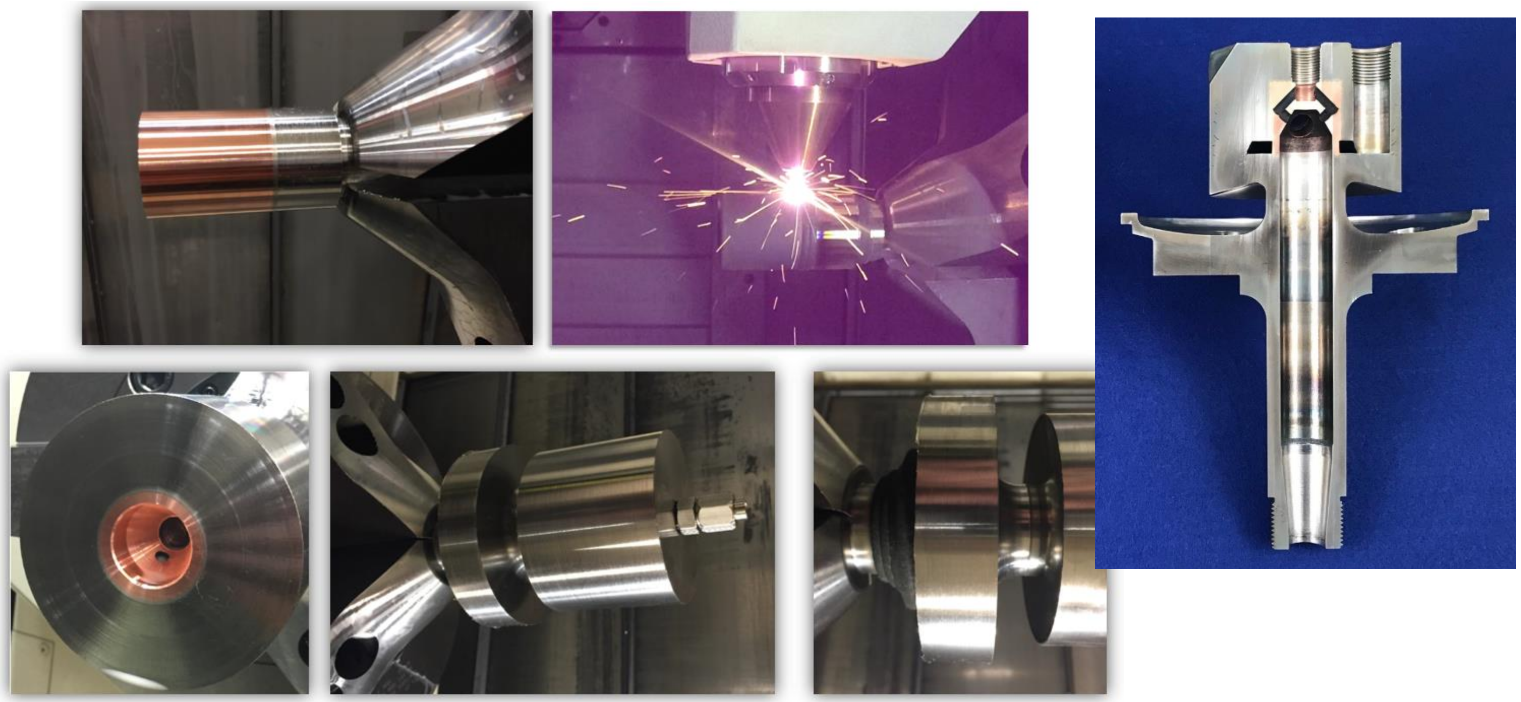
Ref: Chris Protz, Sandy Greene, Ken Cooper/ NASA MSFC



Bimetallic Components using Additive

- NASA has developed bimetallic combustion chambers using Copper-alloy liners and Inconel structural jacket (GRCop-84 to Inco 625)
  - 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 Inco 625)



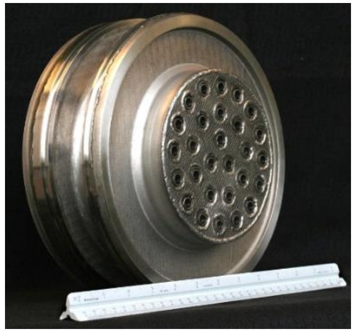


Ref: Chris Protz, Robin Osborne / NASA MSFC

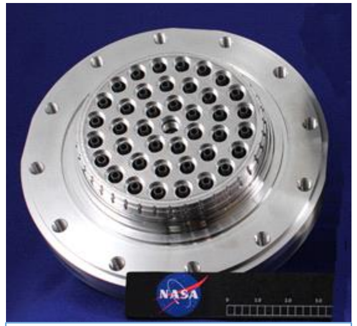
Examples of Injectors

100lbf LOX/Propane Nanolaunch Injector. Built 2012. Tested 2013.

1.2K LOX/Hydrogen Injector First Tested in June 2013. >7200 seconds hotfire

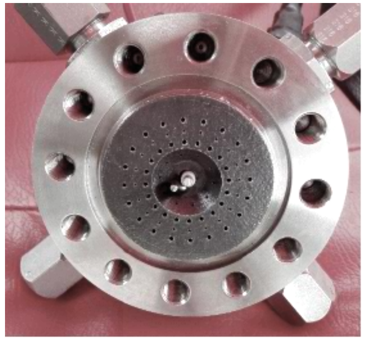


20K LPS Subscale Injector. Tested August 2013



Methane 4K Injector with printed manifolds, parametric features. Tested Sept 2015.

35K AMDE Injector with Welded Manifolds, Tested 2015



LOX/Methane Gas Generator Injector, Tested Summer 2017

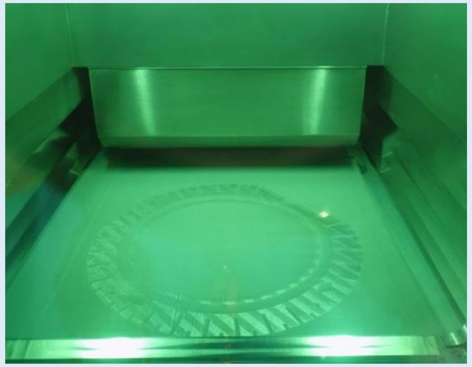
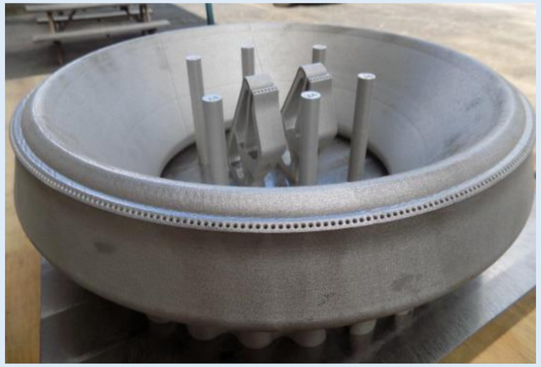
- MSFC has developed a total of 10 unique AM injectors between 2012-2018
  - Materials: Inco 625, Inco 718, Monel K-500
  - Element Types: swirl coax, shear coax, FOF
  - Number of Elements: ranging from 6 to 62
  - Diameters: ranging from 1.125” to 7.5”
  - Hot fire tests performed on 7 of these 10 AM injectors
- To date, all MSFC injector designs have been manufactured with a powder-bed process.
- Advantages of AM application to injectors:
  - Reduction of reducing part count, braze/weld operations, cost, and schedule
  - Allows non-conventional manifolding schemes and element designs
- Challenges of AM fabrication of injectors:
  - Feature size resolution (particularly radial to the build direction)
  - Excessive surface roughness
  - Removing powder prior to heat treatments (even stress relief) is both necessary and challenging

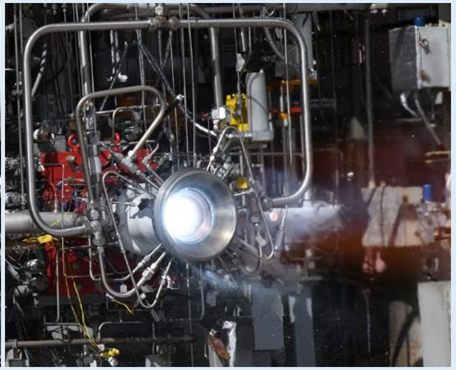
Ref: Brad Bullard, Jim Hulka, Sandy Greene, Greg Barnett, Jessica Wood

Examples of Nozzles

Selective Laser Melting

- Diameter is limited
- High resolution features
- Slow deposition rates

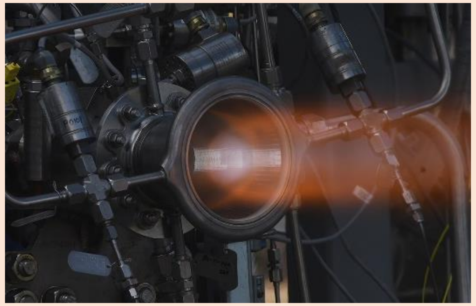





Directed Energy Deposition

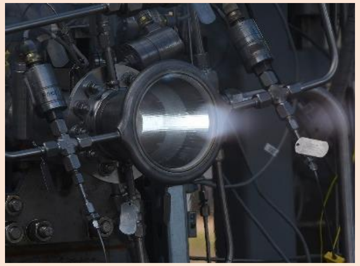
- Scale is not limited
- High deposition rates
- Loss of resolution (compared to SLM)
- (3) DED techniques being evolved
- Potential for casting and forging replacements

Laser Wire Deposition

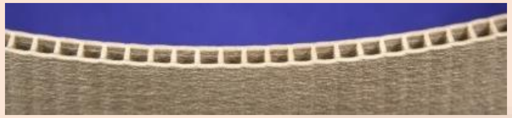
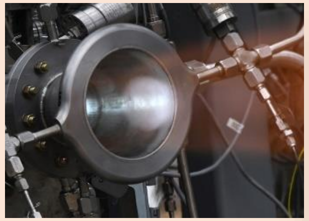
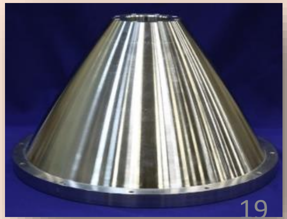
Arc-Wire Deposition



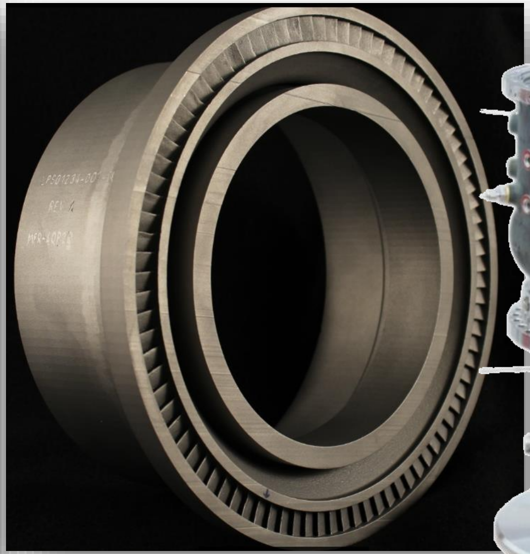
Blown Powder Deposition

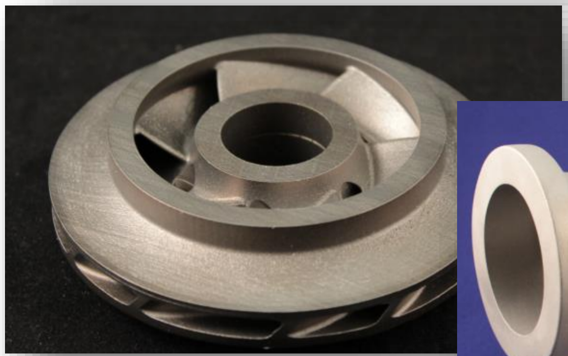


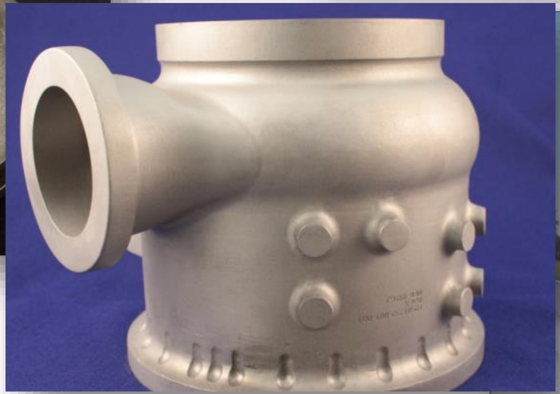




Low Cost Upper Stage Propulsion

Examples of AM Turbomachinery





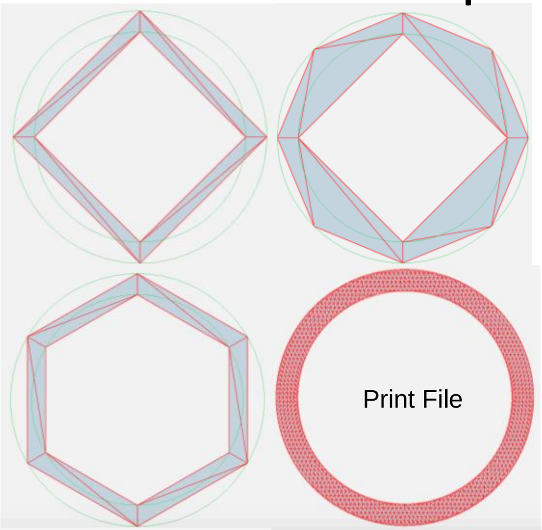


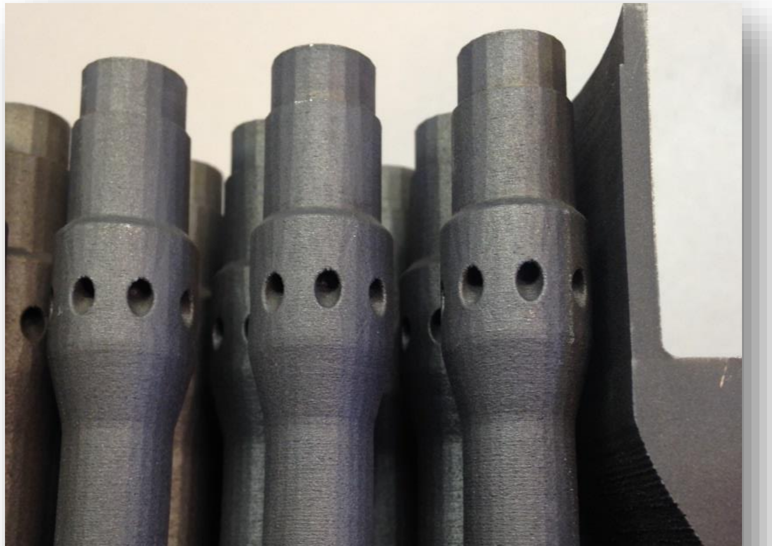
Ref: Derek O’Neal,
Marty Calvert / NASA MSFC

Basic Consideration in Design and Printing

- The printer is going to (attempt to) print geometry based on the CAD model
- Most 3D printers use .stl files (stereolithography)
  - .stl files are flat triangles used to approximate CAD geometry
  - The .stl file is sliced into layers to generate the laser toolpath / code
- Have observed significant differences in surfaces, although based on geometric features
- Finer resolution files are significantly larger and machines can be limited on toolpath code

Same CAD file with different export parameters





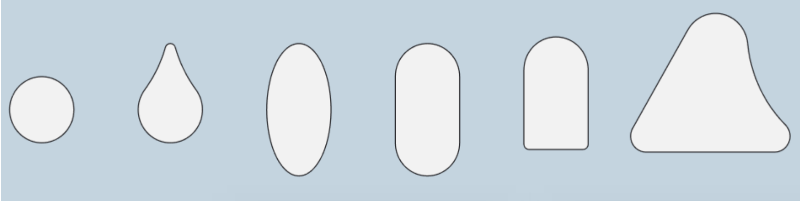
Example of injector elements with facets

Ref: Will Brandsmeier, Kevin Baker, Dwight Goodman

Considerations in Design in Printing

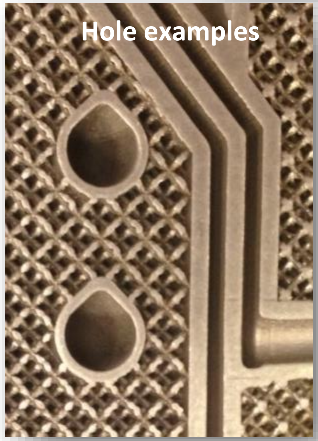
- Angled feature designs are limited (measured from horizontal)
  - Features <45° normally require support
  - Features >45° normally do not require support
  - Consider features in all dimensions
- Holes cannot be printed as true holes if larger diameter
  - Largest unsupported hole ~ .250”
  - Smallest hole/feature ~.030”
- Overhangs can be created, but require supports (and subsequent removal)

Hole design examples

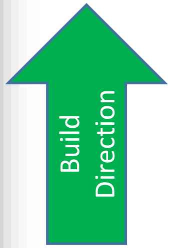


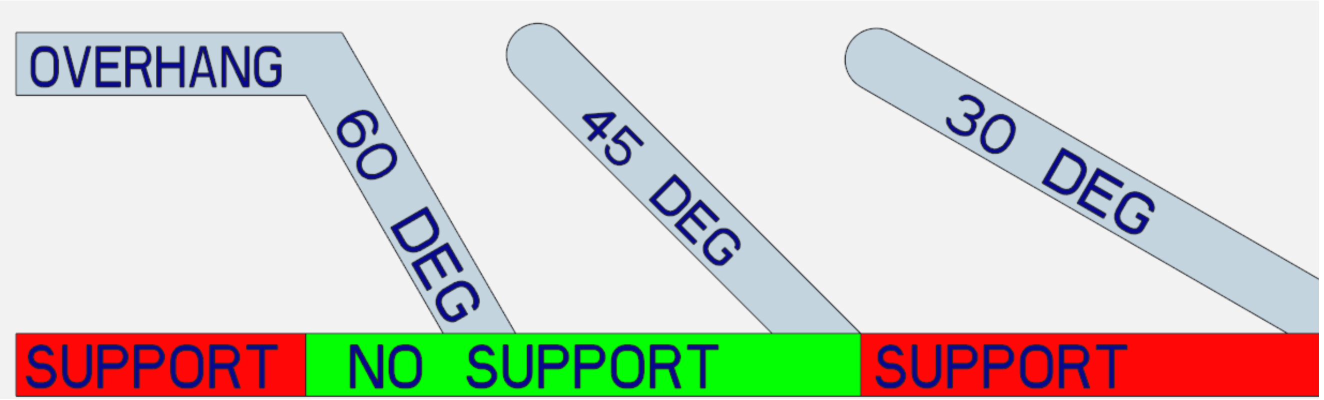

Manifold design


Hole examples


Hole examples


Design support needed for flange

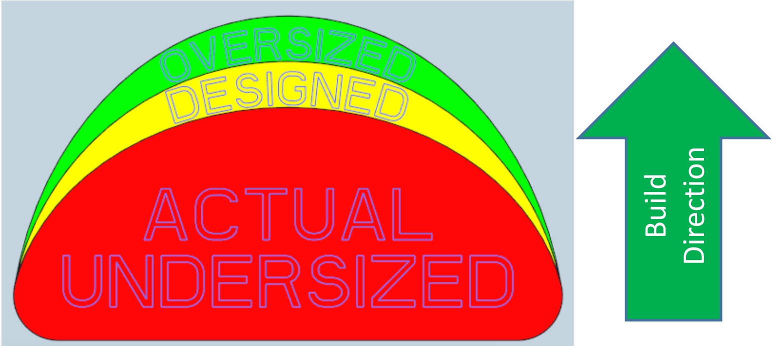




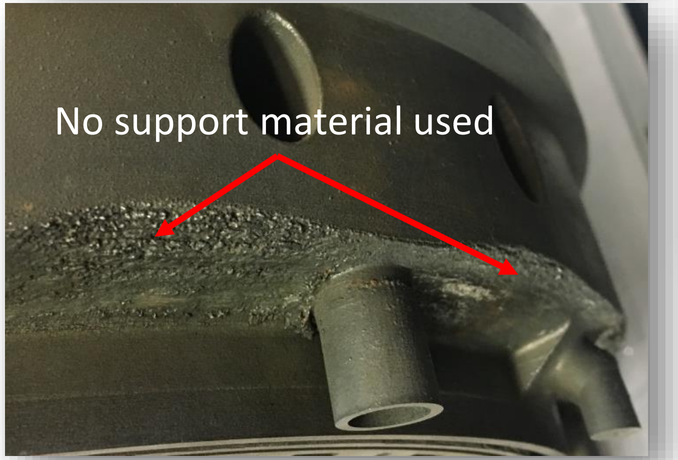
Angled wall design example

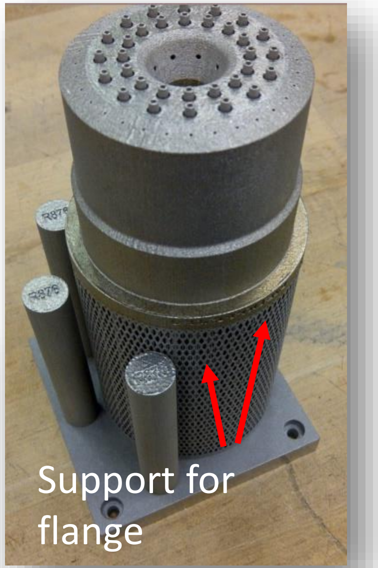
Considerations in Design and Printing

- Design and analysis needs to consider surface finishes for internal and external features
- Internal passages may need to be oversized to account for burn-thru or undersized hole
- Support material should be understood in design phase
  - Placement of support material is important
  - How support material is removed is equally important
  - Ask your operator or vendor
  - Support material highly dependent on print orientation




Burn-thru on "roof" feature

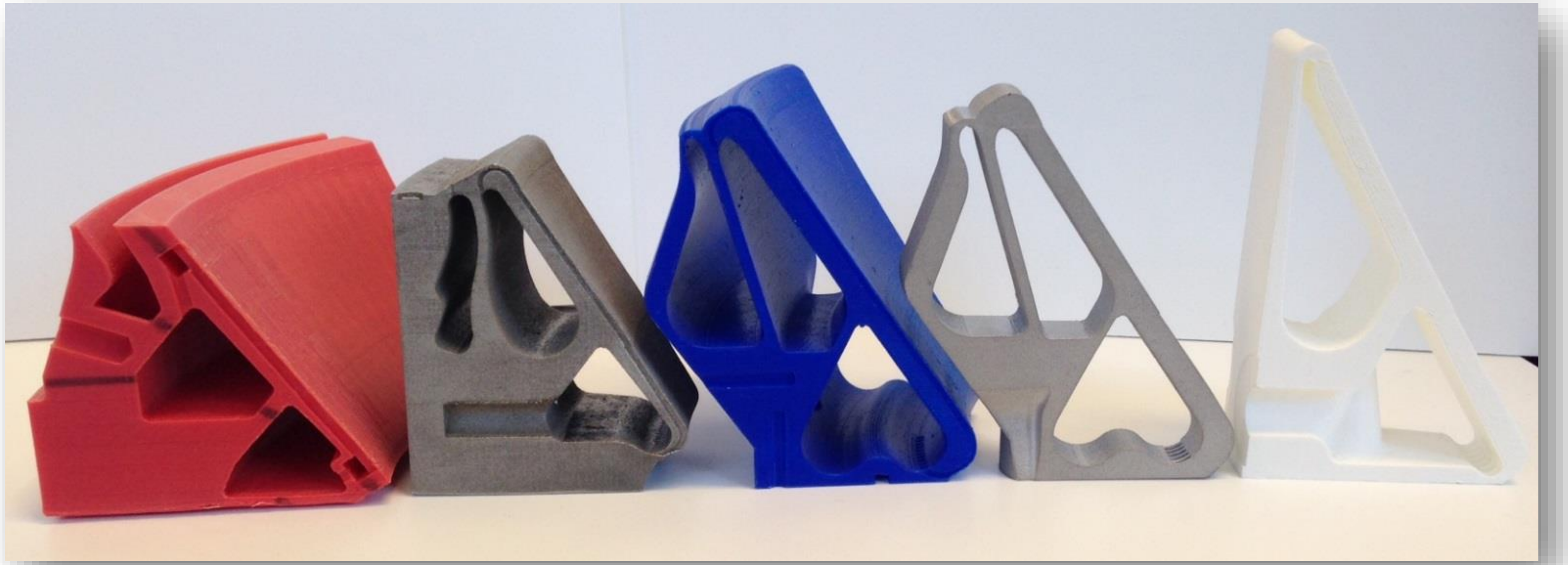

No support material used


Support for flange

Ref: Will Brandsmeier, Kevin Baker, Dwight Goodman / NASA MSFC ER34

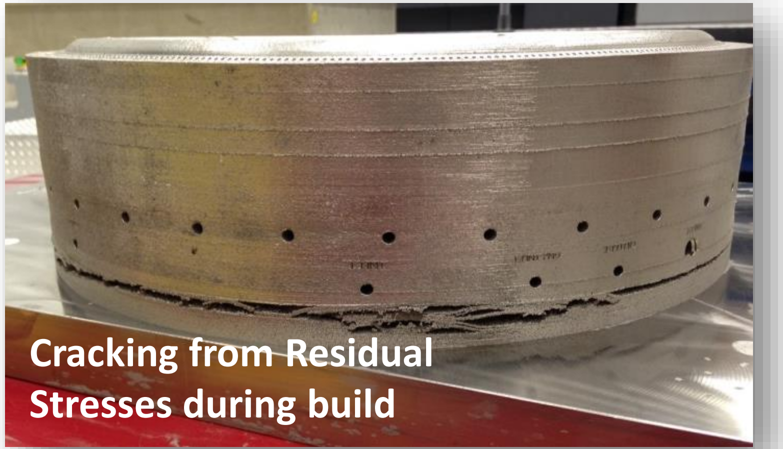
Considerations in Design and Printing

- Print orientation is critical – evolve the CAD design with AM machine operator or vendor
  - Print orientation is not always obvious; supports may be minimized in a complex angled orientation
- Print volume should be considered
  - Bolt holes required for the build plate
  - Build plate (~1” thick) takes up part of the build height
- Test print in plastic during design phase
  - Inexpensive method to identify issues with design and model
  - Determine design issues, bad design features and actual feature issues can be resolved with test prints



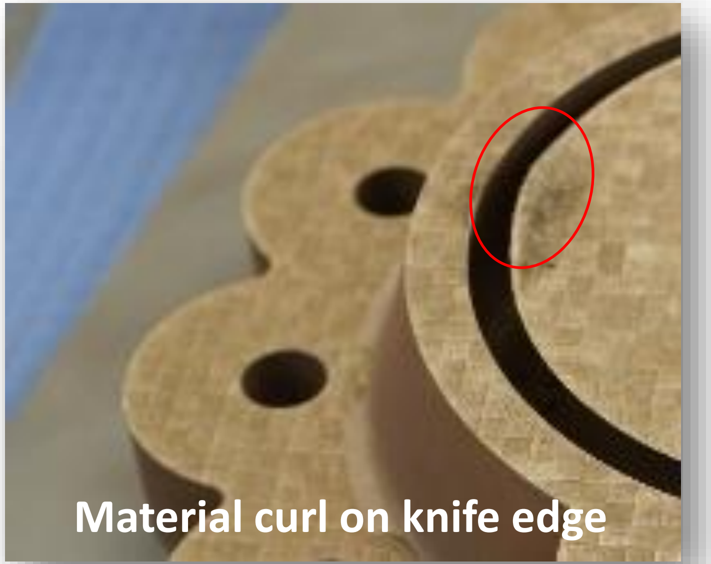
Considerations during Pre-processing and Printing

- Heat control is critical and can cause significant deformations or failures
  - May be driven by original design (too thick or thermal gradients too high across varying cross sections)
  - May be impacted by adjacent parts or witness specimens
- Material curl caused by coater arm damage
  - Based on knife edges during design
- Stops and starts are also common in 3D prints, causes knit lines
  - Refill of powder in dose chamber
  - Issue observed that requires visual



Cracking from Residual Stresses during build

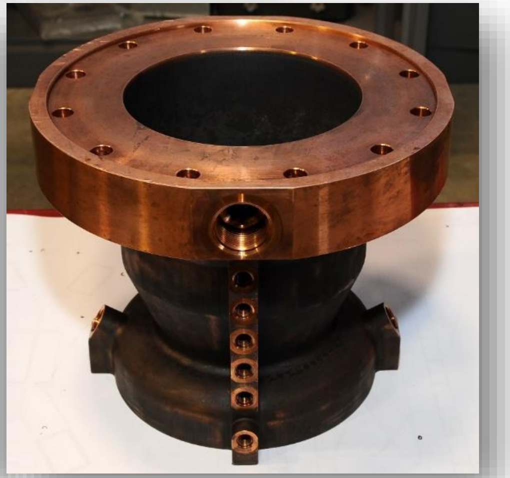
Knot line observed post-build



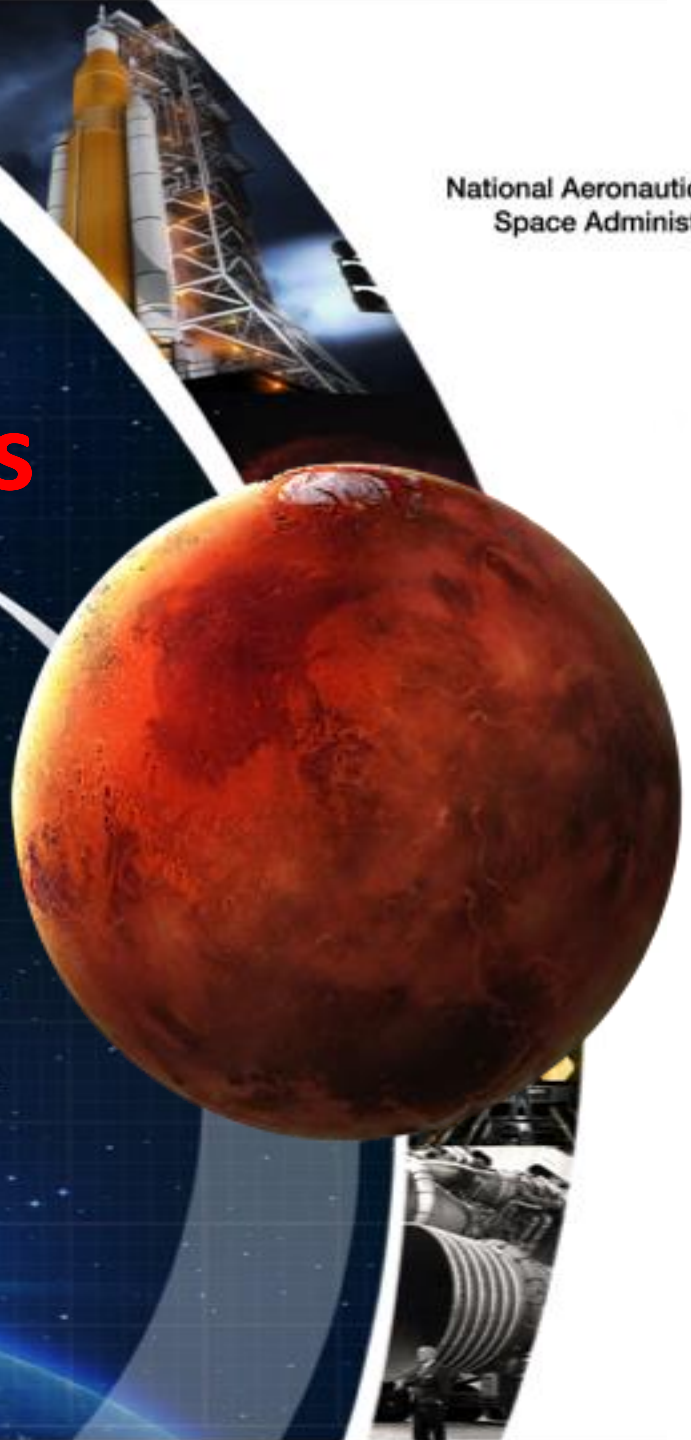
Material curl on knife edge

Considerations during Design and Post-Processing

- **Geometric Dimensioning and Tolerancing (GD&T) needs to be considered during design for ease of post-processing**
  - Cylinders for better positional tolerance at feature level
  - Grooved for axial location
  - Flat surfaces for datums
  - Extra holes for powder removal
  - Additional stock material for critical features that will be post-machined
- **Holes only when required or in softer materials**
  - Existing printed holes can cause machine tools to "walk"
  - Do not print threads; post-machine
  - Undersize holes for reaming and tapping



Intro to Additive Manufacturing for Propulsion Systems



National Aeronautics and Space Administration

SOUTHWEST RESEARCH INSTITUTE

AIAA Joint Propulsion Conference
July 9-11, 2018

Omar Mireles
Paul Gradl
NASA Marshall Space Flight Center (MSFC)
Nathan Andrews
Southwest Research Institute

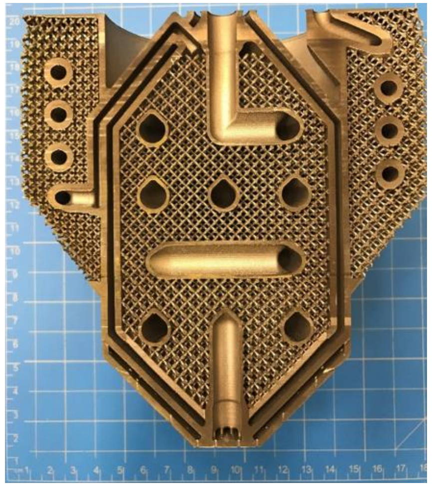
Propulsion Energy and Forum 2018

Additive Manufacture (AM)

- NASA AM Objectives
  - Design optimized components & test at relevant conditions
  - Decrease production lead time & costs
  - Develop Flight Certification Standards
- Appropriate Application
  - High complexity & difficult to manufacture
  - Low production rate
  - Long lead time & 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

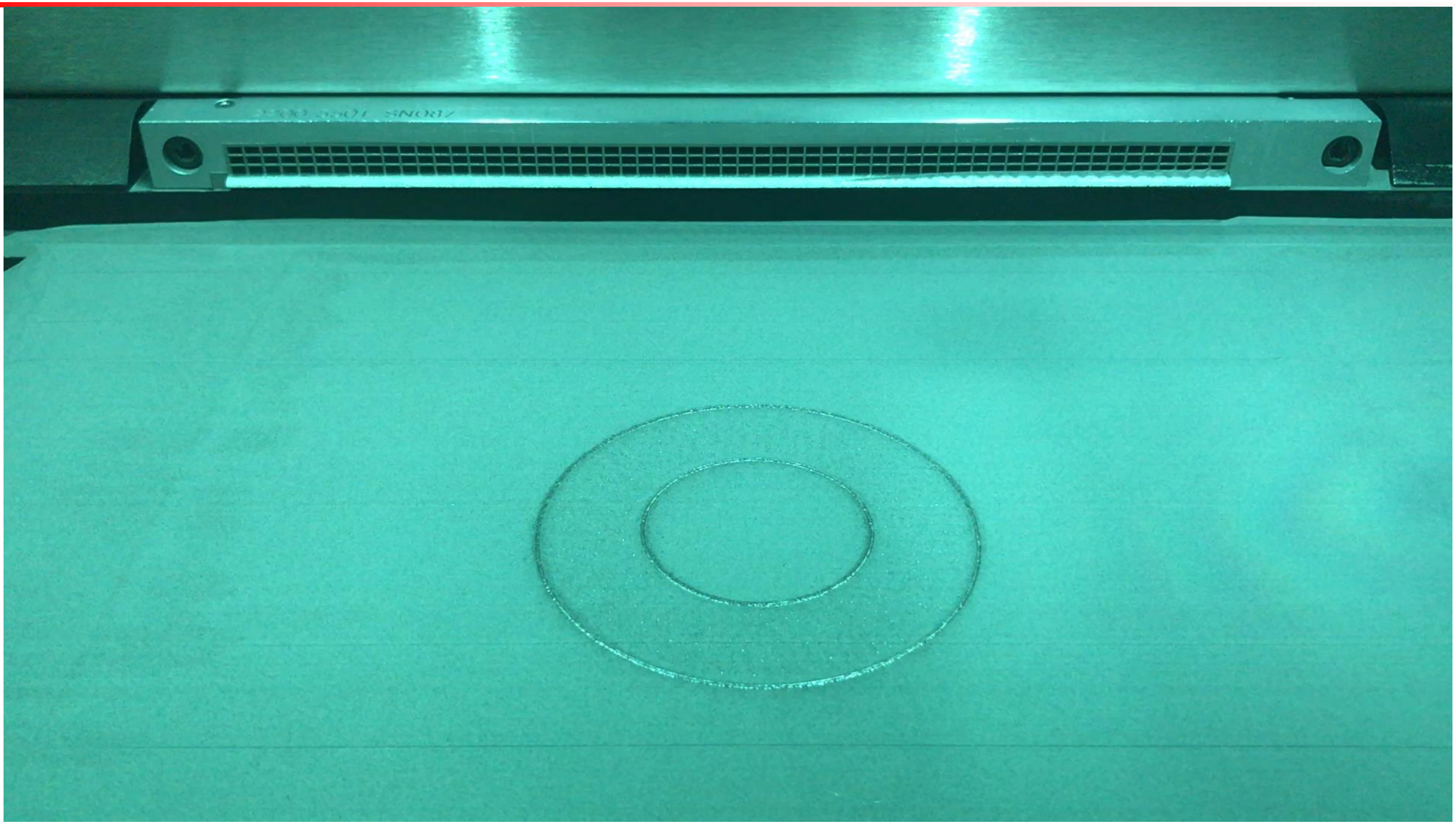
- Property Variability
  - Properties dependent on starting powders, parameters, and post-processing
  - Anisotropic properties in the build direction (Z)
  - Size: small-scale vs. full-scale builds
  - Build volume spatial location


Vacuumed power

COMPLEXITY IS NOT FREE

Think instead: Conservation of Complexity

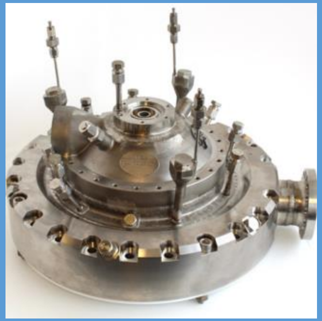
SLM Operations



EOS M290, IN718

Advantages to Rocket Engine Development

Injector
Cost Reduction by 30%
Reduced parts from 252 to 6
Eliminated braze joints
Successfully tested to 100%



Main Oxidizer Valve
Reduced parts from 6 to 1
Successfully tested

Fuel Turbopump
Schedule Reduction by 45%
Reduced parts from 40 to 22
Successfully tested - 90,000 RPM

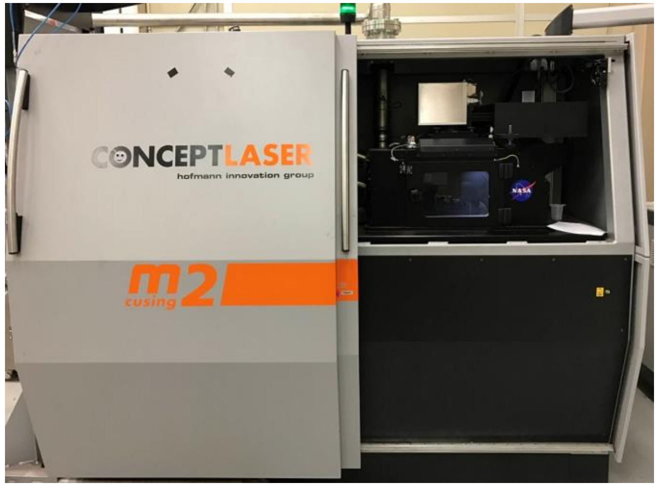
Main Fuel Valve
Reduced parts from 5 to 1
Successfully tested

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

Oxidizer Turbopump
Reduced parts from 80 to 41
Currently being tested

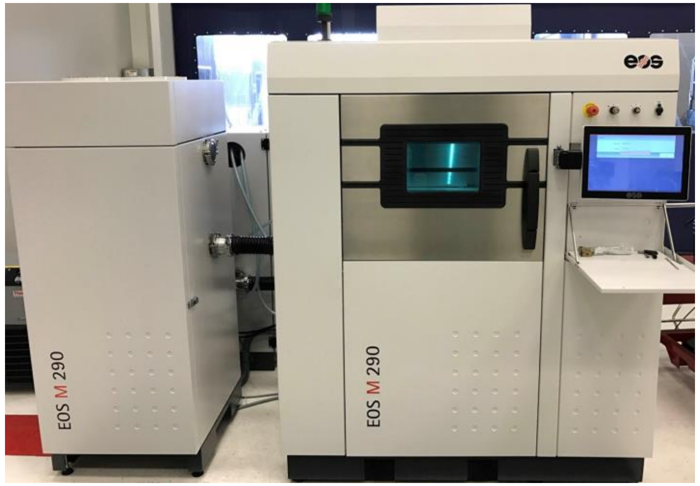
Cost Data Courtesy Graham Nelson

MSFC Metal AM Machines

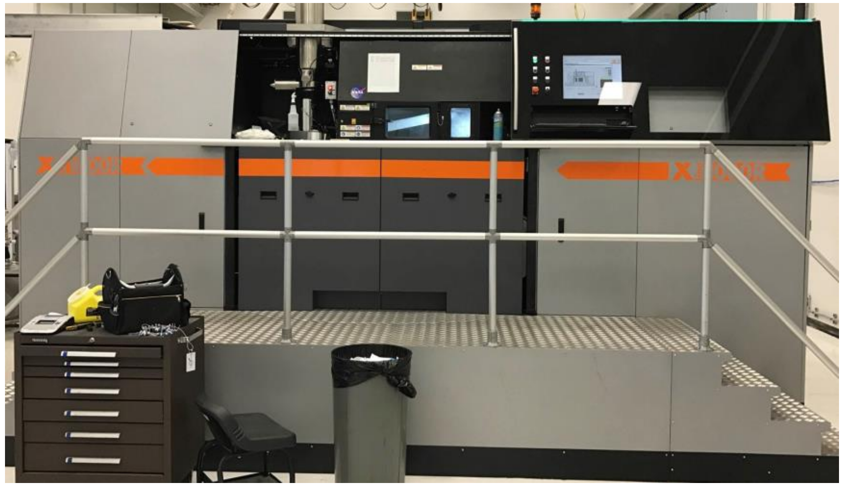


Concept Laser M2
250x250x280 mm
Power 400 W
Laser Diameter: 70 µm
Material: GRCop84, GRCop42

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.

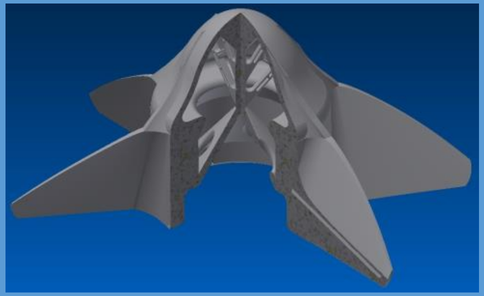


Concept Laser X-Line 1000R
630x400x500 mm
Power 1000 W
Laser Diameter : 70 µm
Material: IN718

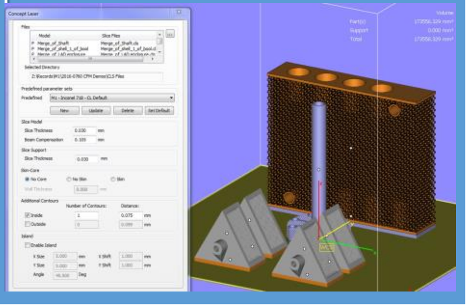
EOS M100
Ø100x95 mm
Power: 200 W
Laser Diameter: 40 µm
Material: Ti64, 316L, CoCr, W, Haynes 230.
In-development: Monel K500, Haynes 282, Ta, W-25Re, Mo, Mo-41Re, Mo-47.5Re, C103, etc.

AM Process Flow

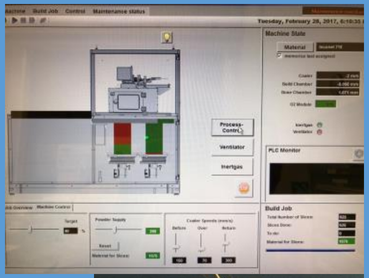
DESIGN & ANALYSIS
- Performance Requirements
-Design for AM, GD&T, export .stl

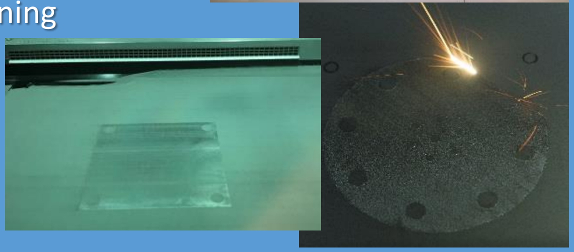


BUILD PREPARATION
- Repair .stl
- Build placement & orientation
- Thermal stress/distortion prediction
- Support generation
- Slicing
- Scan strategy

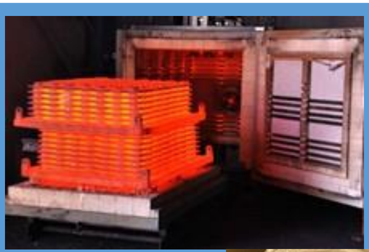


BUILD OPERATIONS
- Machine preparation
- Build via parameters
- Process Controls
- Powder refill
- Lens cleaning
- Restarts

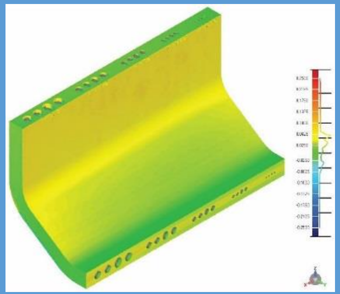




POST-PROCESS
- Powder Removal
- Stress Relieve
- Support Removal
- Plate Separation
- HIP
- Heat Treatments
- Machine/Surface mod
- Mechanical Testing



NONDESTRUCTIVE EVALUATION
- Structured light scanning
- X-ray CT
-Compare inspection models to CAD

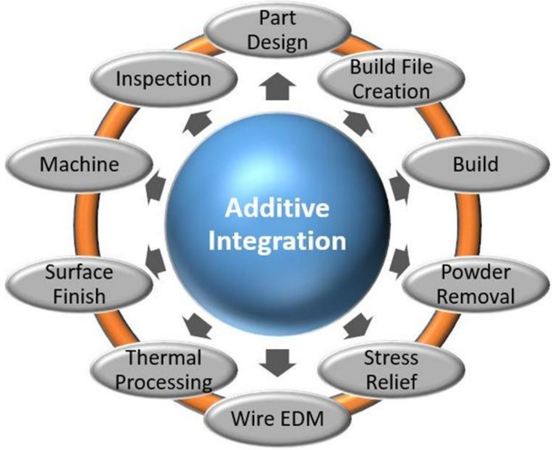


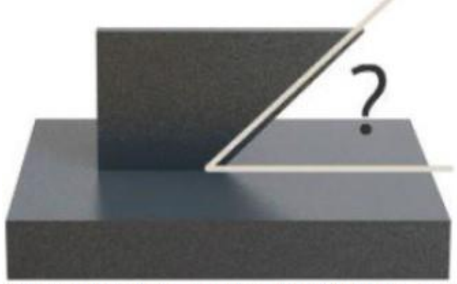
IMPLEMENTATION
- Test & post-ops inspection
- NDE / Destructive evaluation

Holistic AM Design Flow & Considerations

Courtesy Melissa Orme, Morf3D

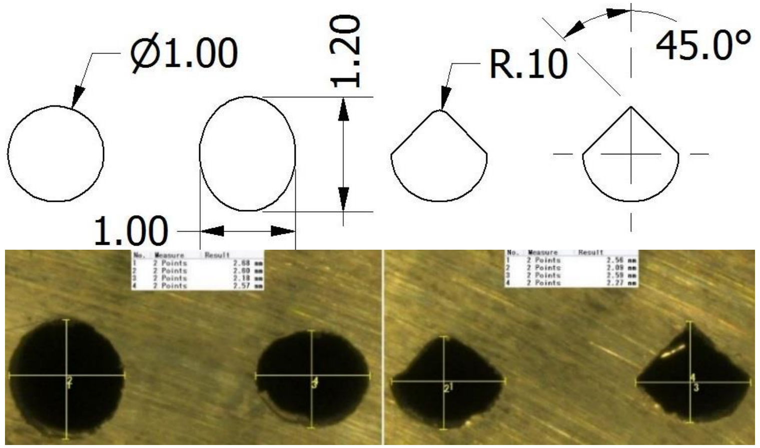
- Holes & Passages
  - Size limits (Horizontal: Min: 0.4 mm, Max: 8 mm; Vertical: Min: 0.4 mm, Max: unlimited).
  - Channel surface roughness variable on size: powder sintering for smaller OD and overhang angle for larger OD.
  - Hole sag in the Z-axis: circular hole becomes a horizontal ellipse, vertical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





The minimum angles that will be self supporting are approximately:
- Stainless steels: 30 degrees
- Inconels: 45 degrees
- Titanium: 20-30 degrees
- Aluminium: 45 degrees
- Cobalt Chrome: 30 degrees

Self-Supporting Angles



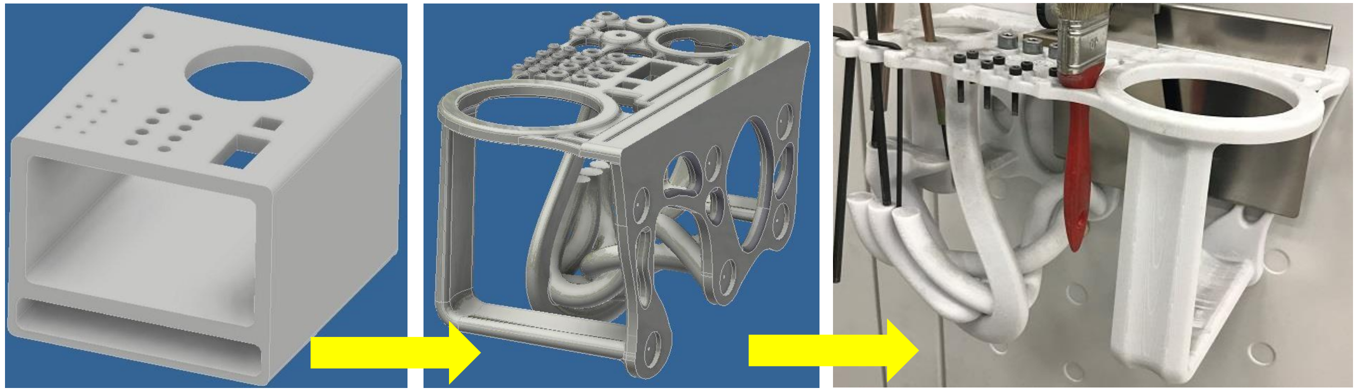
1 mm hole array micrographs (45°)

Hole size & surface roughness

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

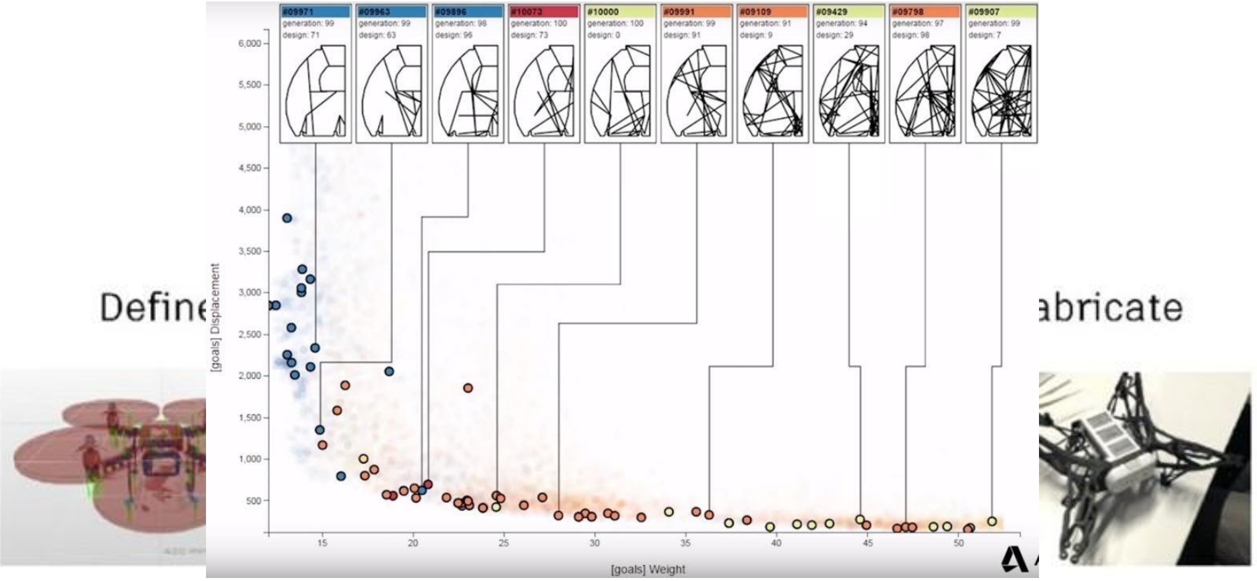
Advanced Design for AM

- 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.

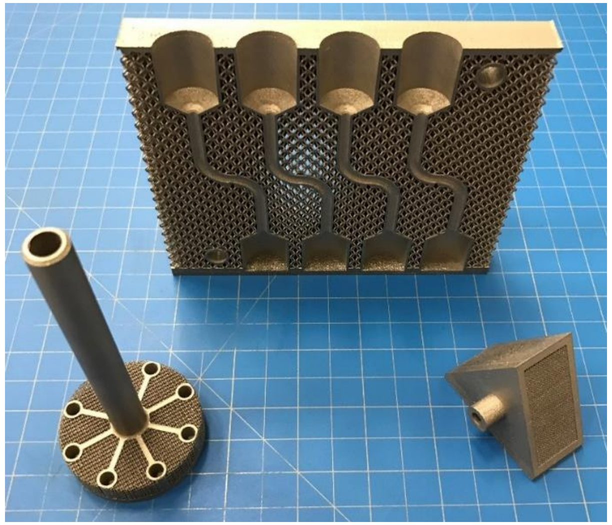
- Generative Design
  - Define interface geometries, enclosure, constraints, loads, material and FS.
  - Software generates numerous point designs and displays an an Ashby chart.
  - Select and prioritize optimized designs: mass, strength, stiffness.
  - Apply when mass and structure dominate.



Generative Design. Courtesy Autodesk.

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.

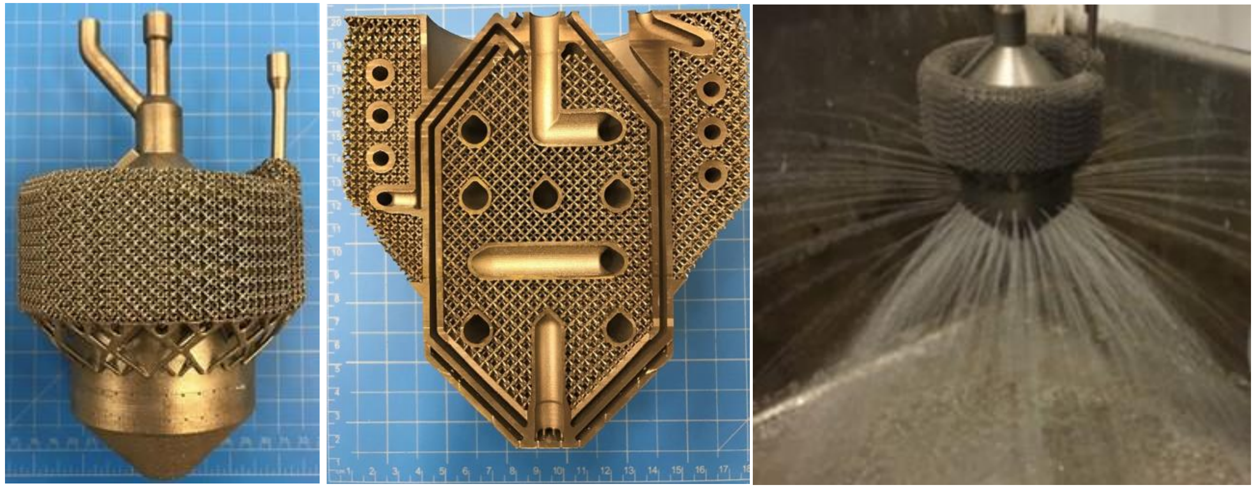


CFM Magnetically Coupled Rotor, Heat Exchanger, LAD demos

Lattice Regen Chamber Demo

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

Green Propulsion Thruster & Stand-Off

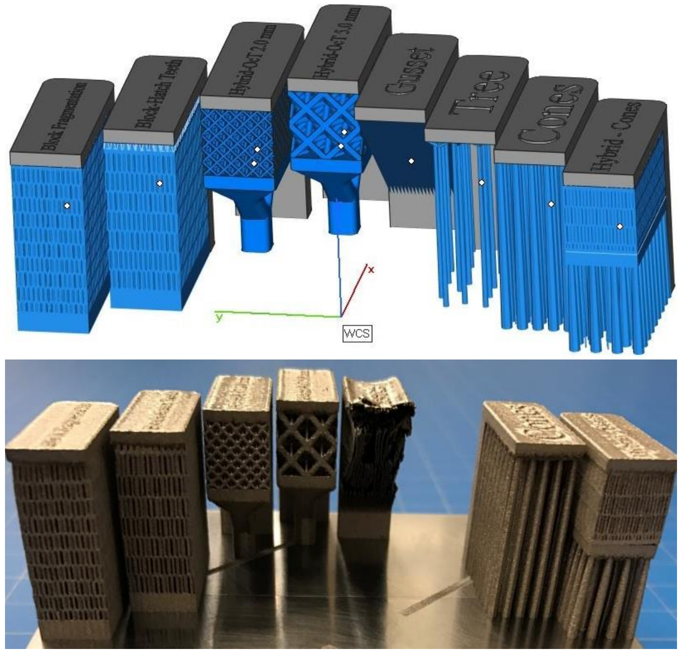


Cryo Heat Exchanger-Injector-Condenser Demo

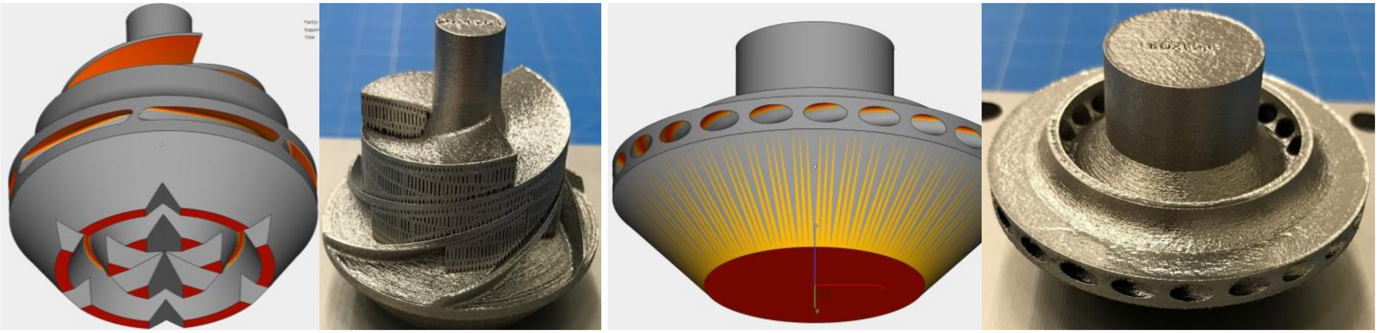
KSC O_2 Generator Cold-Head

Part Orientation, Supports, Slicing, Parameters

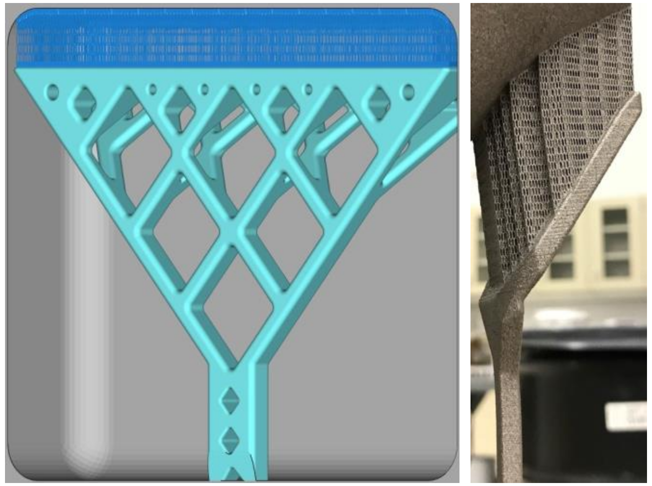
The purpose of support structures in metal AM are to hold down the part to the build plate, preventing upward distortion. Supports are sacrificial and are built to be less dense and thin.



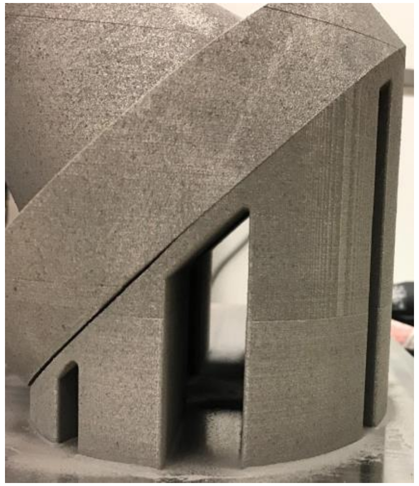
Supports examples



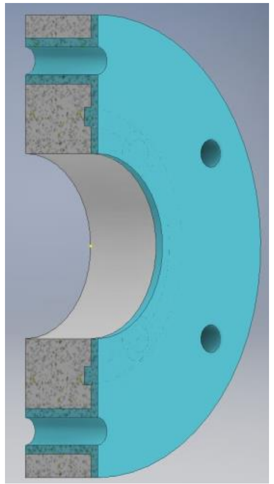
AMPed LOX Impeller Iterations vs. overhang surfaces. Courtesy Marty Calvert.



Hybrid crown & perforated block support

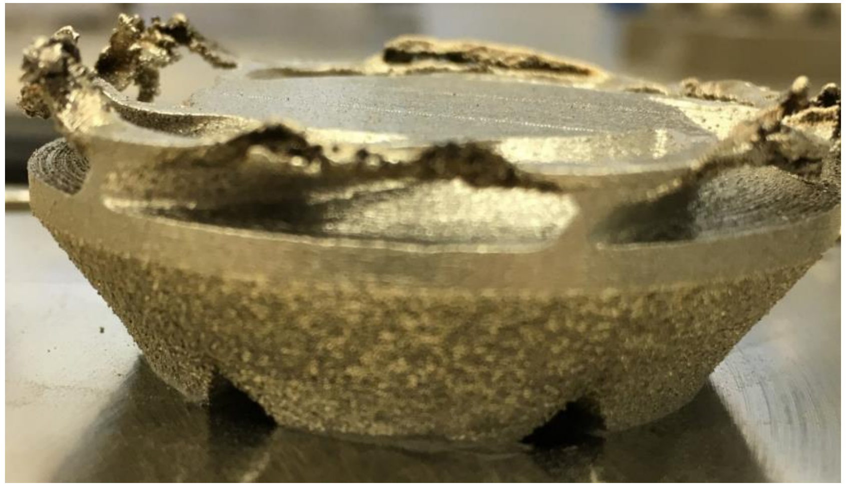


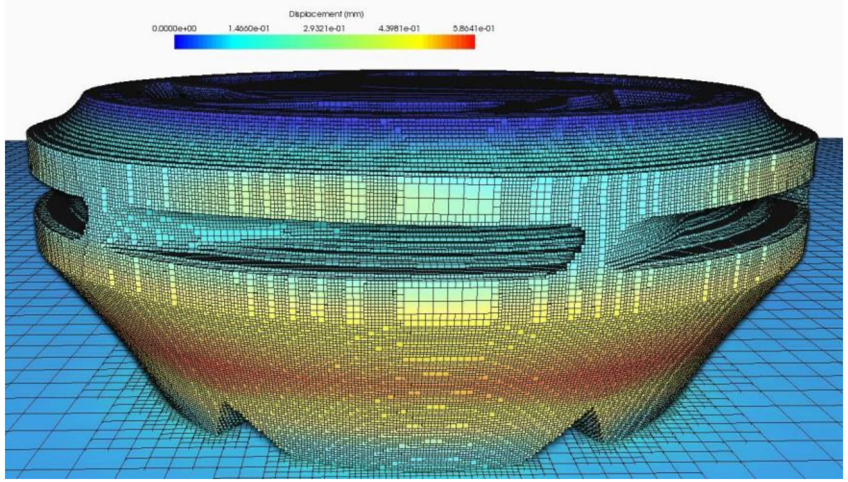
Powder Removal Features

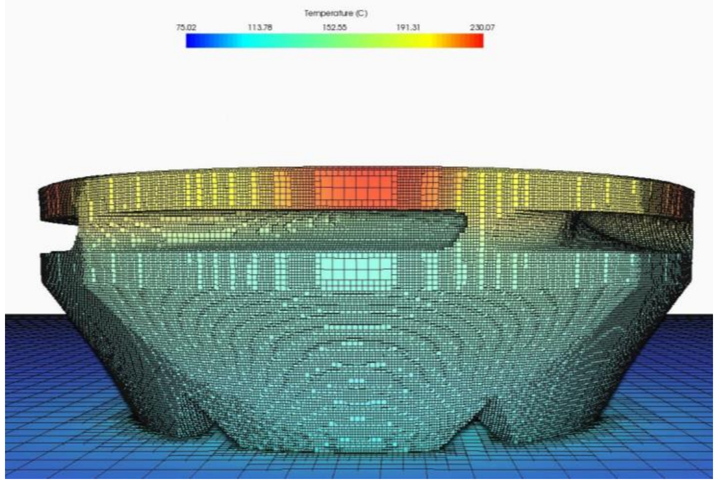


Machine interfaces

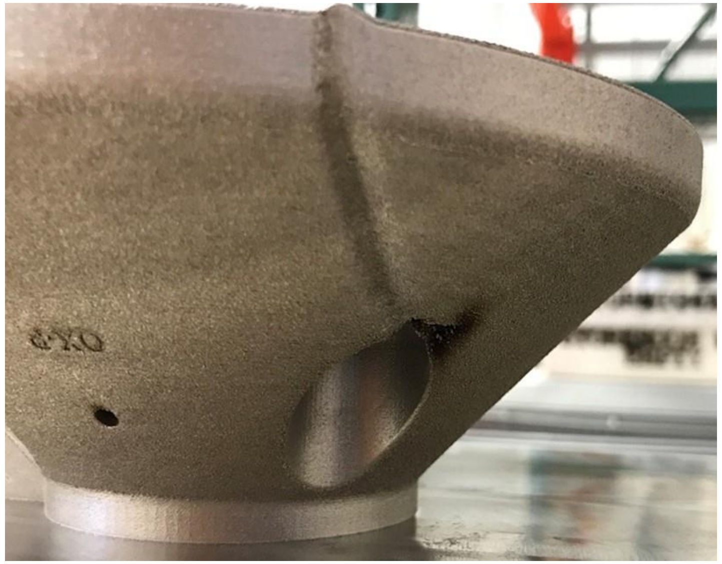
Build Simulation: Residual Stress & Distortion Failure Prediction

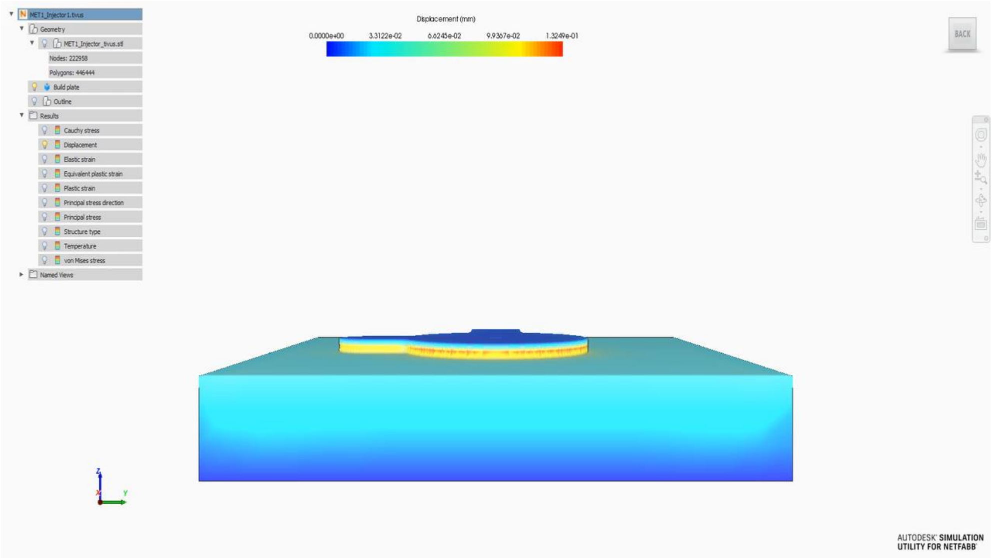






AMPd Engine LOX Impeller (Shrouded) V1 on EOS M290. Build time - $0.3k (3 hrs), Powder - $ 0.01k (0.25 kg), Saw - $0.2k, Plate resurface - $0.2k, Total - $0.71k





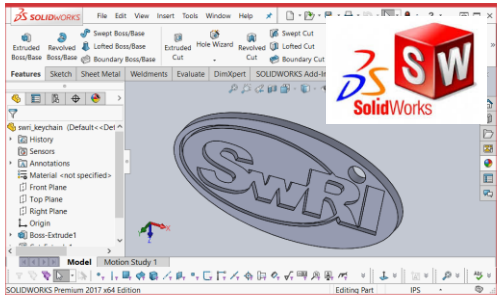
MET1 Injector V1 on EOS M290. Build time - $5.5k (55 hrs), Powder - $ 0.32k (5.82 kg), Saw - $0.2k, Plate resurface - $0.2k, Unsuccessful total - $6.22k. Successful total $6.22k. Total Cost $12.44k. 15 minute long simulation.

Printing Exercise #1

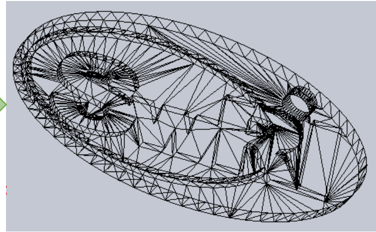
Your widget will change the world……..how can you print it?

Printing Exercise #1

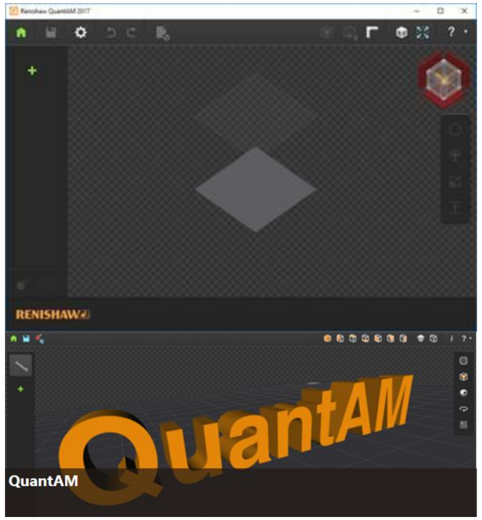
Create CAD



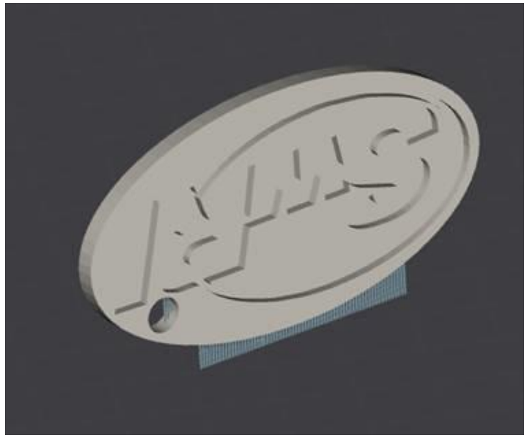
Generate STL



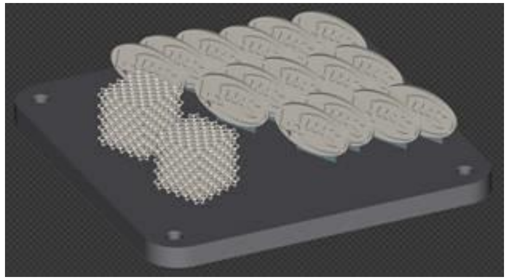
Build Software



Create Single Part Layout

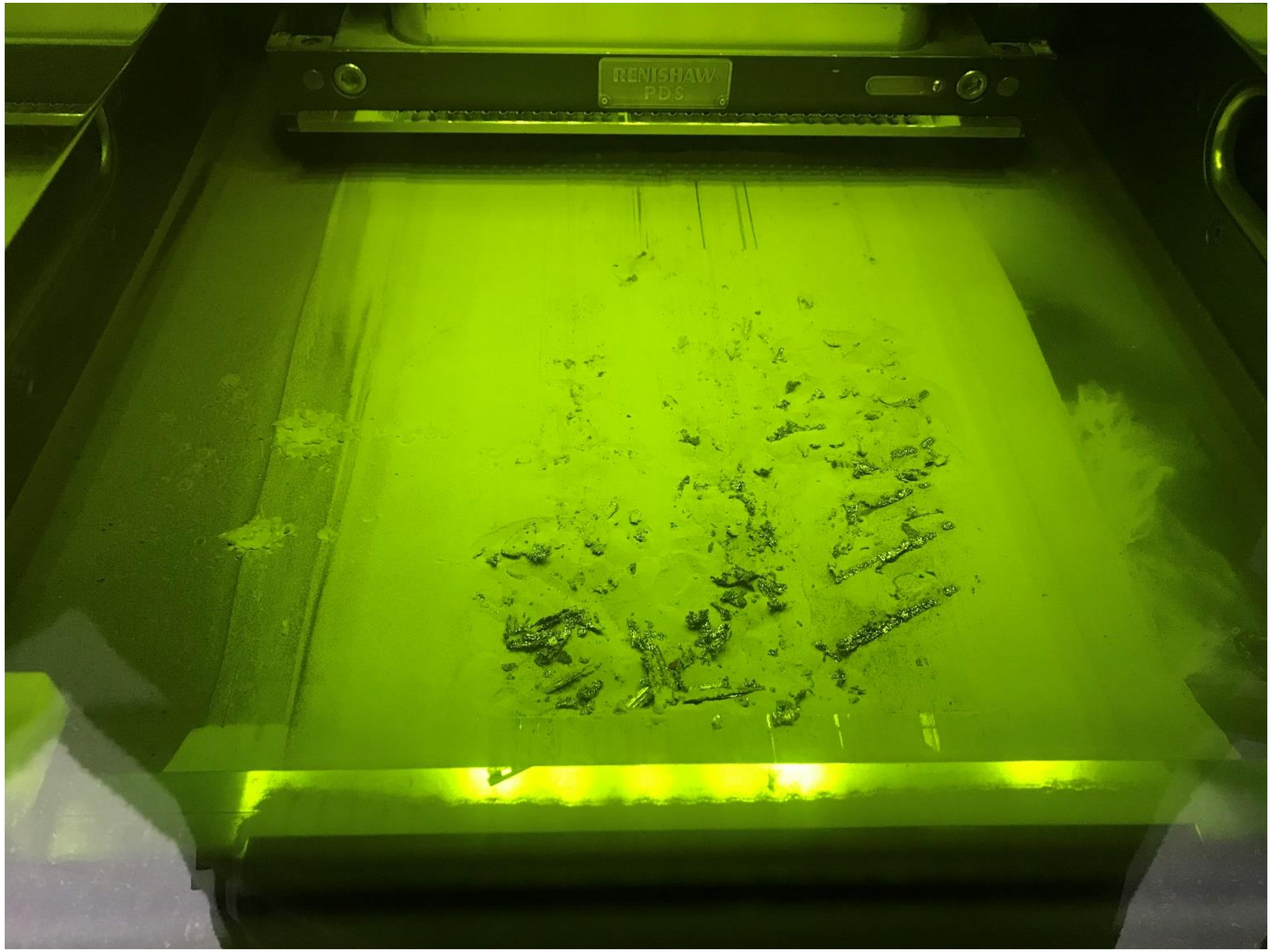


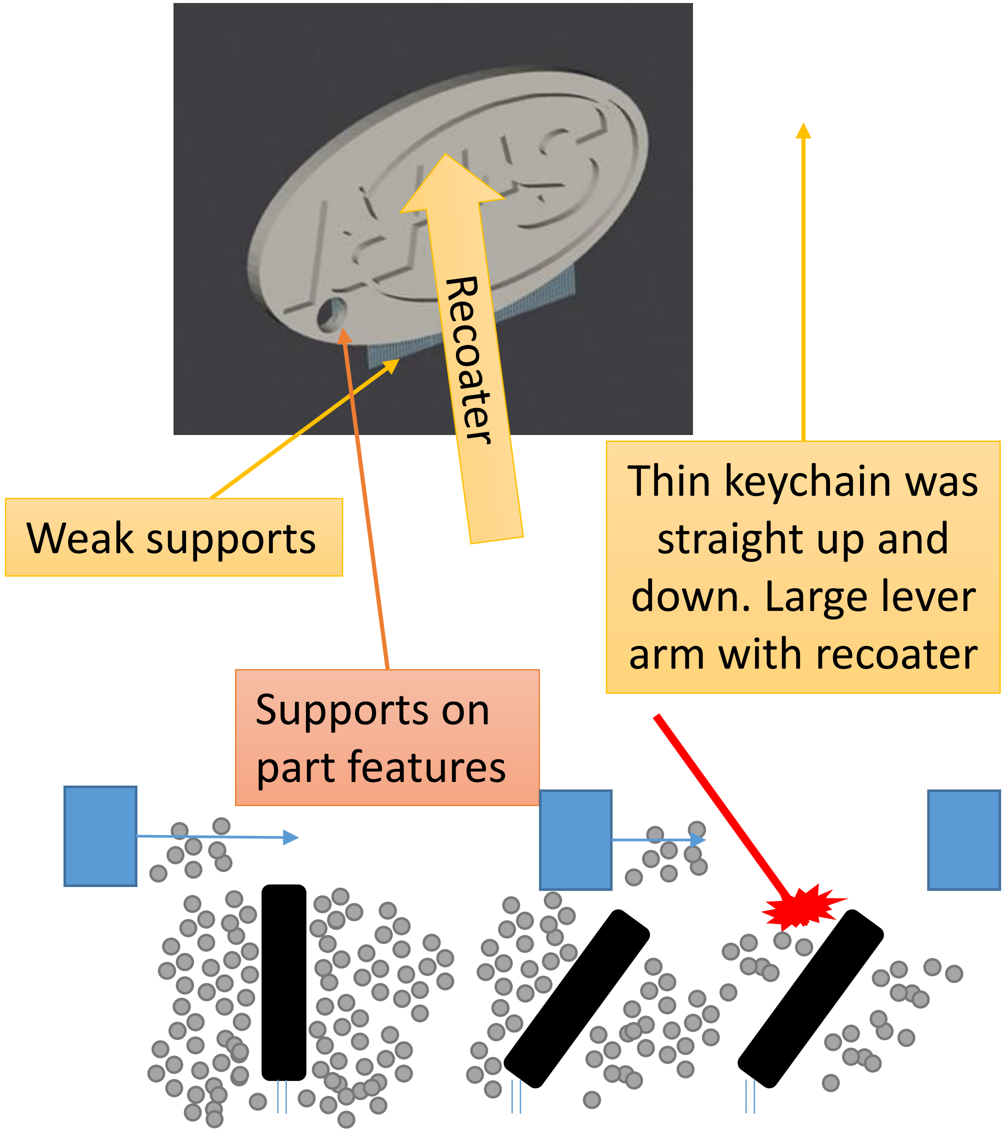
Create Build Layout



Off to the Machine!

Printing Exercise #1

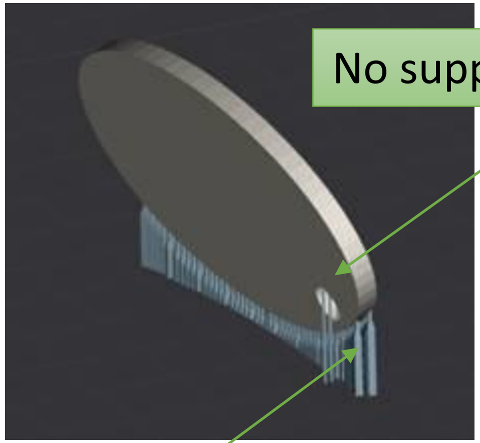




What happened?!?!

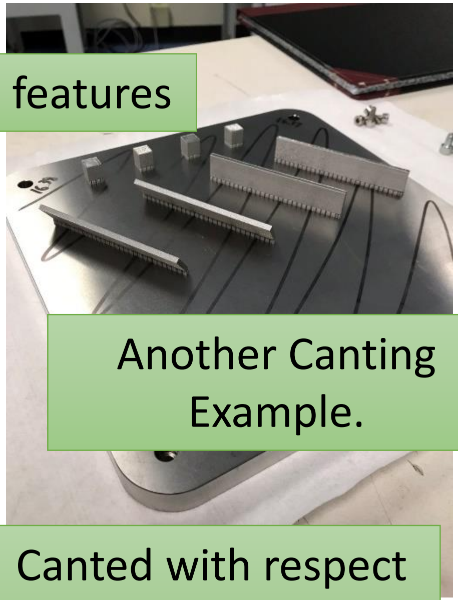
Printing Exercise #1

Improvements to build plan.

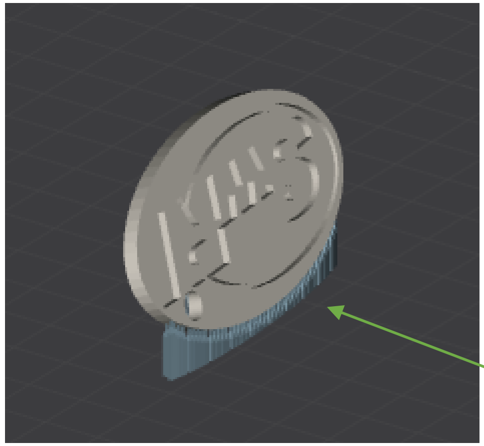


No supports on features

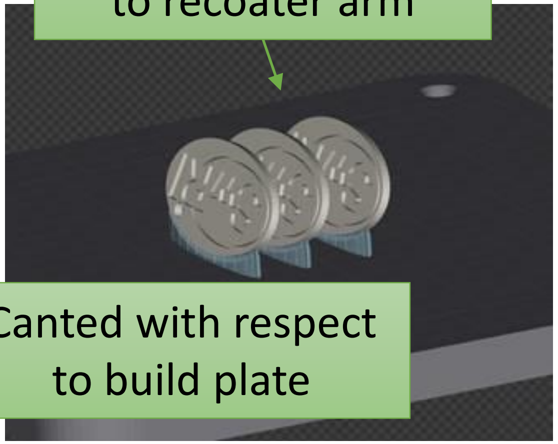
Stronger supports



Another Canting Example.



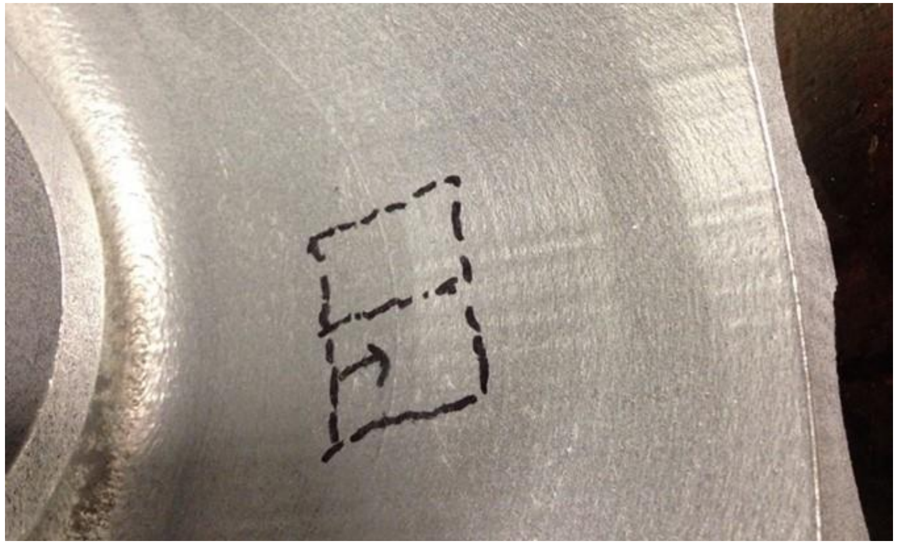
Canted with respect to build plate

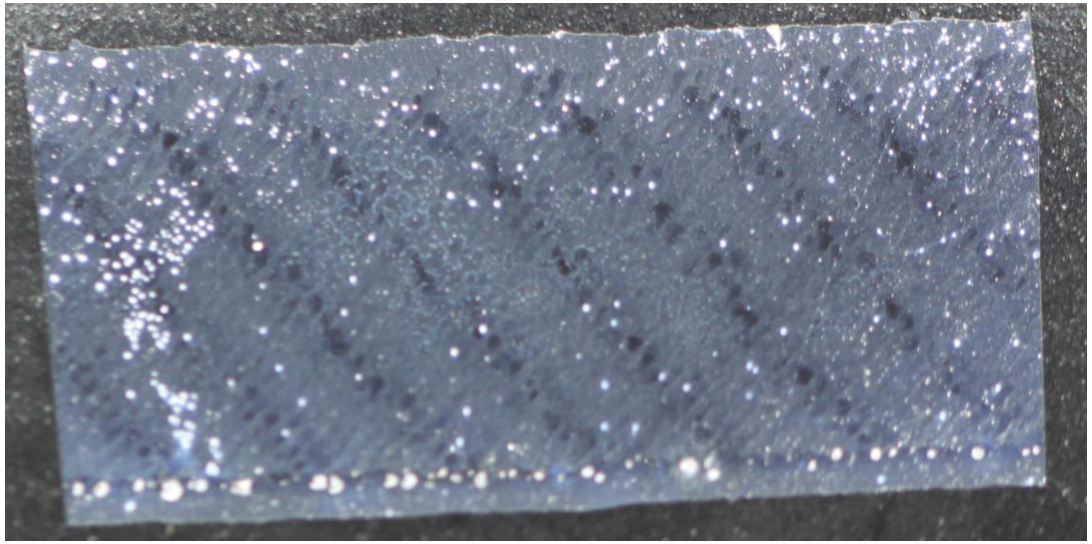


Canted with respect to recoater arm

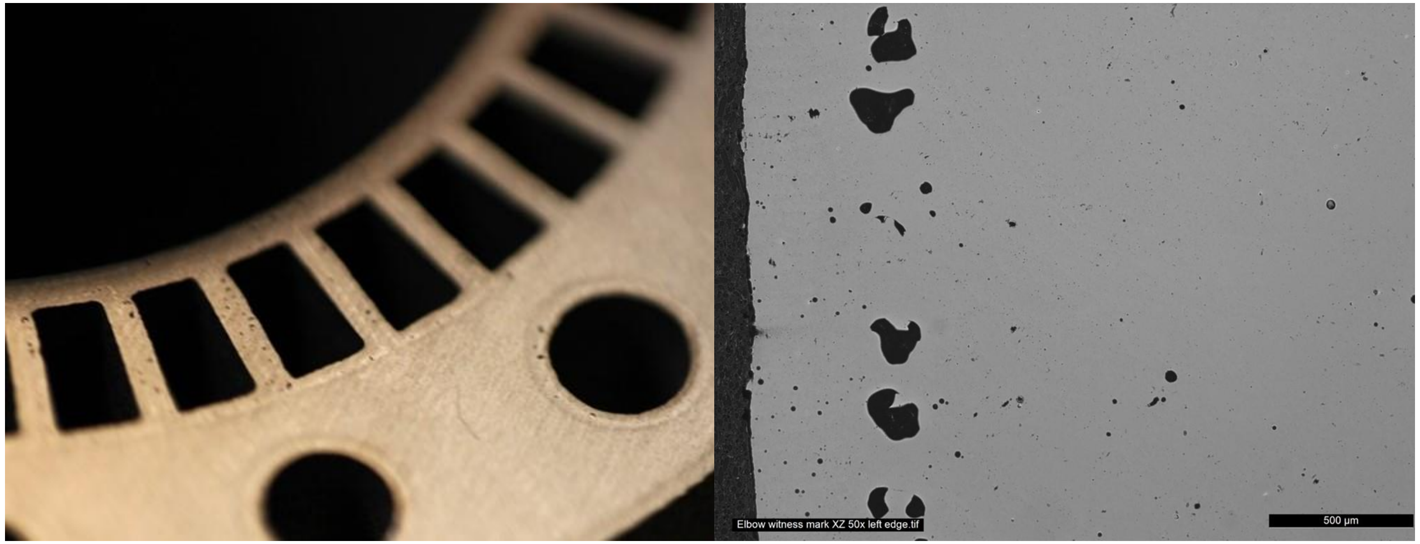
Successful build!

Build Artifacts & Defects

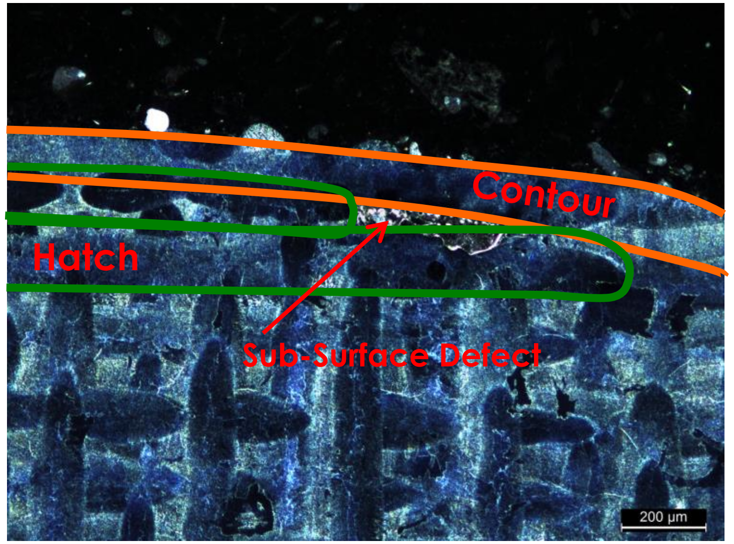




Witness marks on the surface and interior



Edge Porosity



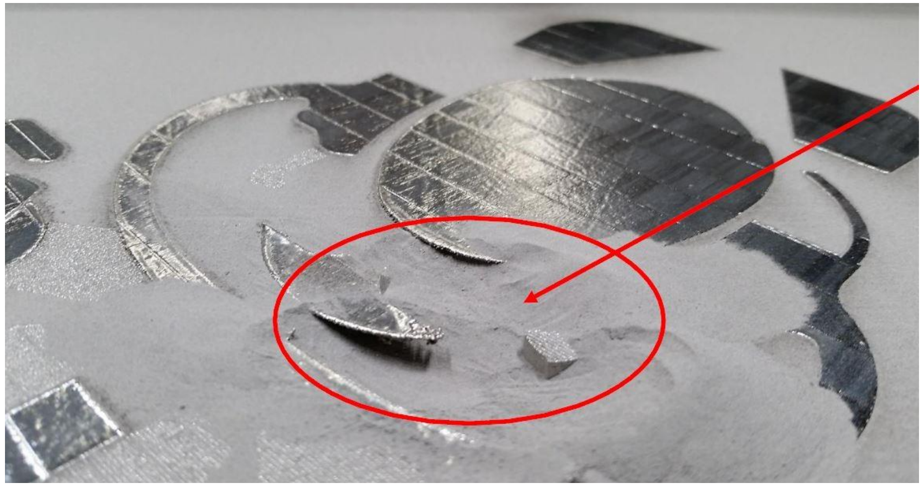
Edge Porosity can result from an excessive beam offset.

Build Failure Examples

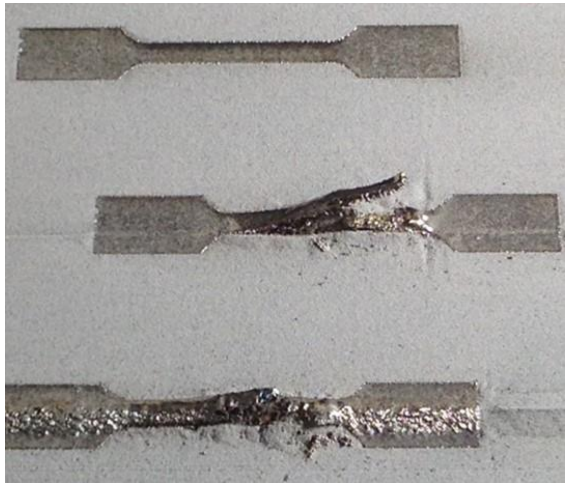
Short feed where insufficient/non-uniform powder distribution occurs. Over time the powder layer will be excessively thick when corrected and the laser melt pool will not be sufficiently deep to bond the thick layer to substrate underneath. The re-coater blade is eventually damaged by curling.

Swelling (curling) results from geometries that taper (overhangs) to thin segments and are susceptible to local overheating then swelling. The thin segment can then be curled by the re-coater blade resulting in downstream short feeds. This can result in part delamination.

Build Failure Examples



Unsupported overhanging surface. Courtesy Travis Davis.



Part separation from support structure

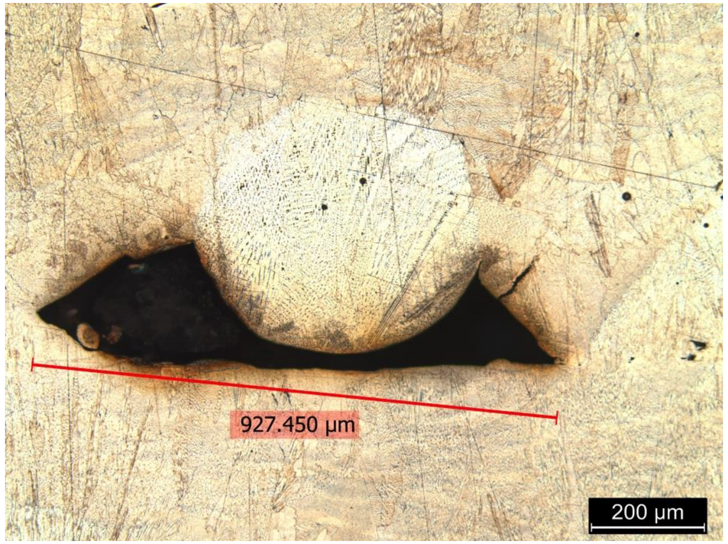
Corrupted build file

Machine to machine variation

Damaged re-coater blade

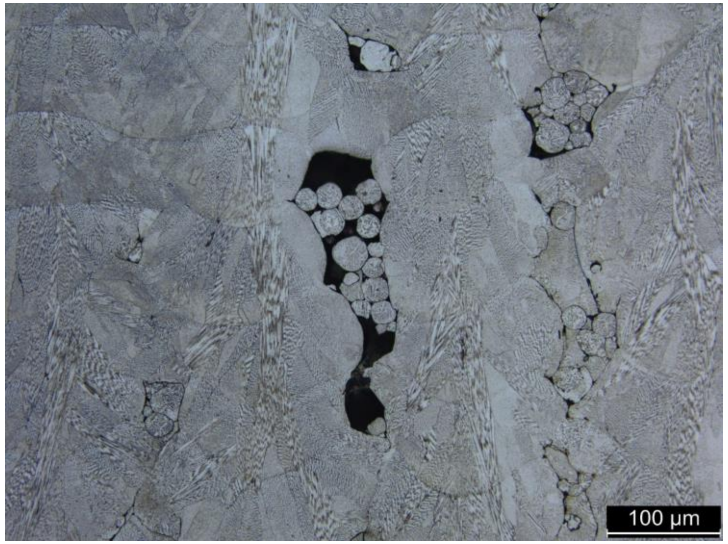
Stray vectors

Build Failure Examples

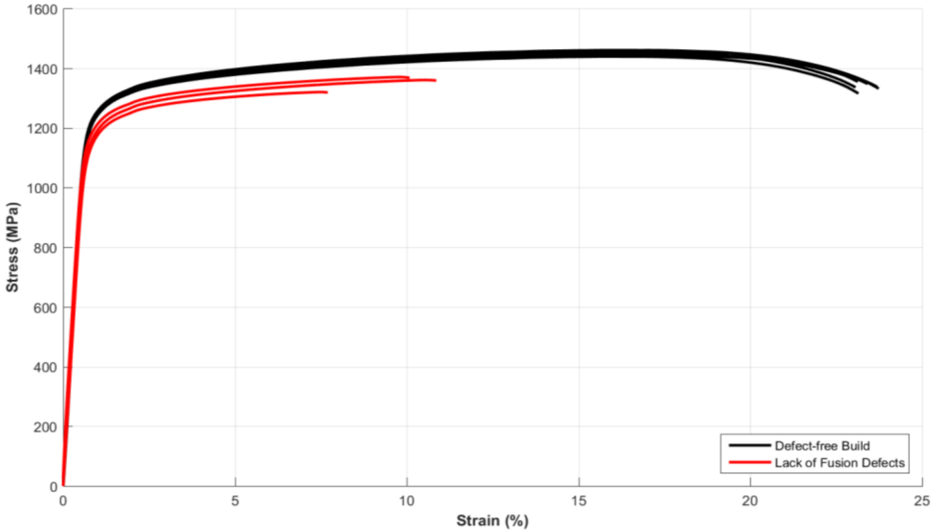


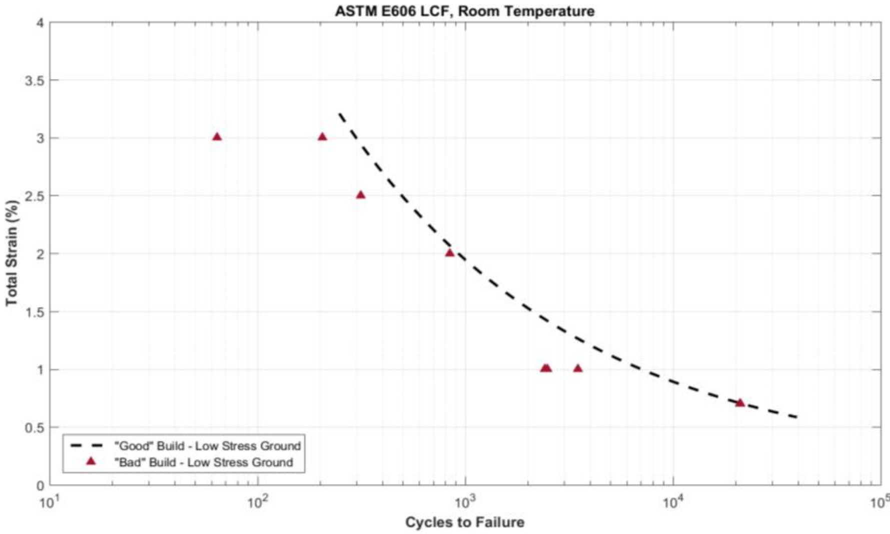
Horizontal Lack of Fusion (LOF) defect from ejecta.

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



Vertical-LOF defect from wide hatch spacing.



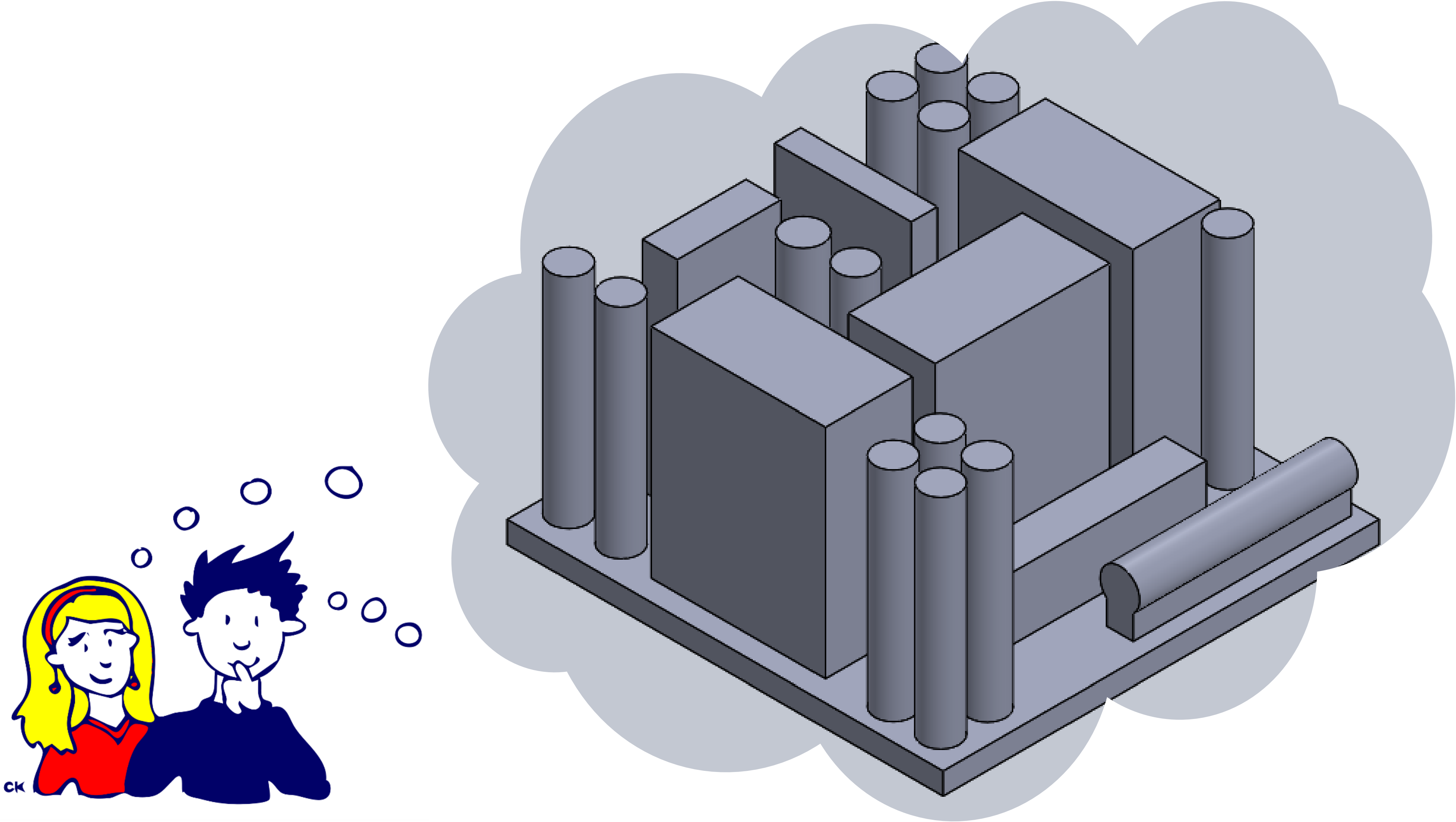


LOF defects decrease mechanical properties such as tensile strength, elongation, high cycle fatigue.

Courtesy Arthur Brown

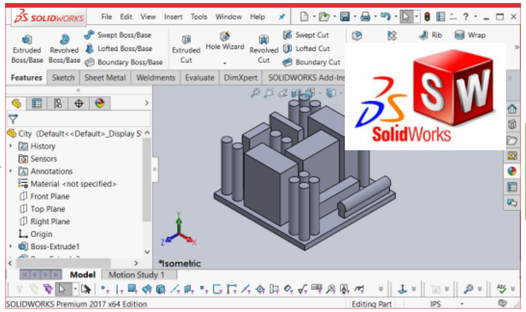
Printing Exercise #2

It's simple geometry, what couple possibly go wrong?

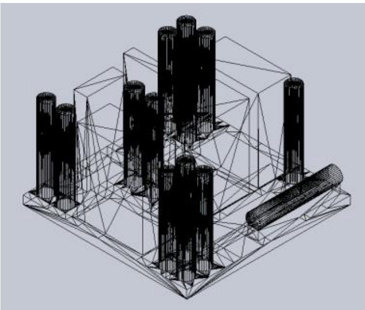


Printing Exercise #2

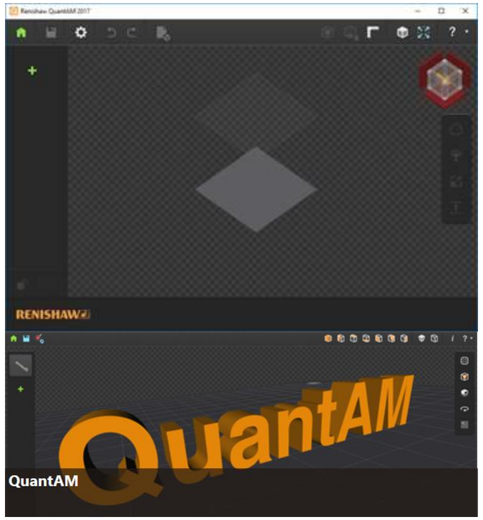
Create CAD



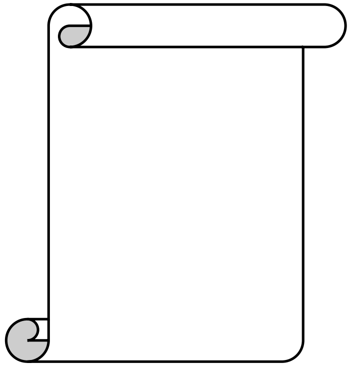
Generate STL



Build Software

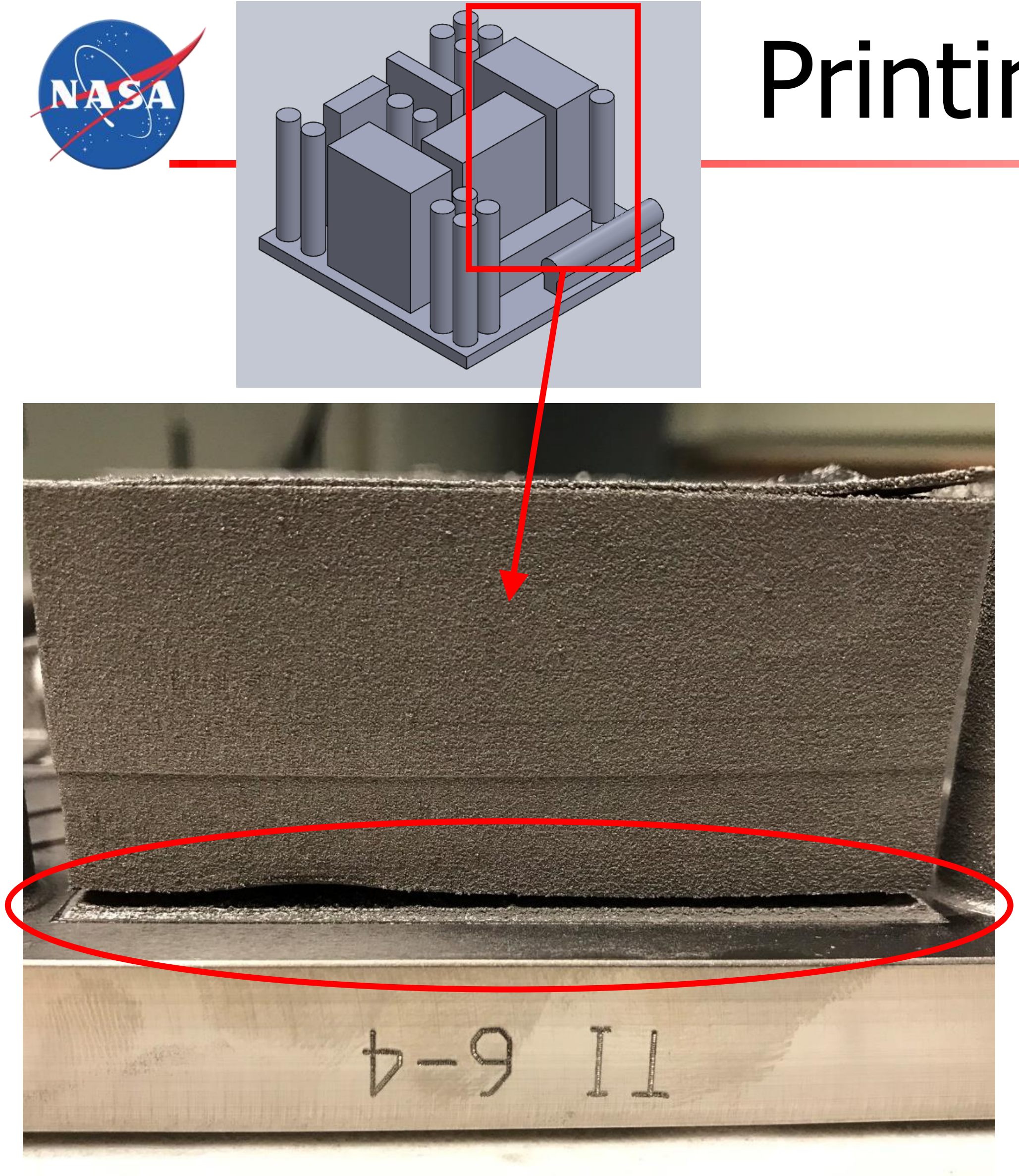


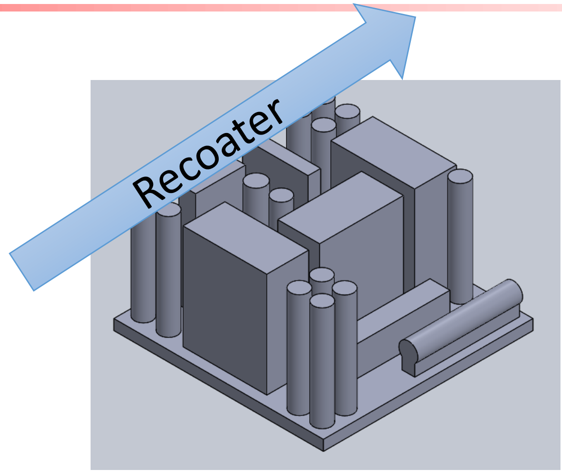
Set Machine Build Parameters

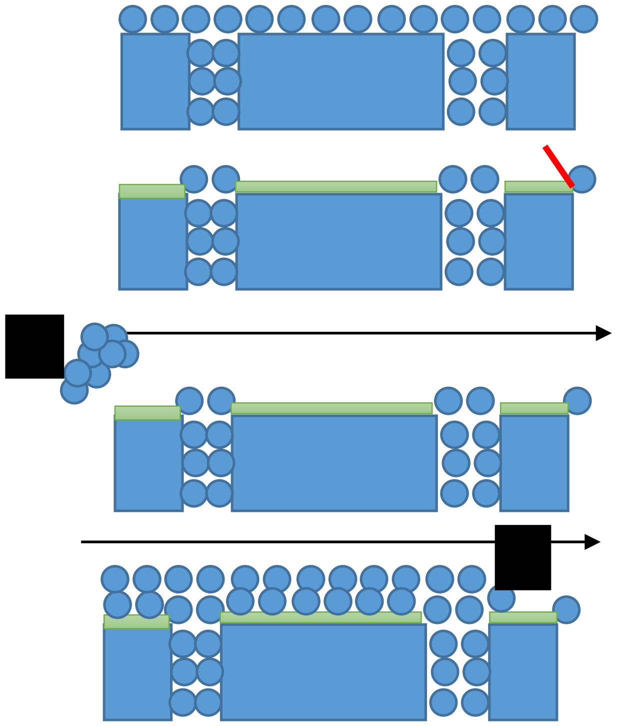


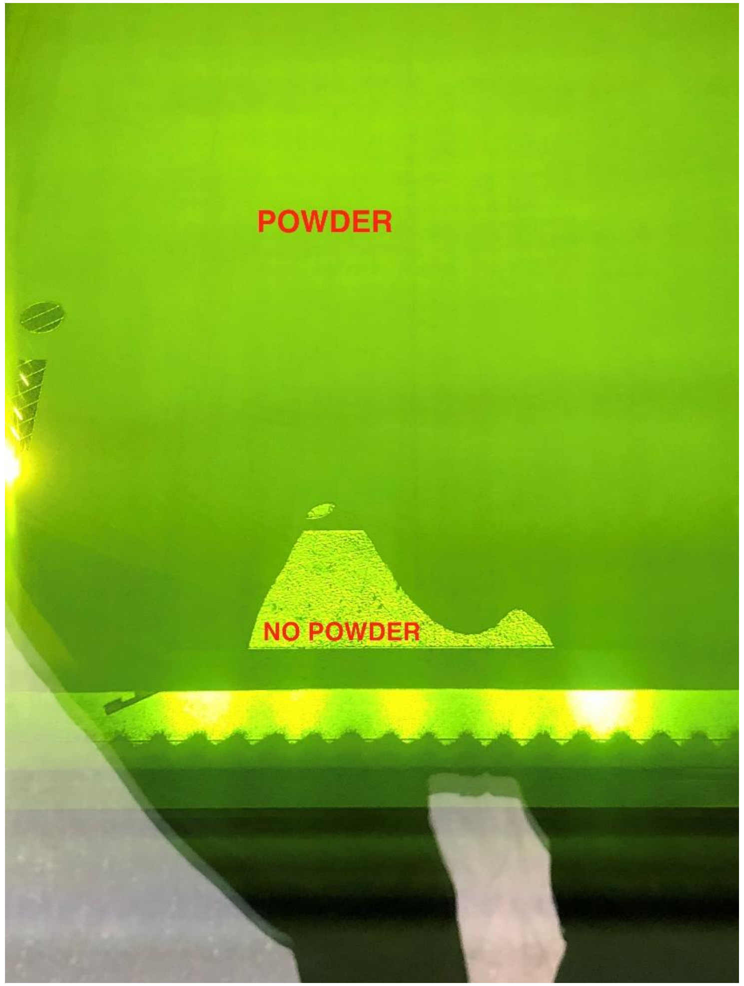
Off to the Machine!

Printing Exercise #2



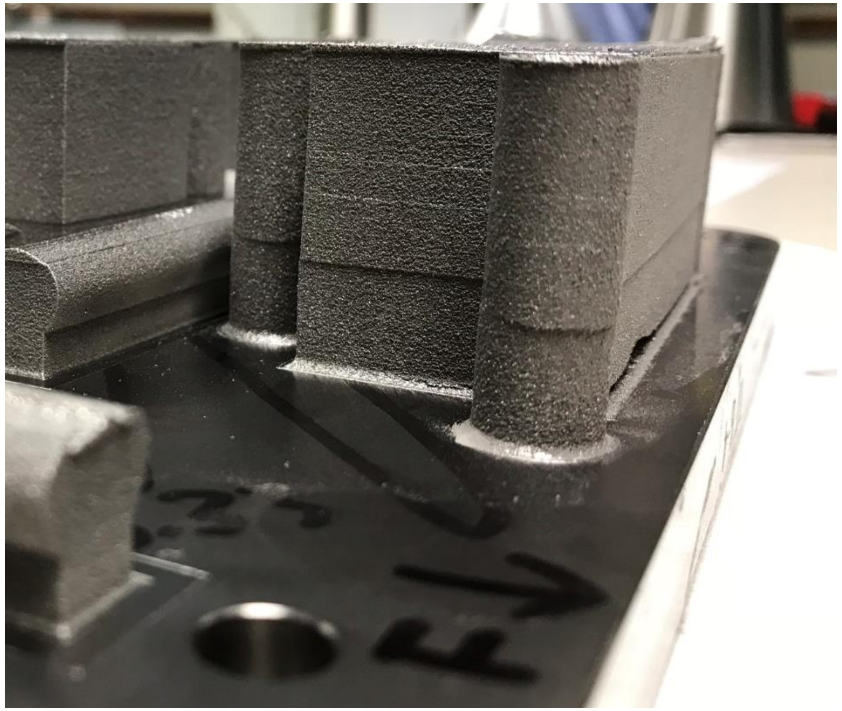


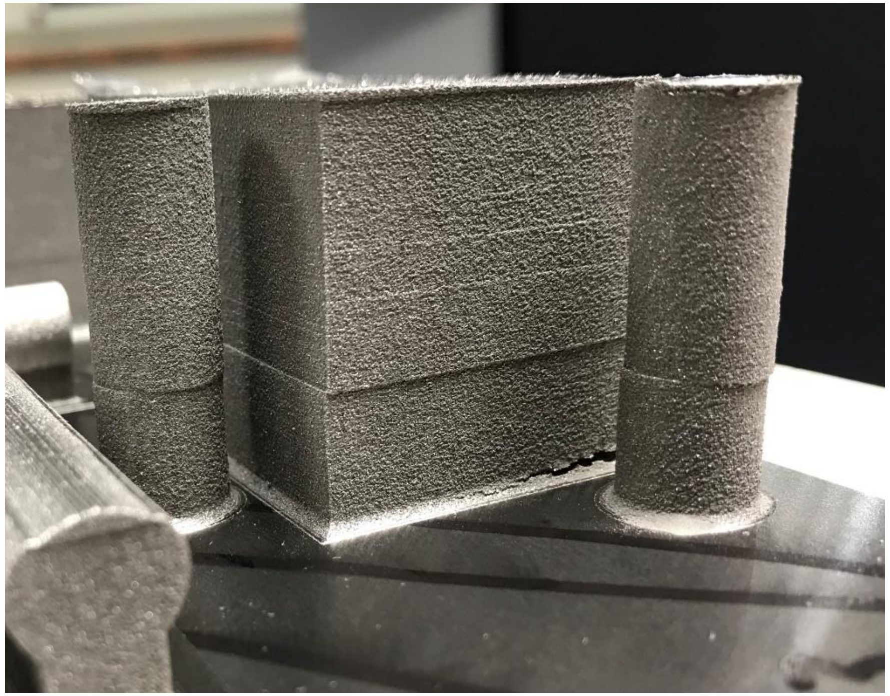




What happened?!?!

Printing Exercise #2





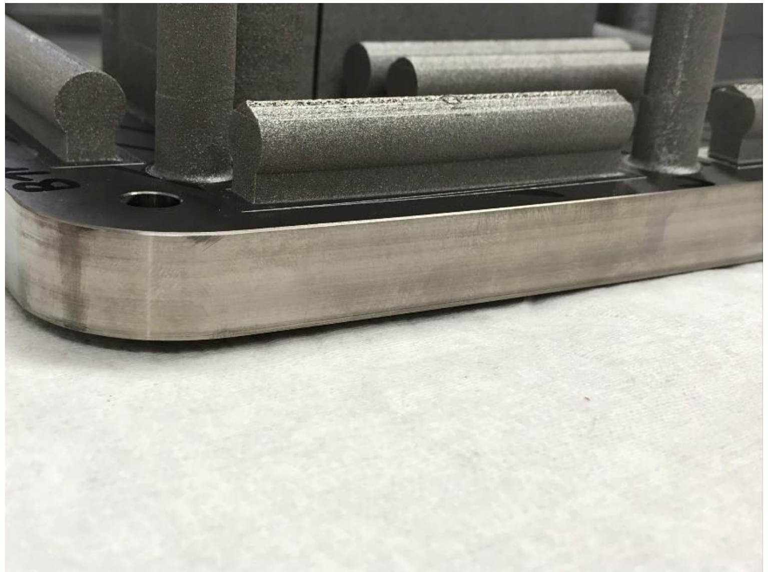
What happened?!?!

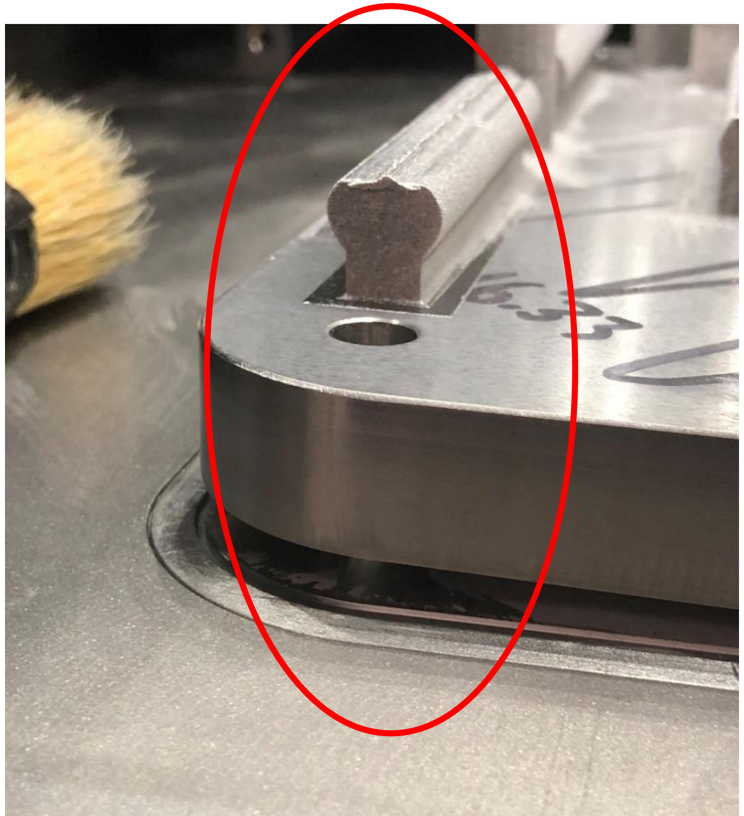
Printing Exercise #2

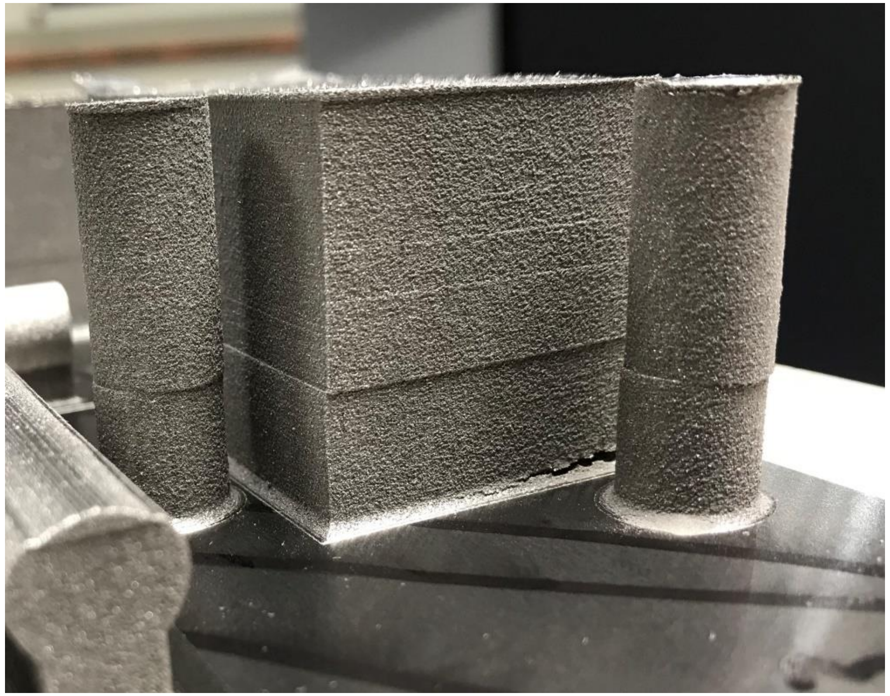
What happened?!?!…Another Clue

Printing Exercise #2

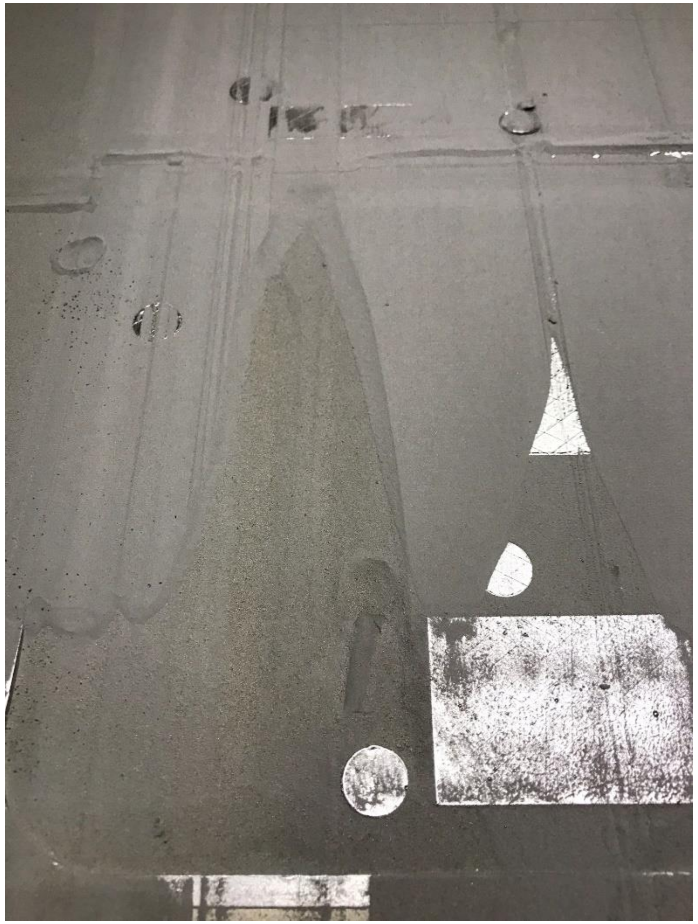
- Large amounts of sintered material -> Thermal stresses in build plate
- Bolt broke
- Corner elevated resulting in offset of parts
  - Laser doesn’t know (or care) so it keeps printing original coordinates onto “new shifted datum”

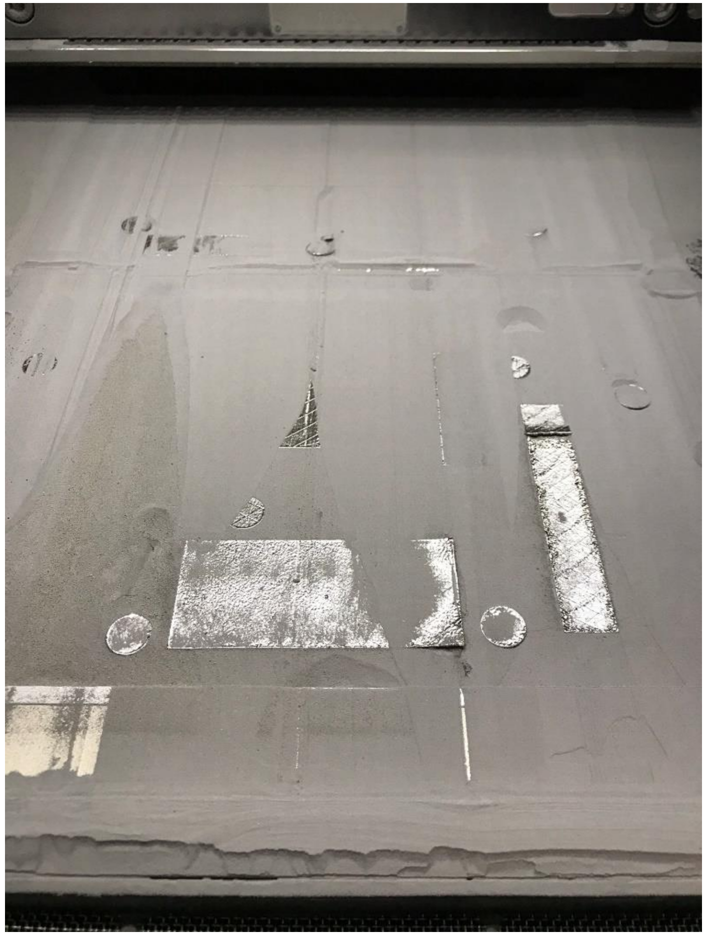






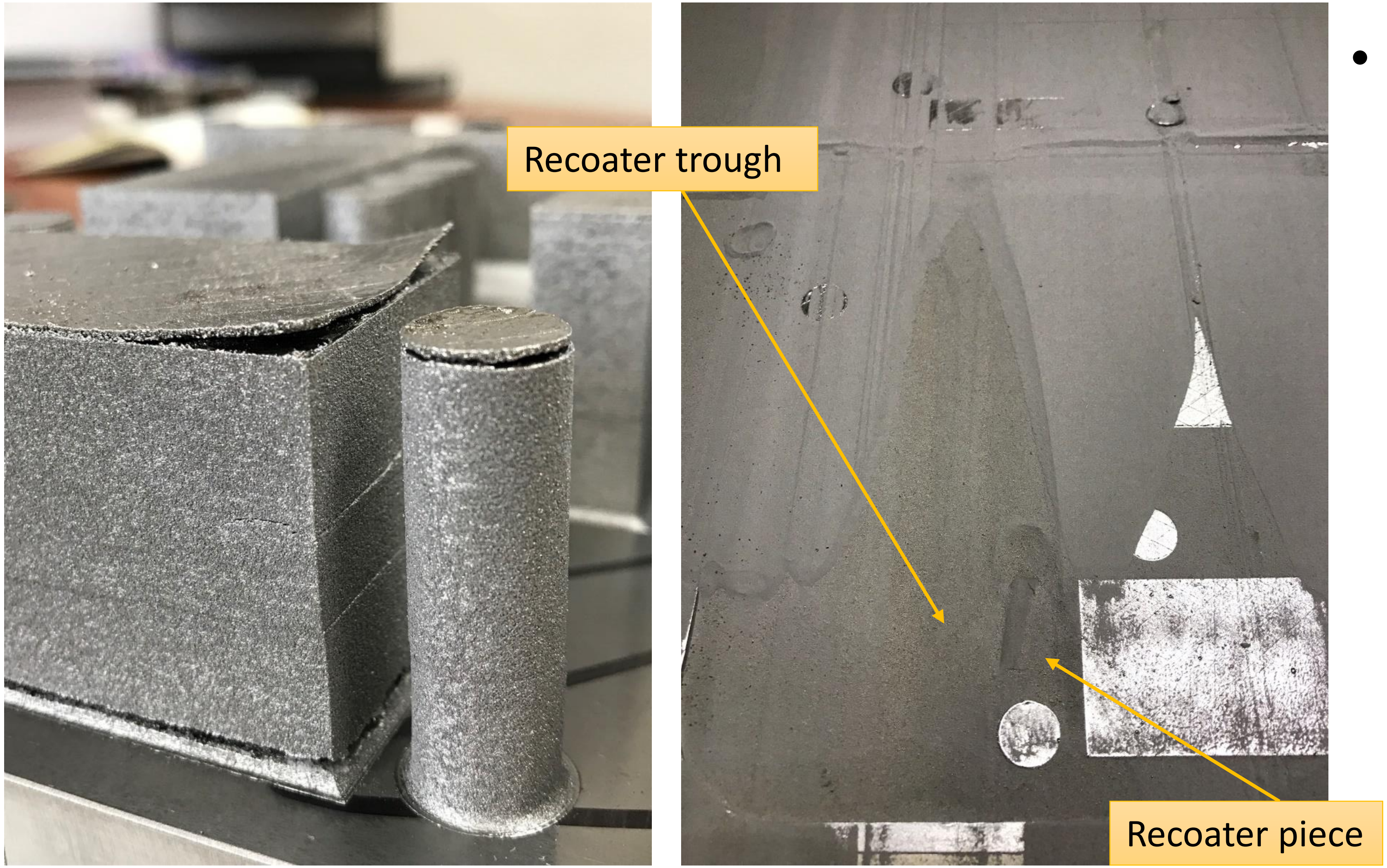
Printing Exercise #2





What happened?!?!

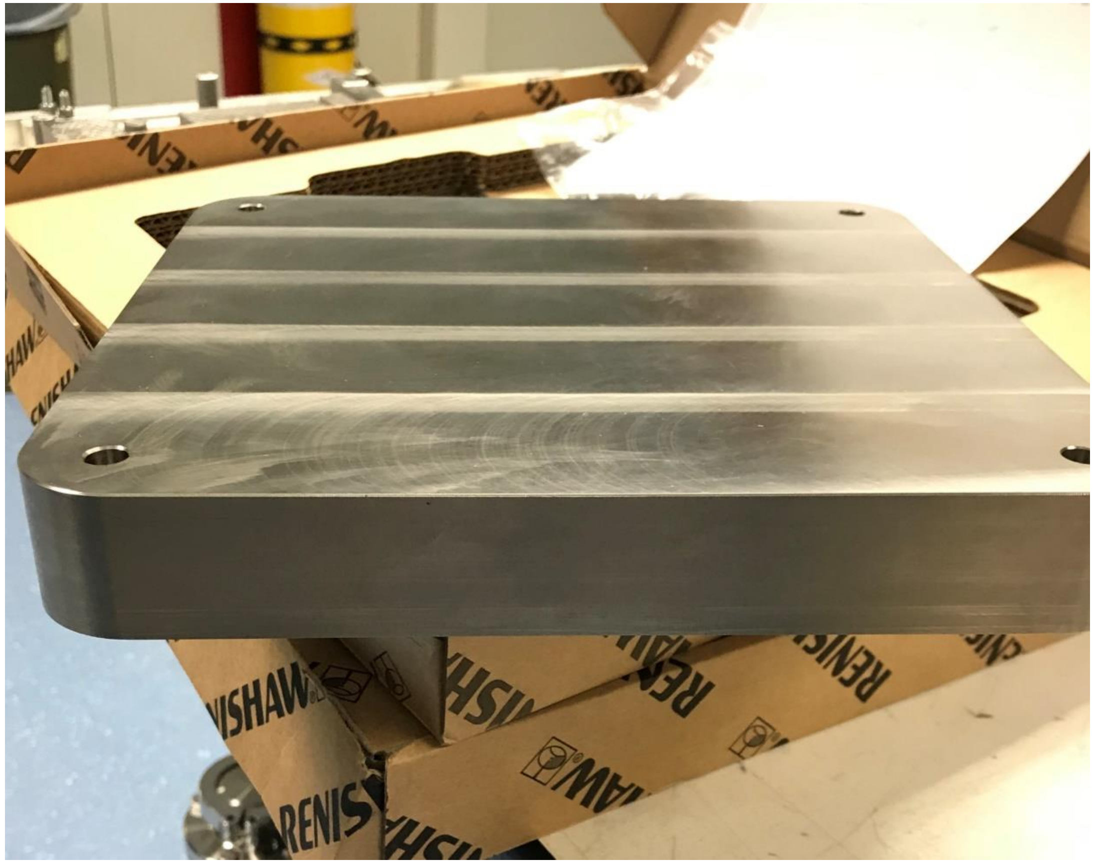
Printing Exercise #2



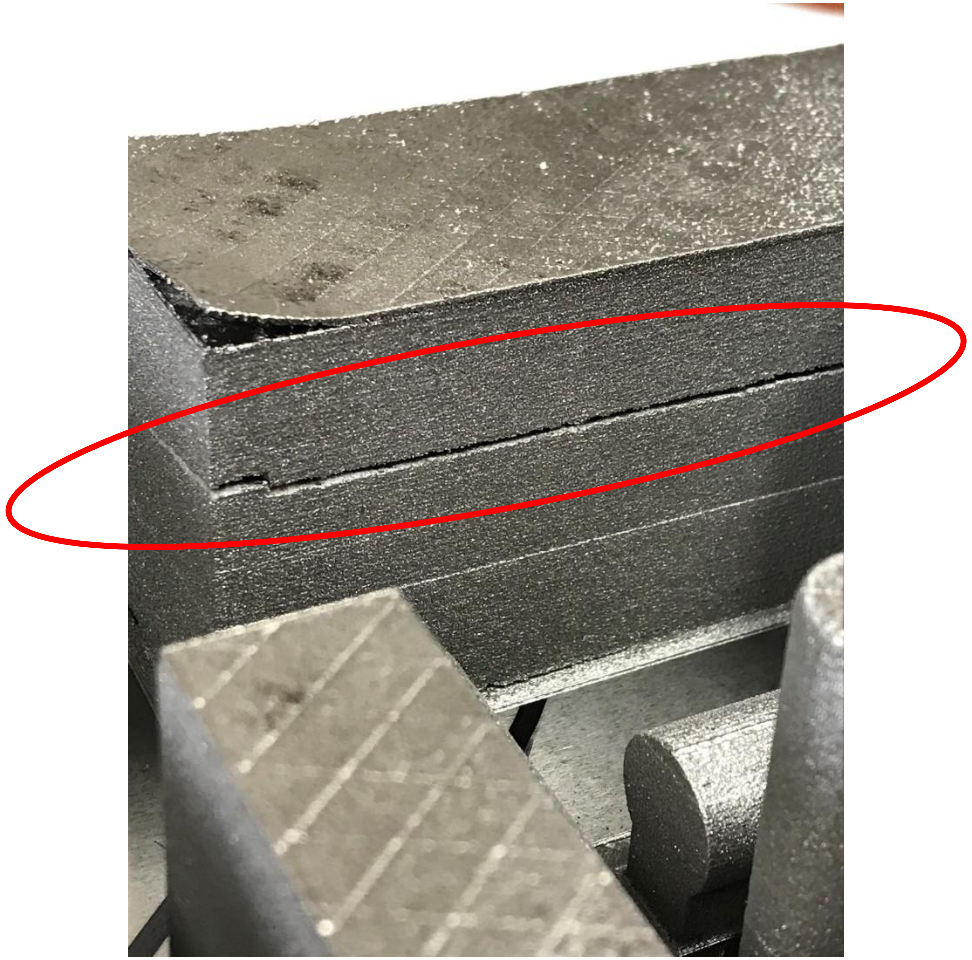
- Root Cause: Second bolt broke causing an additional shift in build plate
  - Symptom 1: Offset in laser/part datum
  - Symptom 2: Newly created layers now “overhung” and were able to curl and separate
  - Symptom 3: Recoater blade strikes deformed layers and is damaged
  - Symptom 4: Complete recoater mayhem

Printing Exercise #2

- Use a thicker build plate
- Increased dosage factor on build setup



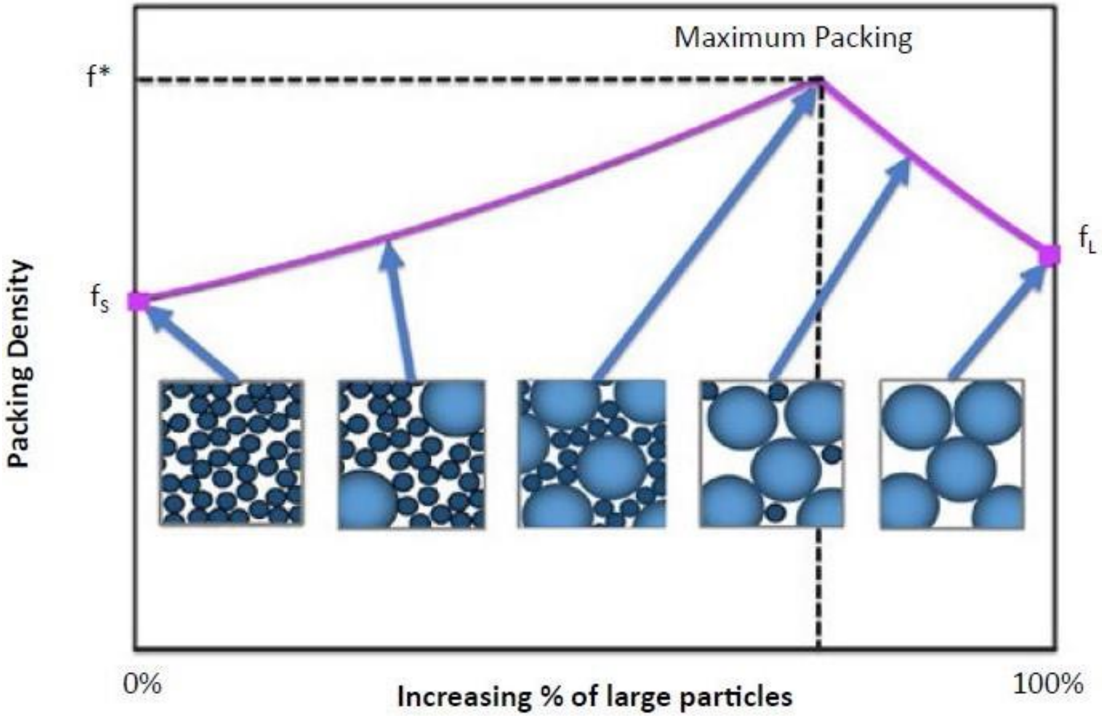
Printing Exercise #2



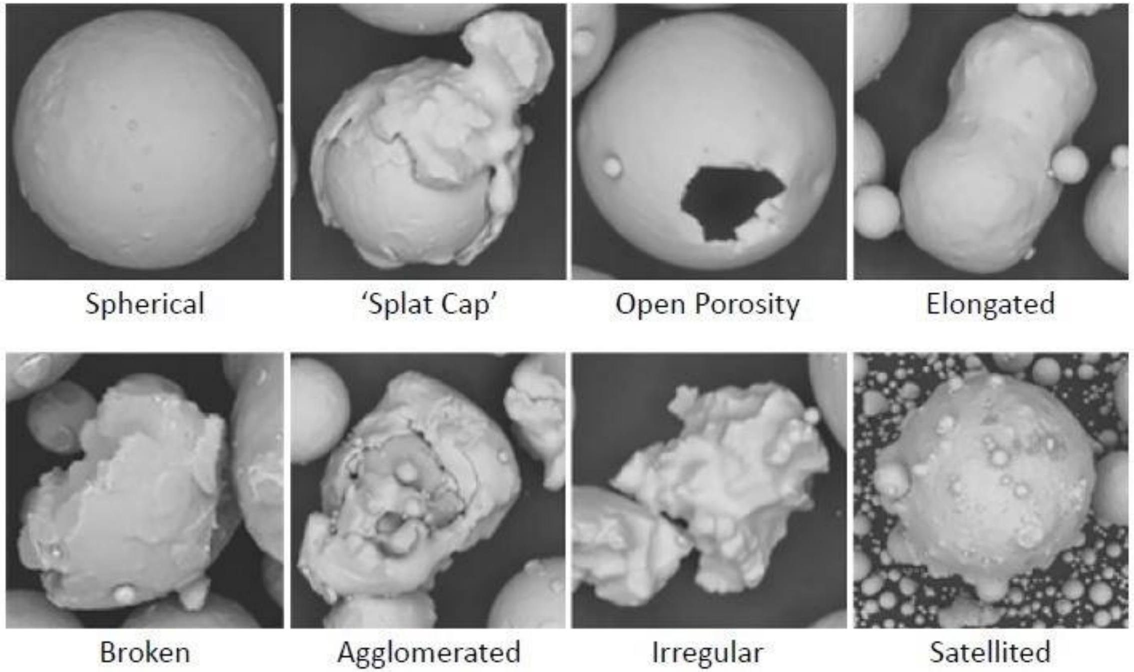
- Residual stresses in part were allowed to remain (part not removed from plate, no heat treat, etc.)
- Crack initiated and eventually spread through part.

What happened?!?!

Powder

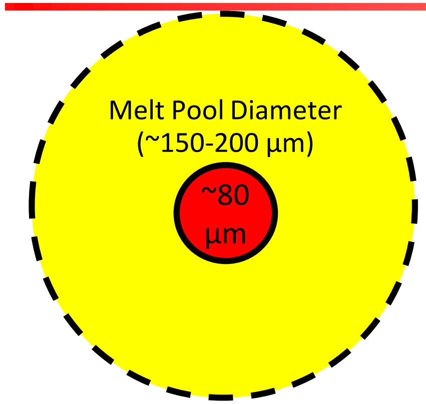


Packing density & PSD. Courtesy Metal AM, Winter 2017.

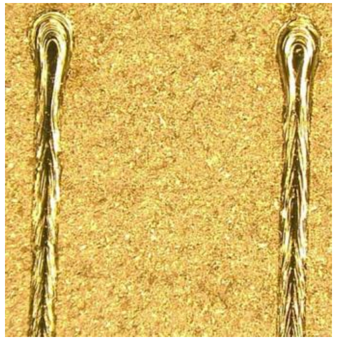


Powder Morphology. Courtesy Metal AM, Winter 2017.

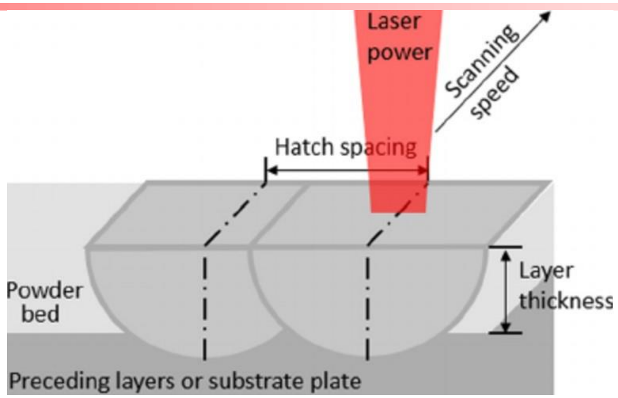
Build Process



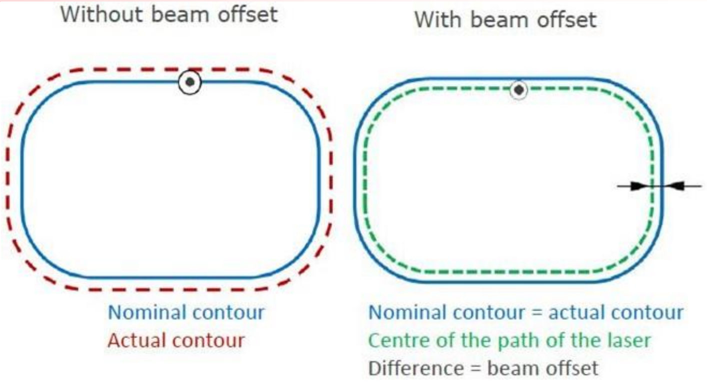
Laser Focus Diameter. Courtesy EOS.



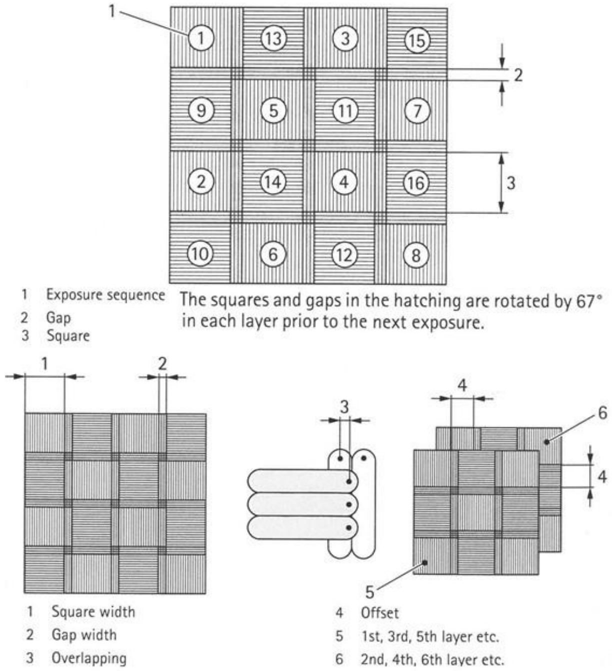
Melt Pool Track



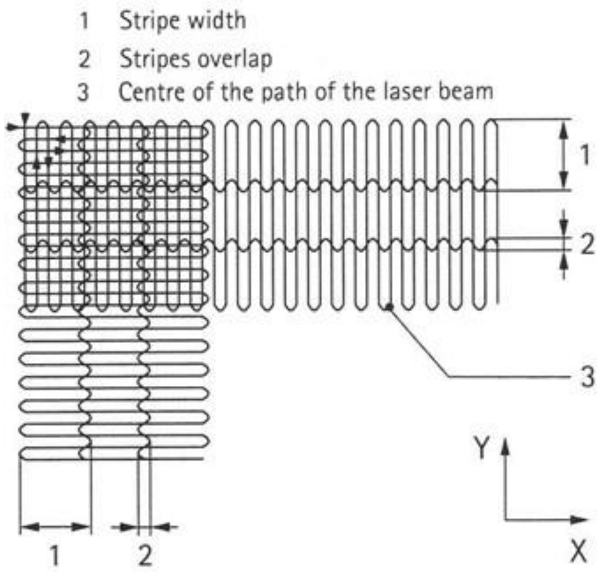
Hatch spacing



Beam Offset. Courtesy EOS.



Chess Rotated Exposure Strategy.
Courtesy Concept Laser.

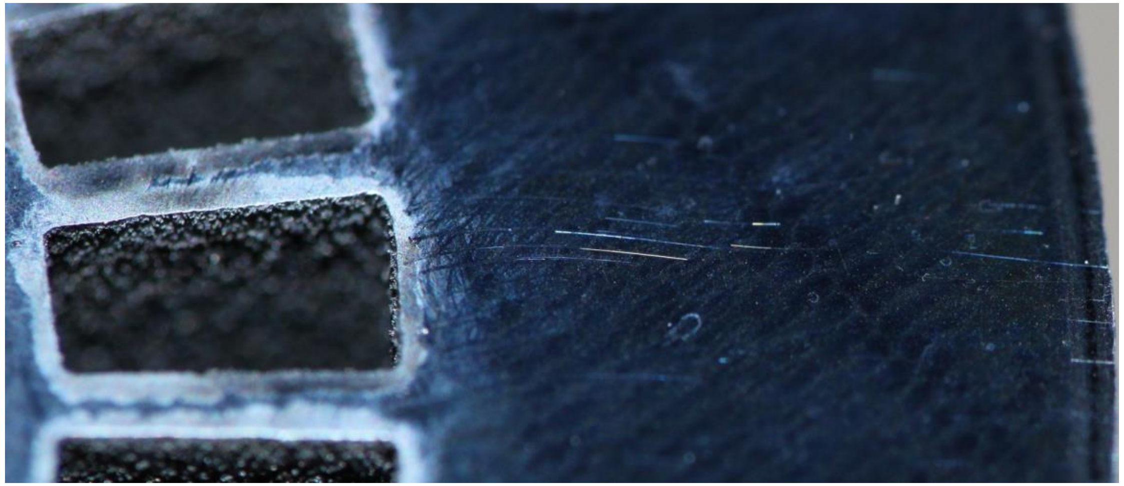


Stripe Exposure Strategy. Courtesy EOS

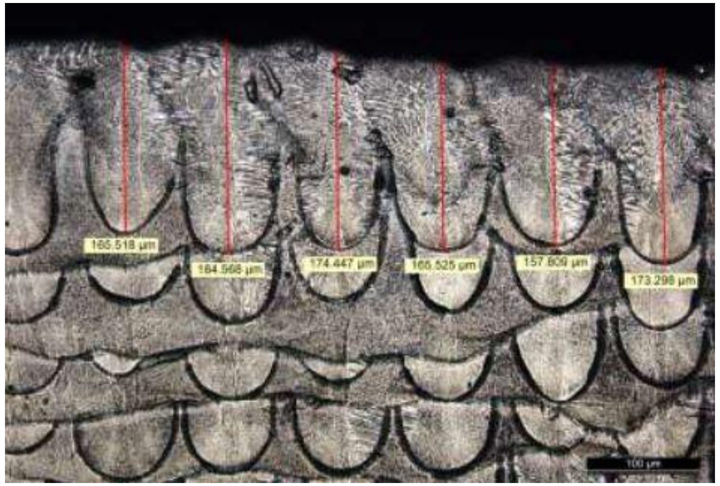
Parameter	Description
Thickness (t)	Powder layer thickness (mm)
Power (P)	Laser power set-point (W)
Speed (V)	Laser scan speed (mm/s)
Hatch Distance (D)	Distance between centerlines of weld pools (mm)
Overlap	Melt pool overlap (%)
Beam Offset (BO)	Compensates for melt pool size to part (mm)
Scan Pattern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

Scan Strategy & Microstructure

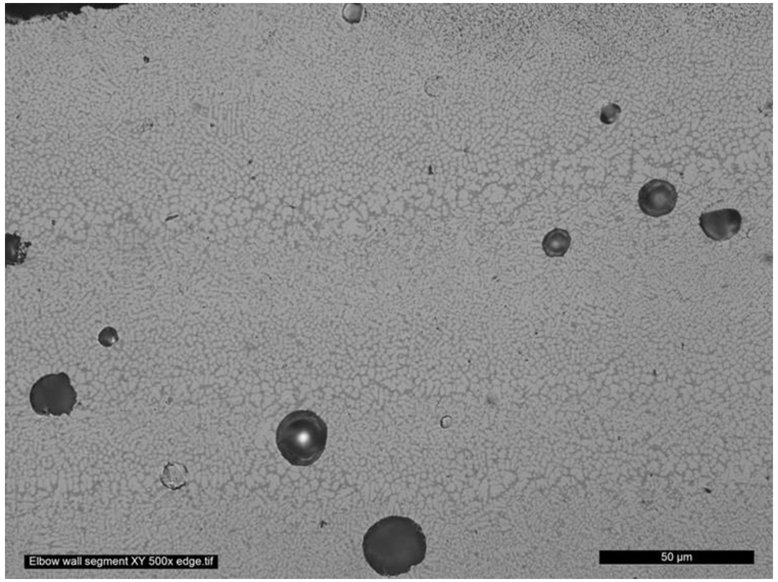
Porosity & weld pool path in AlSi10Mg



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.

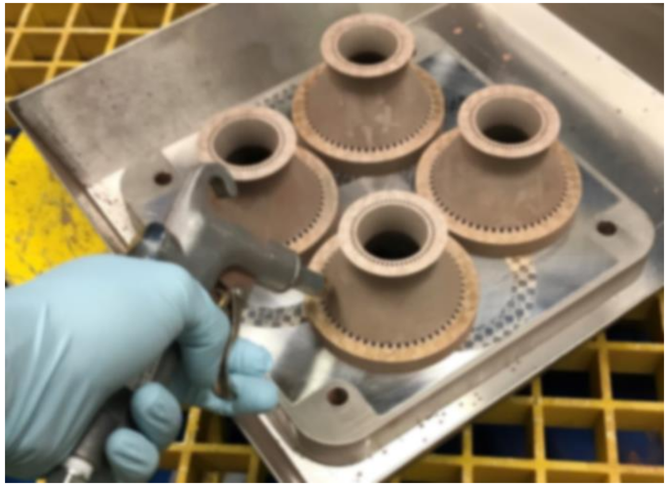
Shrinkage (keyhole) porosity in IN718 results from high laser power or fast scan speed.

Post-Processing

Unpack & Vacuum

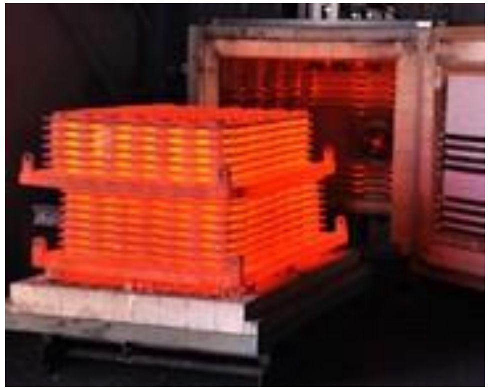
Vibration & Mechanical Removal

Downdraft Table



Compressed Air

Sintered Powder



Stress Relief

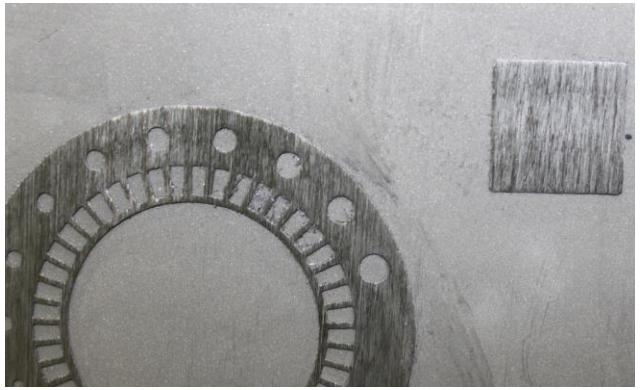


Plate removal (band saw or wire EDM)

Support Removal

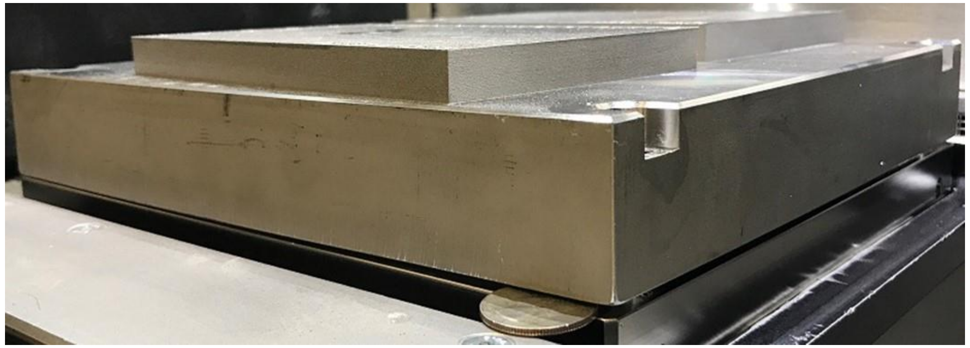
Sieve Powder

Stress Relief

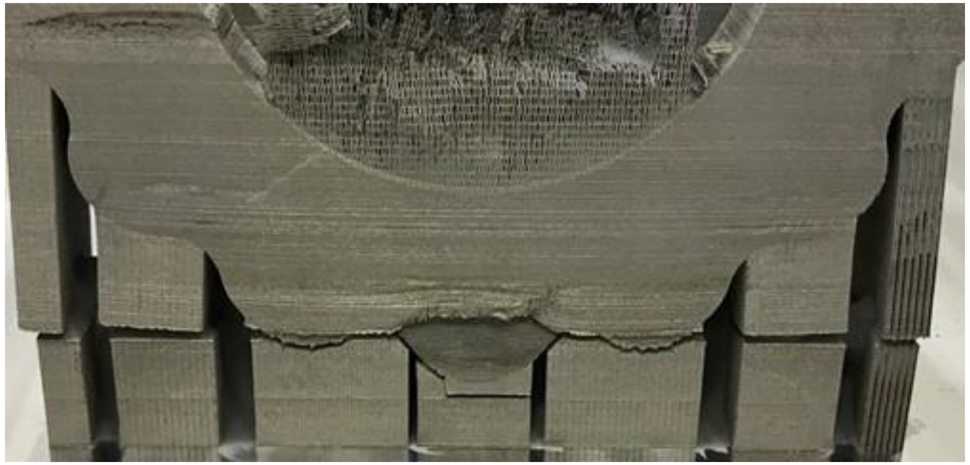
- *Stress Relief* – Reduces residual stress as a result of the SLM process.
  - IN718: 1065 ± 14 °C, 1.5 hrs -5/+15 min in argon, furnace cool venting to air as soon as allowable.

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

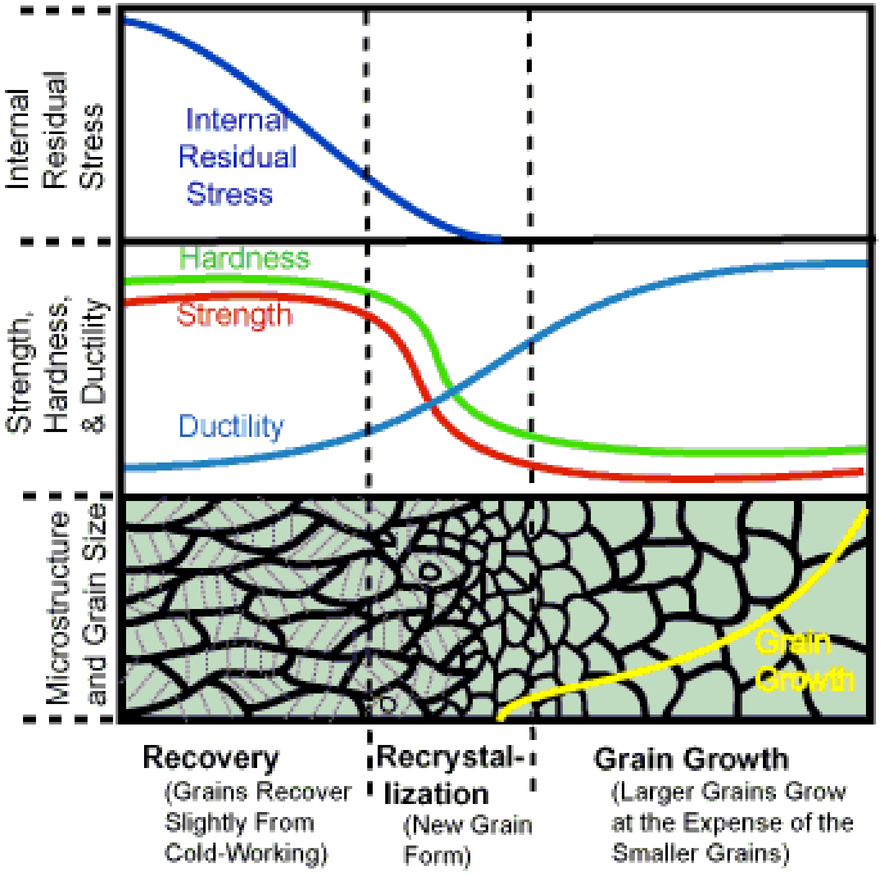
Cooling shrinkage behavior.



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



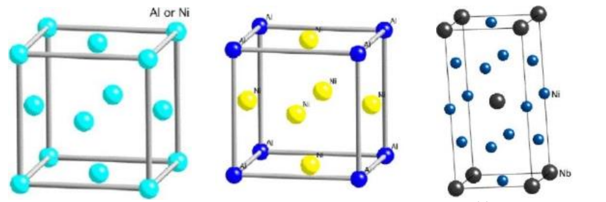
Residual stress induced failure.



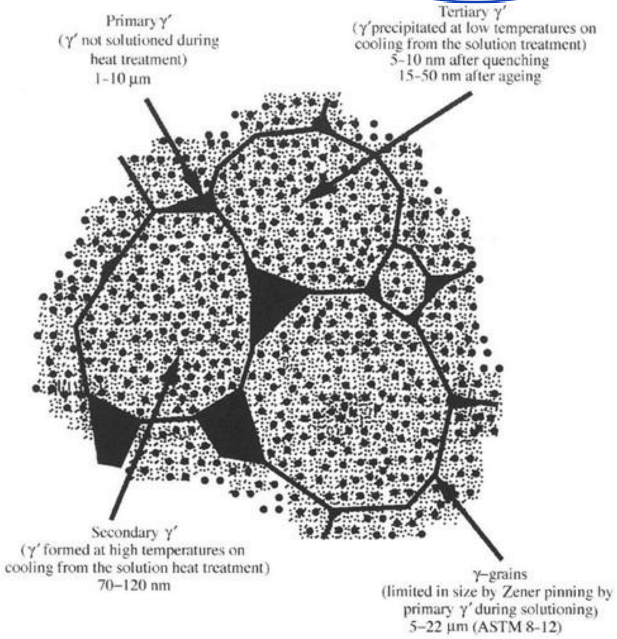
Nucleation, Recrystallization & Grain Growth

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.

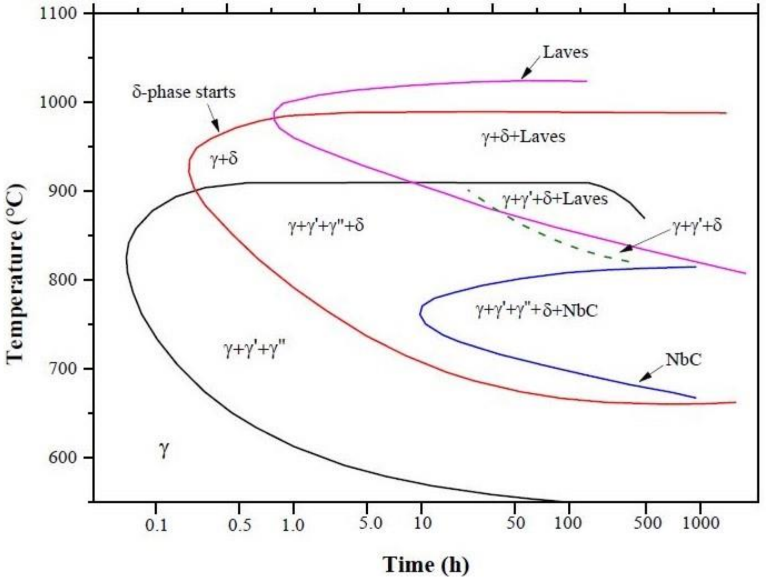


γ FCC structure[3] γ' FCC structure[3] γ'' BCT structure[3]

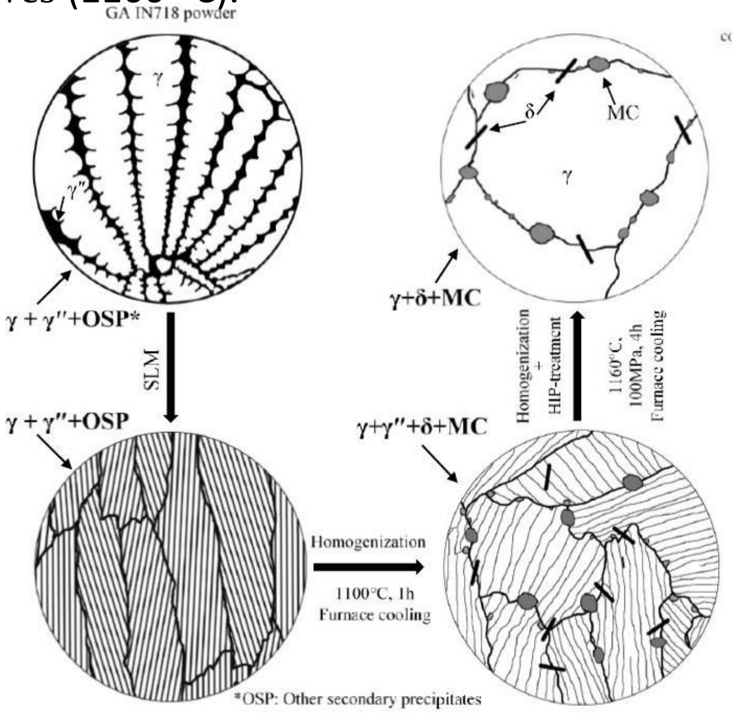


IN718 Microstructure. Courtesy Reed.

- 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].

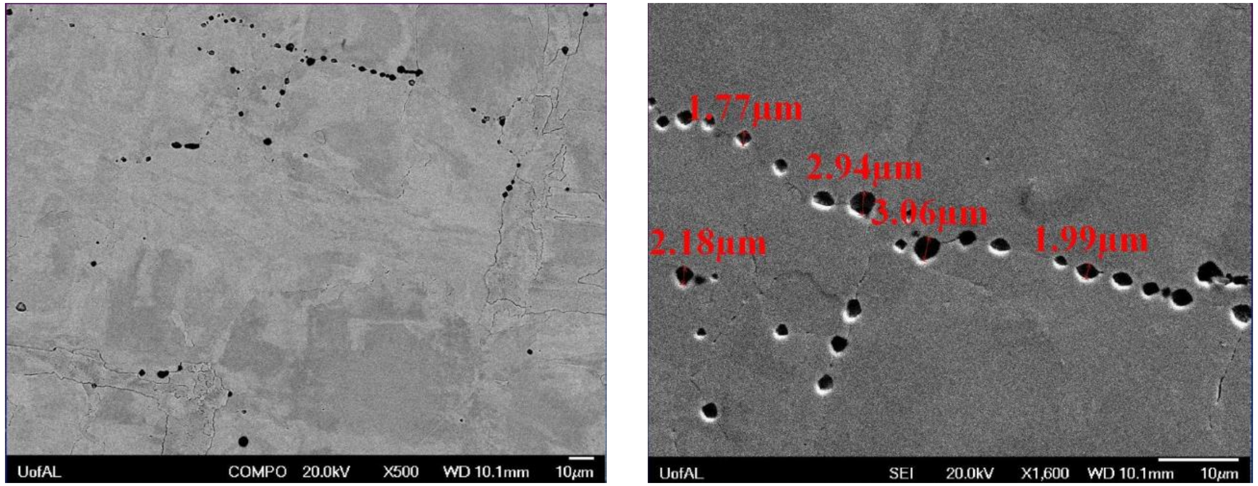


Microstructural change & phase evolution of IN718[1].

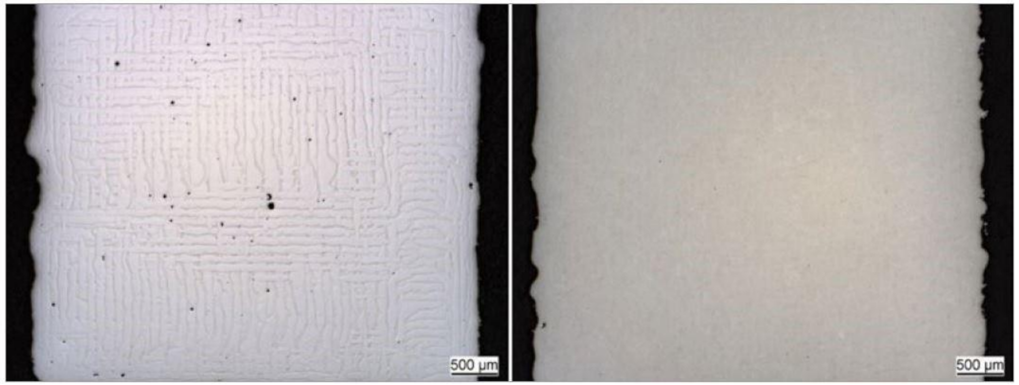
[1]Courtesy Mostafa et. al, 2017.
[2]Manikandan, 2015.
[3]Courtesy Bhadeshia, 2018.

Hot Isostatic Press (HIP)

HIP – Closeout porosity and potential to heal defects.



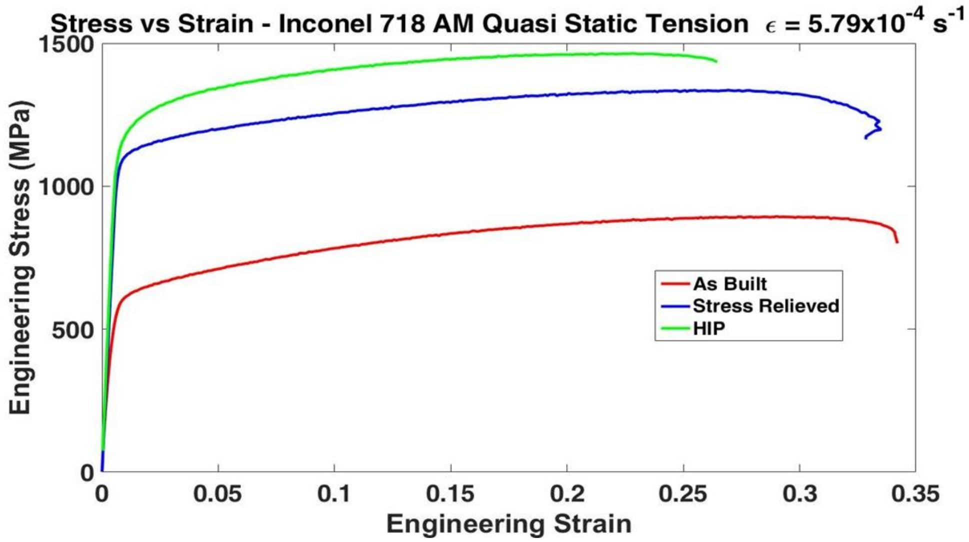
Monel K500 SEM BSE micrographs 500x (L) and 1600x (R) showing porosity along grain boundaries. Courtesy UA Senior Materials Team.



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

MSFC HIP Furnace

large machined cavity in a 1" diameter In625 bar that they were able to close with HIP; Courtesy Mark Battison (Quintus)

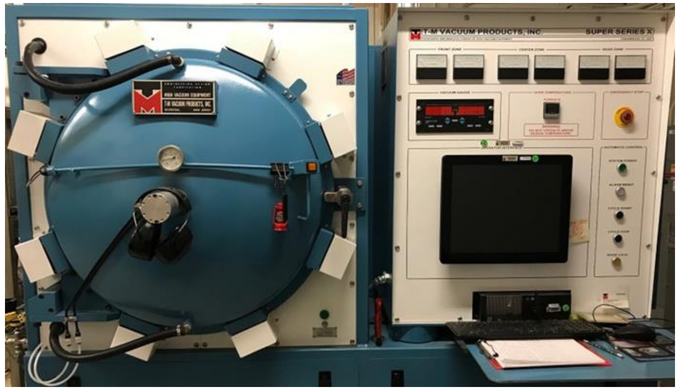


SLM IN718 Tensile Strength vs. Condition. Courtesy Hazeli.

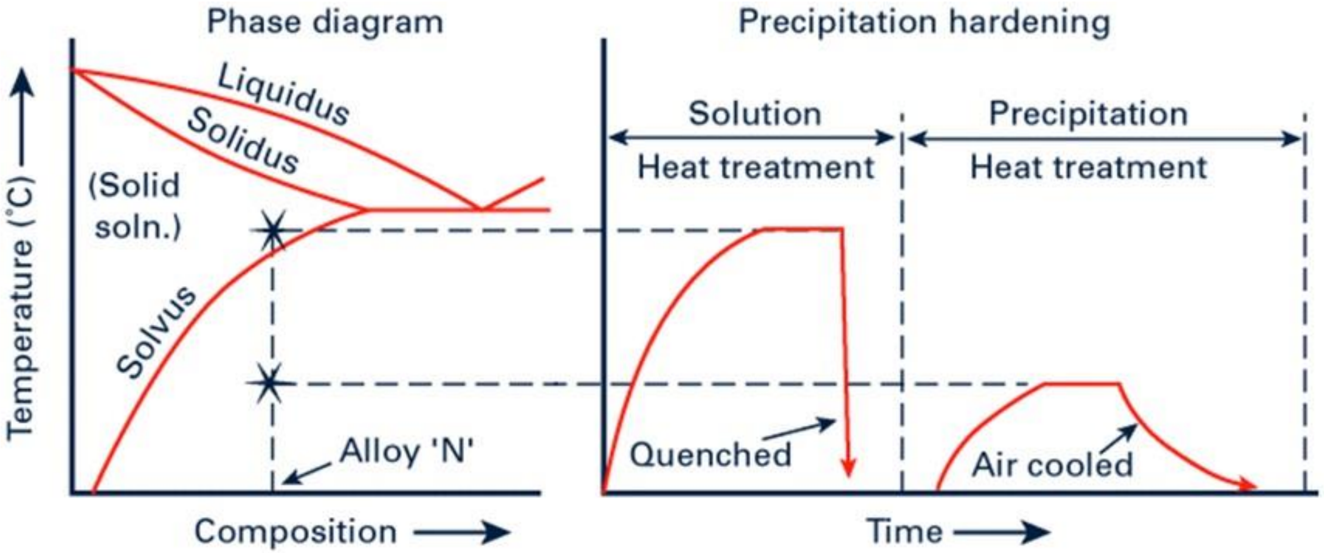
Homogenization: Solutionize & Age

- *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.

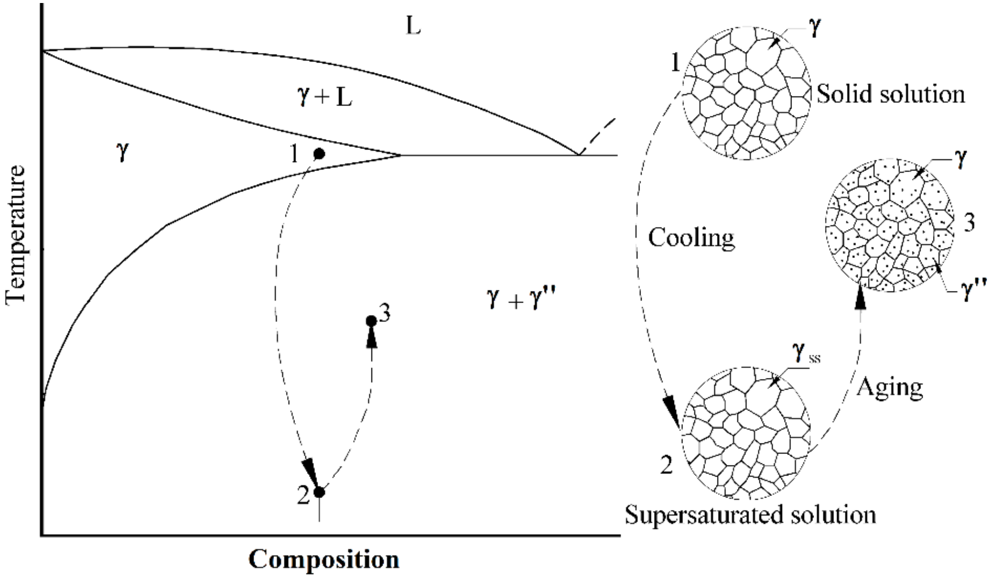
- *Age*: γ'' nucleate uniformly in the microstructure and grown to an optimal size.
  - AMS 5664: 760°C for 8h (γ'' forms), cool to 650°C, hold for 20 h (γ'' grow), air cool.



MSFC Vacuum Furnace



General phase diagram showing heat treatments.



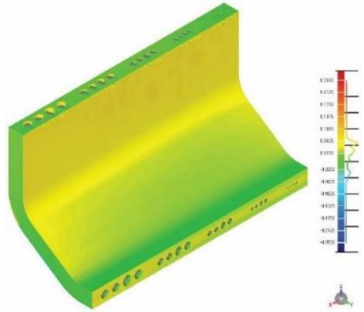
Notional Phase Diagram- IN718

NDE

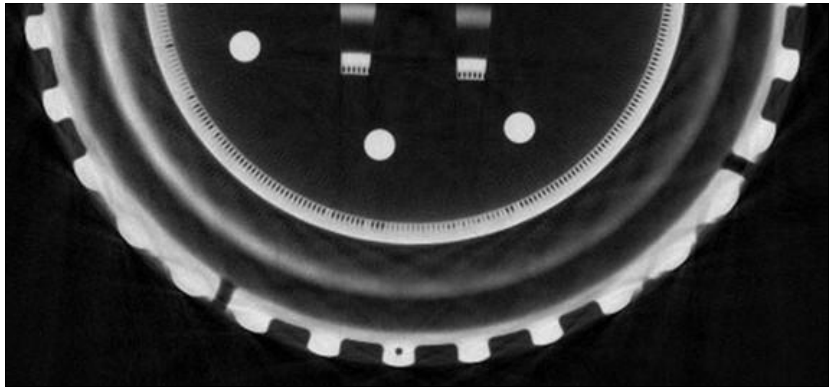
- Structured Light Scanning
  - Surface mapping
  - Geometric distortion/deviation
  - Limited spatial resolution
  - Equipment expensive but operation relatively inexpensive
- X-ray radiography & CT
  - Detect trapped powder
  - Large flaws
  - Limited spatial resolution (excludes micro-focus CT)
  - Material determines scan time/resolution
  - Expensive & time consuming
- Other
  - Visual / Borescope
  - In-situ
  - Ultrasonic
  - Penetrant
  - Infrared

Visual Borescope

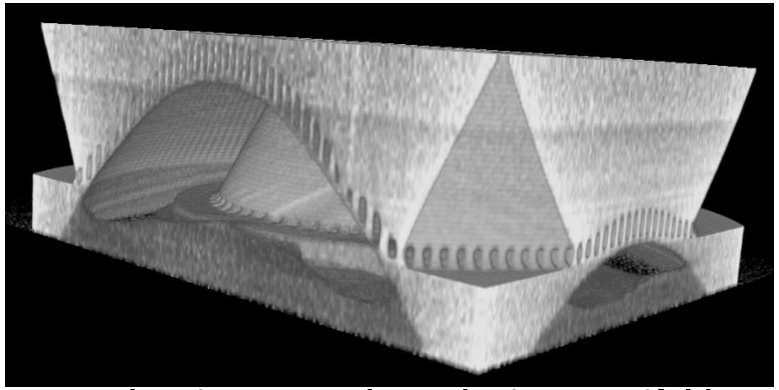
Structured Light Scanning



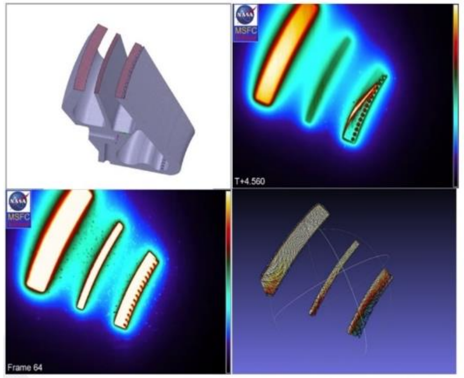
CAD-scan data comparison



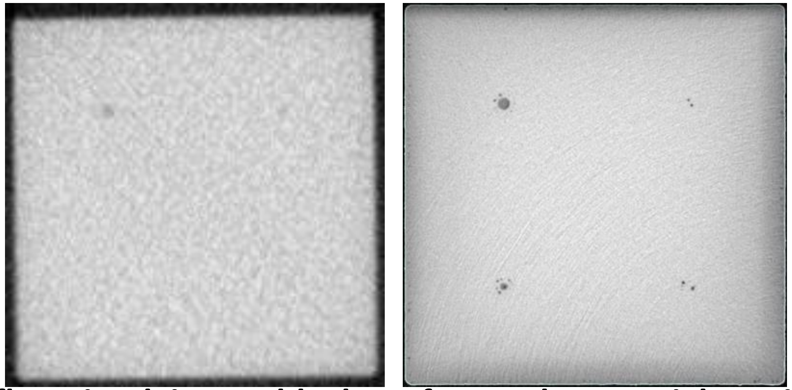
Radiograph showing powder filled channels



CT showing trapped powder in a manifold



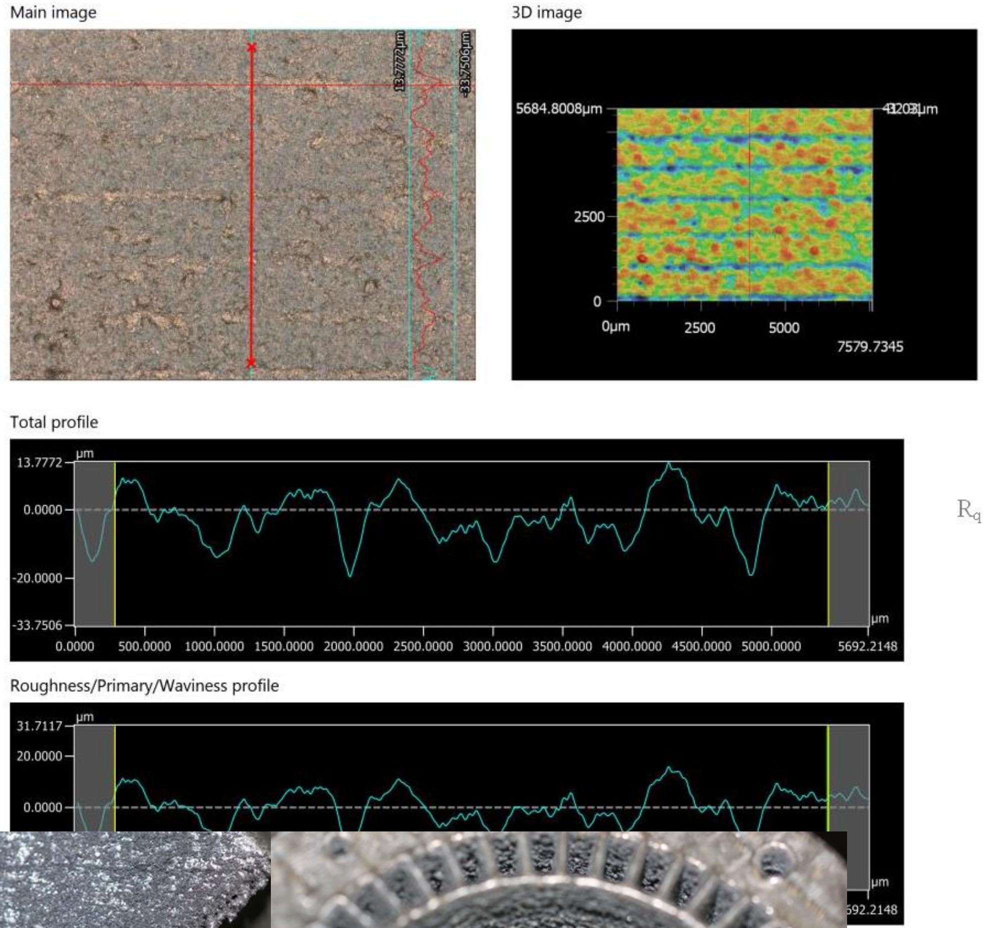
In-situ Inspections



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



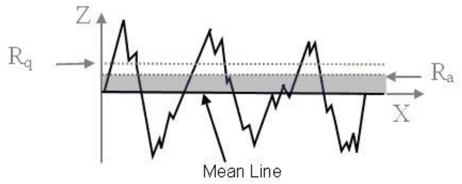
Measurement equipment: KEYENCE VR-3000 G2

Analysis condition

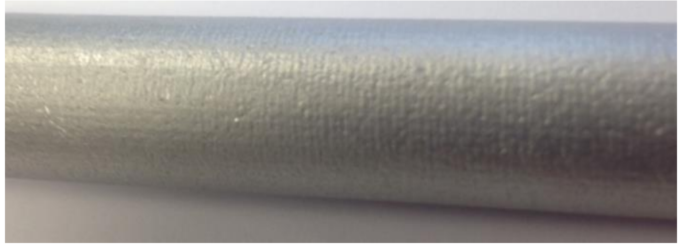
Correct tilt	Auto
Measurement type	Roughness
Cutoff	λs =None λc =None
End effect correction	Enabled
Double gaussian	OFF
No. of sampling lengths	1

Measurement result

No.	Measurement name	Measured value	Unit
1	Ra	5.4351	μm



$$R_a = \frac{1}{l}\int_0^l |Z(x)|\, dx$$



Software induced tesselation

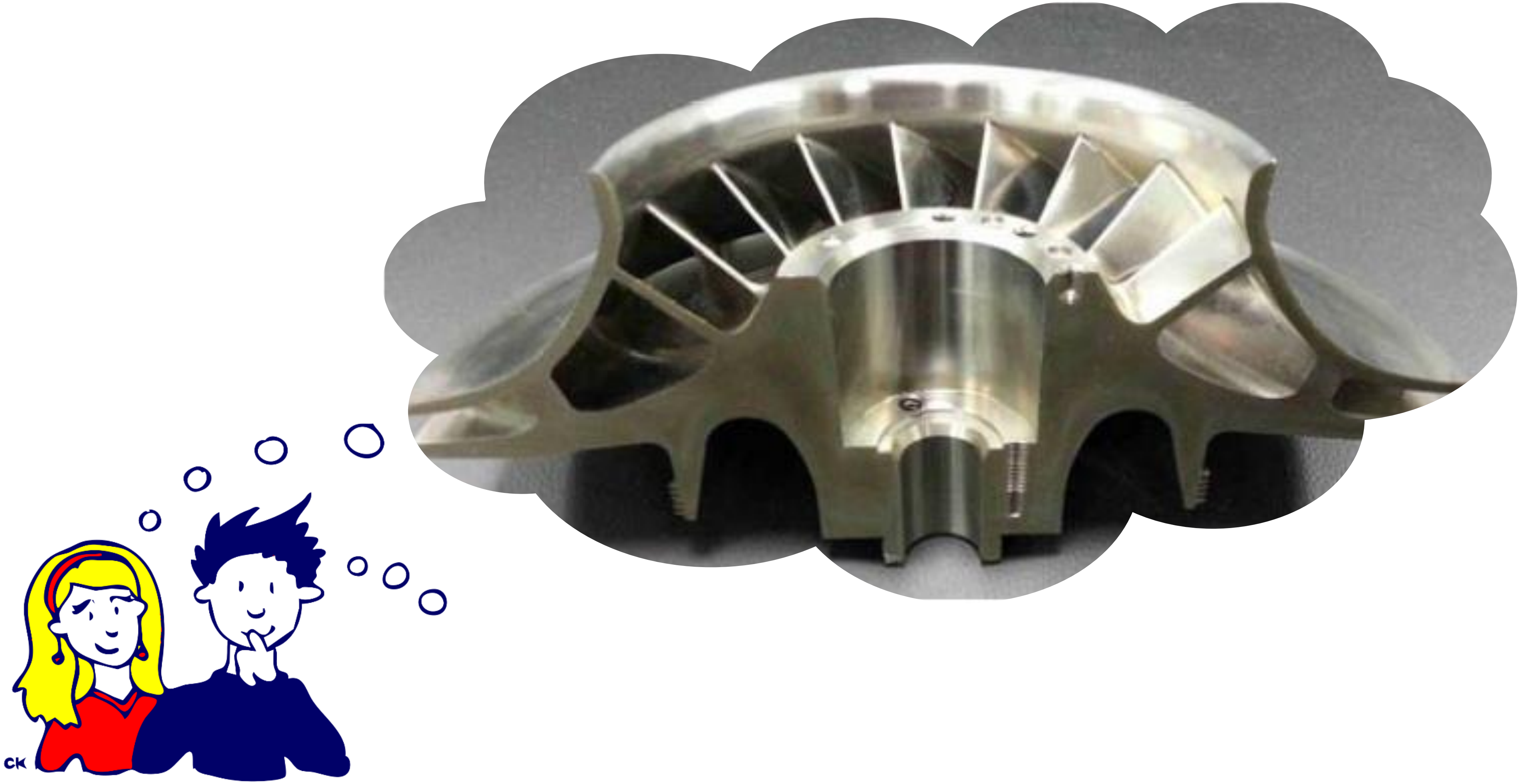
As-built surfaces of AlSi10Mg on Concept Laser X-Line.

Material	R_a (μm)
Inconel 718	5.05
GRCop-84	5.44
AlSi10Mg	3.29

Typical as-built surface roughness (SLM)

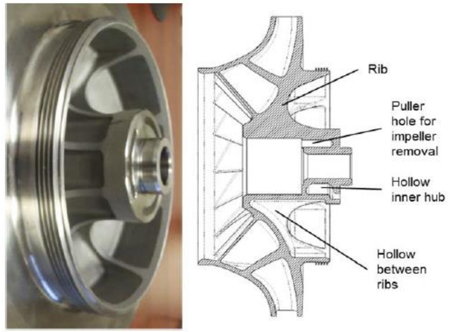
Printing Exercise #3

I want to try something I'd actually use…



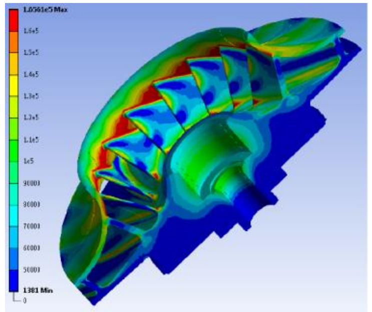
Printing Exercise #3

Design for AM

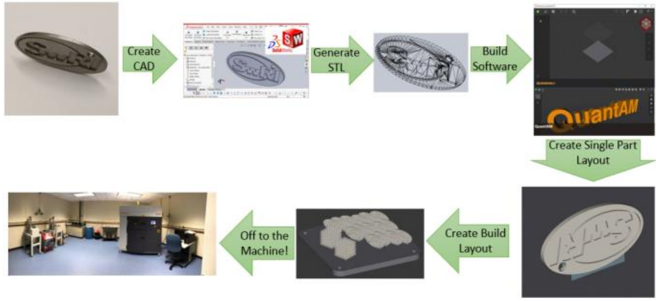


Closed Centrifugal Compressor Impellors

Material:
SS 17-4 PH

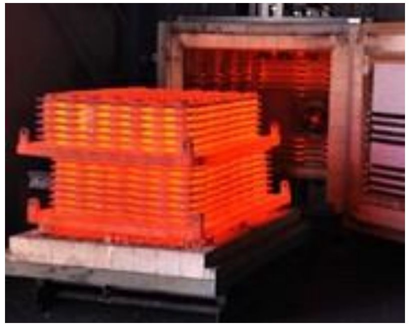


Prepare for Printing

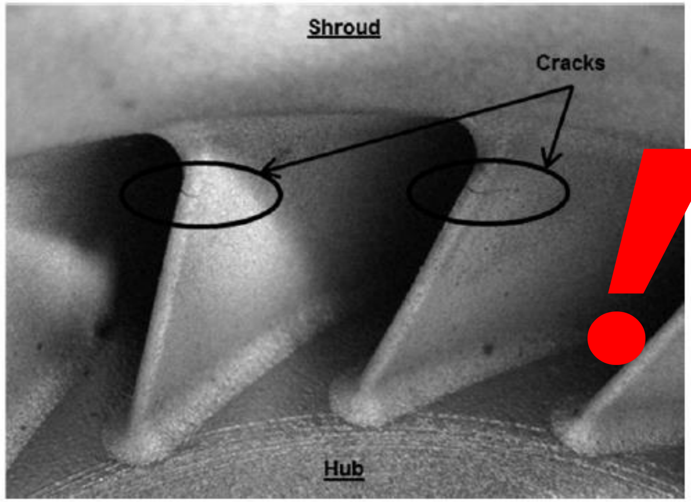


Print and Remove Part

Post Process



Inspect

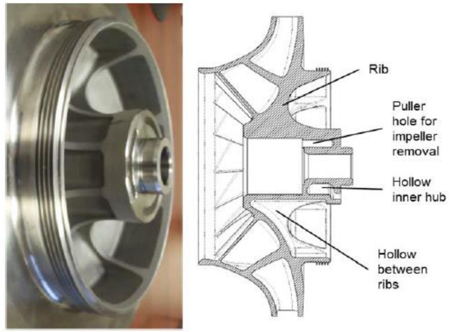


!

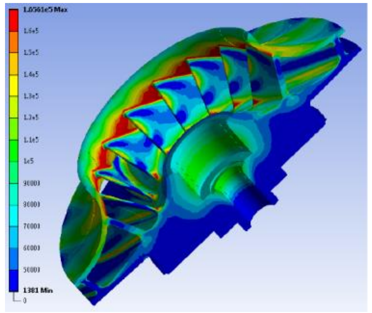
What happened?!?!

Printing Exercise #3

Design for AM

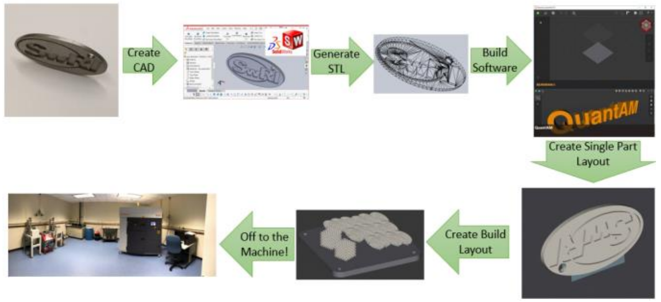


Material:
Inconel 718
Ti-6Al-4V



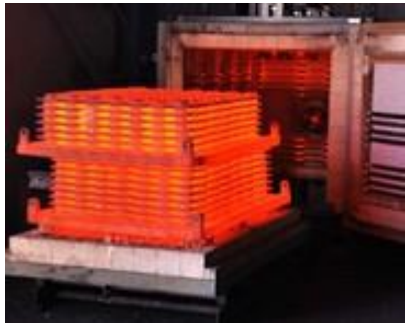
Closed Centrifugal Compressor Impellors

Prepare for Printing



Print and Remove Part

Post Process



Inspect

Looks Good So It Must Be Right? How Can We Make Sure?

Printing Exercise #3

NDE

Support material remains after extrude hone finish

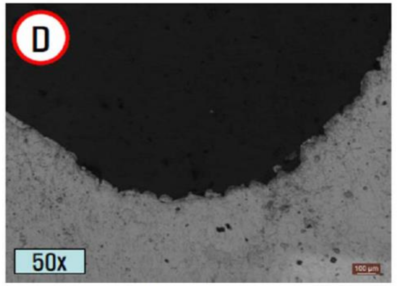


Figure 12. Magnified View of Fillet Region Between Impeller Blade and Shroud

Destructive Evaluation

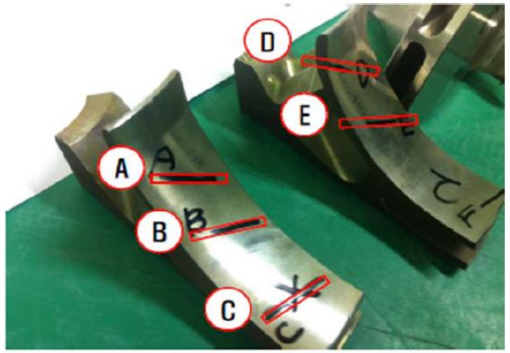


Table 2. Dimensional Accuracy of Manufactured Impellers

Impeller	Impeller Exit Width Accuracy (inches)	Flow Path Surface Roughness (R_a)
1st Generation 0.08 ϕ Impeller	+0.011	NA
1st Generation 0.11 ϕ Impeller	NA	NA
2nd Generation 0.08 ϕ Impeller Variation ‘a’	-0.015 to -0.010	63-125
2nd Generation 0.08 ϕ Impeller Variation ‘b’	-0.011 to -0.005	7-32
2nd Generation 0.08 ϕ Impeller Variation ‘c’	-0.005 to +0.000	16
2nd Generation 0.11 ϕ Impeller Variation ‘a’	-0.014 to -0.012	63-125
2nd Generation 0.11 ϕ Impeller Variation ‘b’	-0.005	63-125
2nd Generation 0.11 ϕ Impeller Variation ‘c’	-0.003	16-92

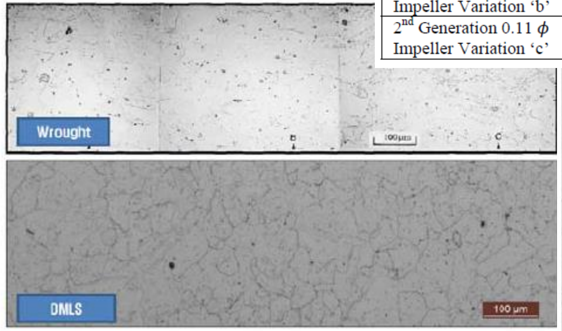


Figure 13. Comparison of Grain Size Between Wrought Inconel 718 and DMLS Inconel 718

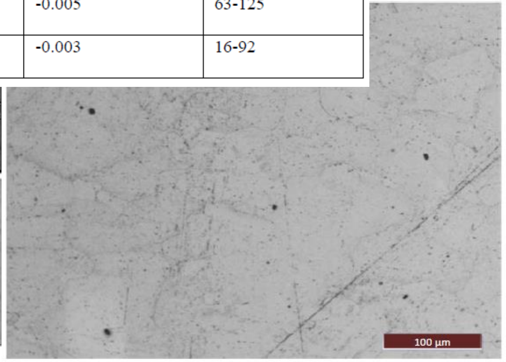


Figure 14. Magnification of DMLS Inconel 718 Sample Showing Micro-Porosity

Application Testing

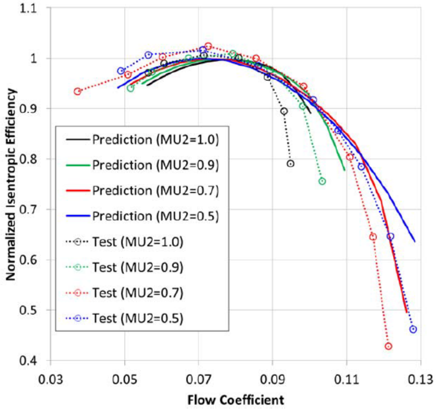


Figure 18. Comparison of Predicted and Tested Normalized Isentropic Efficiency vs. Flow Coefficient

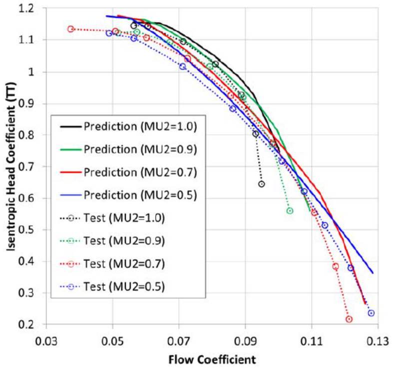


Figure 17. Comparison of Predicted and Tested Head vs. Flow Coefficient

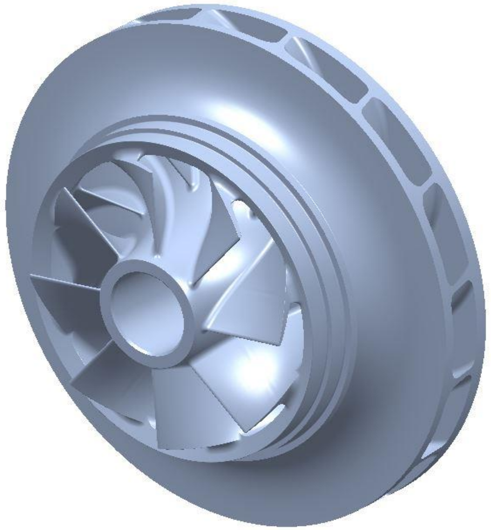
Allison, T.C., Moore, J.J., Rimpel, A.M., Wilkes, J.C., Pelton, R., Wygant, K., “Manufacturing and Testing Experience with Direct Metal Laser Sintering for Closed Centrifugal Compressor Impellers,” *Proceedings of 43rd Turbomachinery Symposium*, Houston, TX, September 2014.

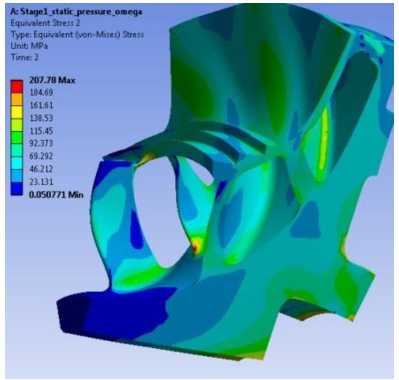
Printing Exercise #3

- Covered impeller for a compressor operating near the critical point in sCO2 cycle.
- Made using DMLS using Inconel 718
- Hanwha Techwin and SwRI have tested several impellers manufactured using this process
  - Internal testing has shown very good material properties can be achieved
- Passed spin testing for balance, over-speed, and performance
  - Geometry scaled up and performed in air.
- The resulting design is expected to achieve a significant range improvement over a traditional stage design.

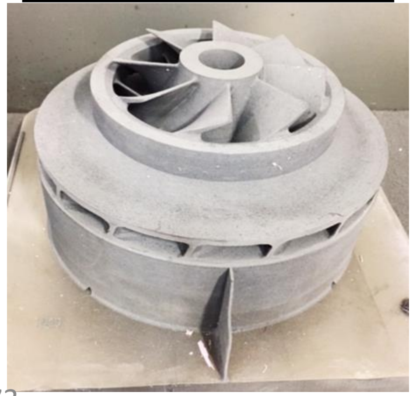
Pelton, R., Allison, T.C., Smith, N., Jung, J., “Design of a Wide-Range Centrifugal Compressor Stage for Supercritical CO2 Power Cycles,” *Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition*, Charlotte, NC, June 2017.

Extend Into New Applications





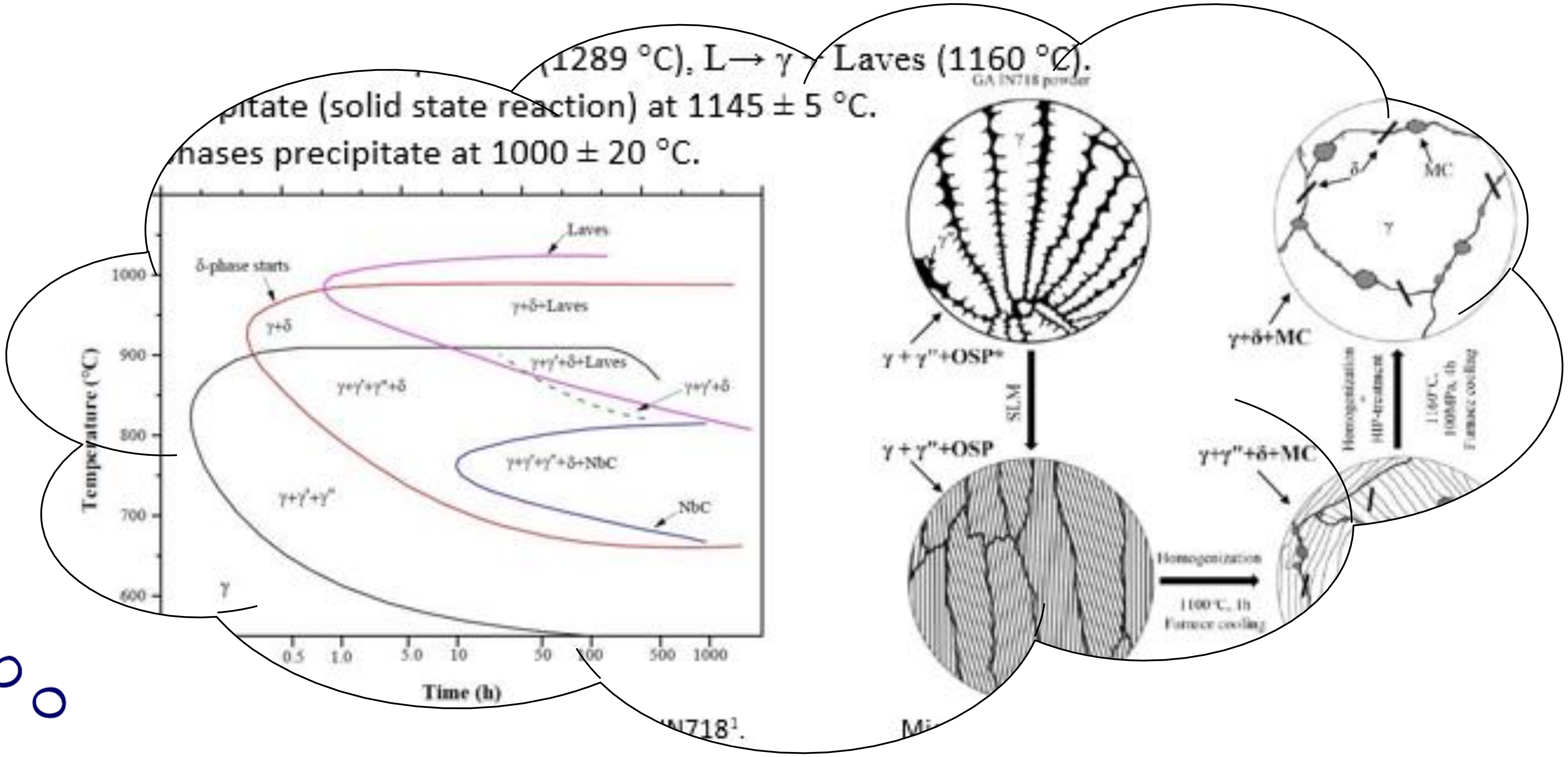
3D Printed Part (Unfinished)



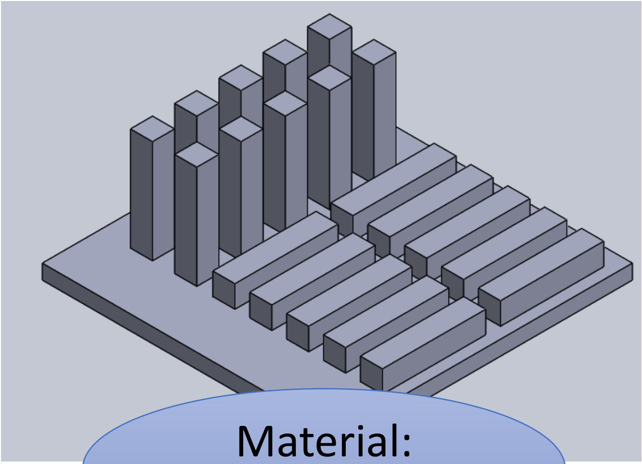
3D Printed Part (Finished)

Printing Exercise #4

What is my material……really?

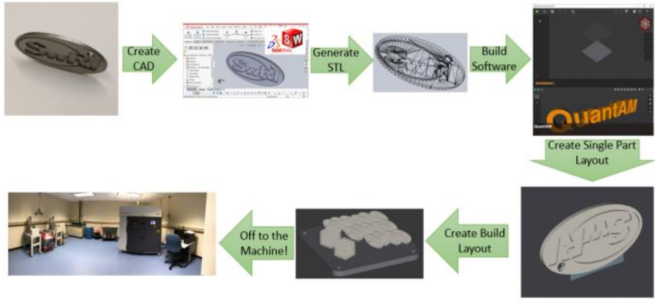


Printing Exercise #4

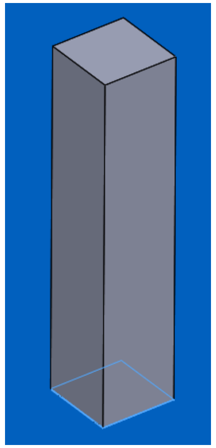


Material:
Inconel 738LC

Prepare for Printing

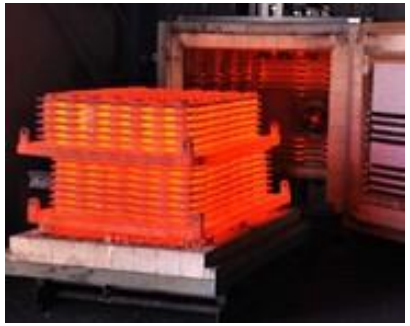


Print and Remove Part



Post Machining

Post Process



HIP/Heat Treat

Material Test

What Could You Learn?

Printing Exercise #4

Historical Cast In738 Data

Printed In738LC Data

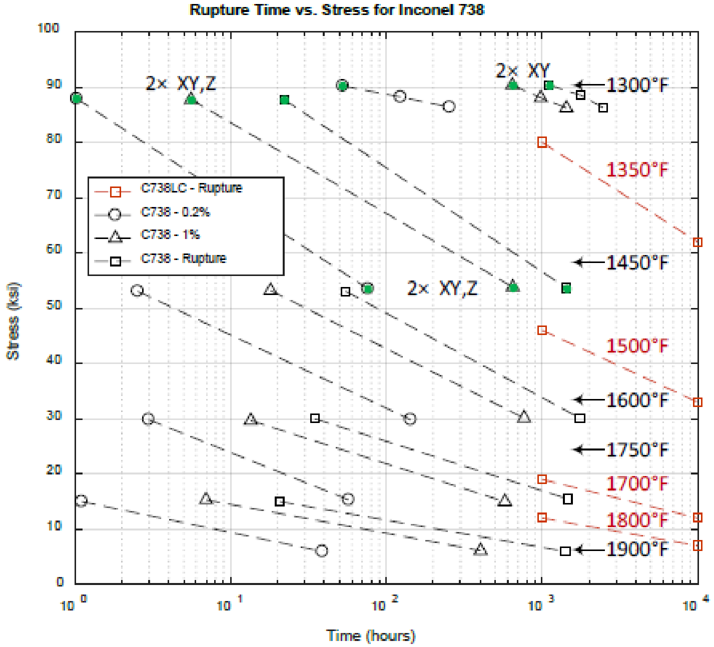
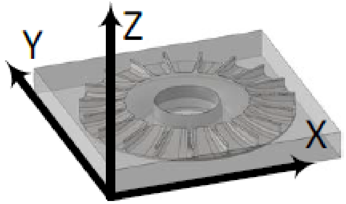
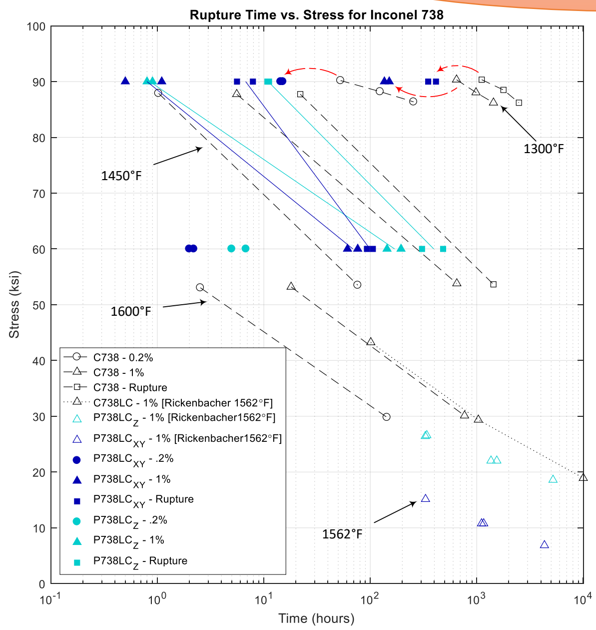
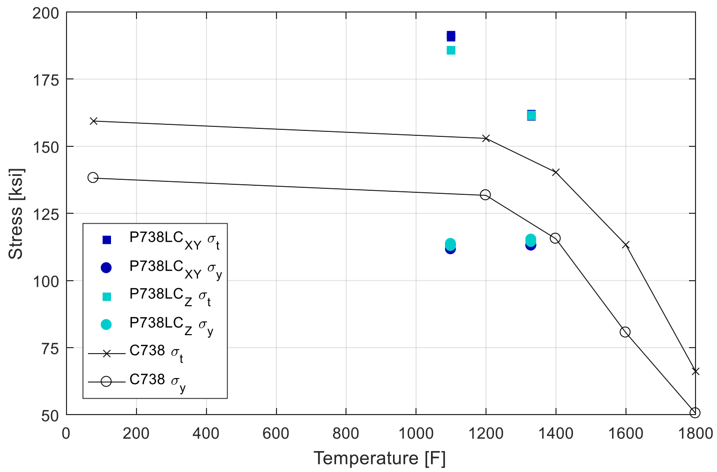


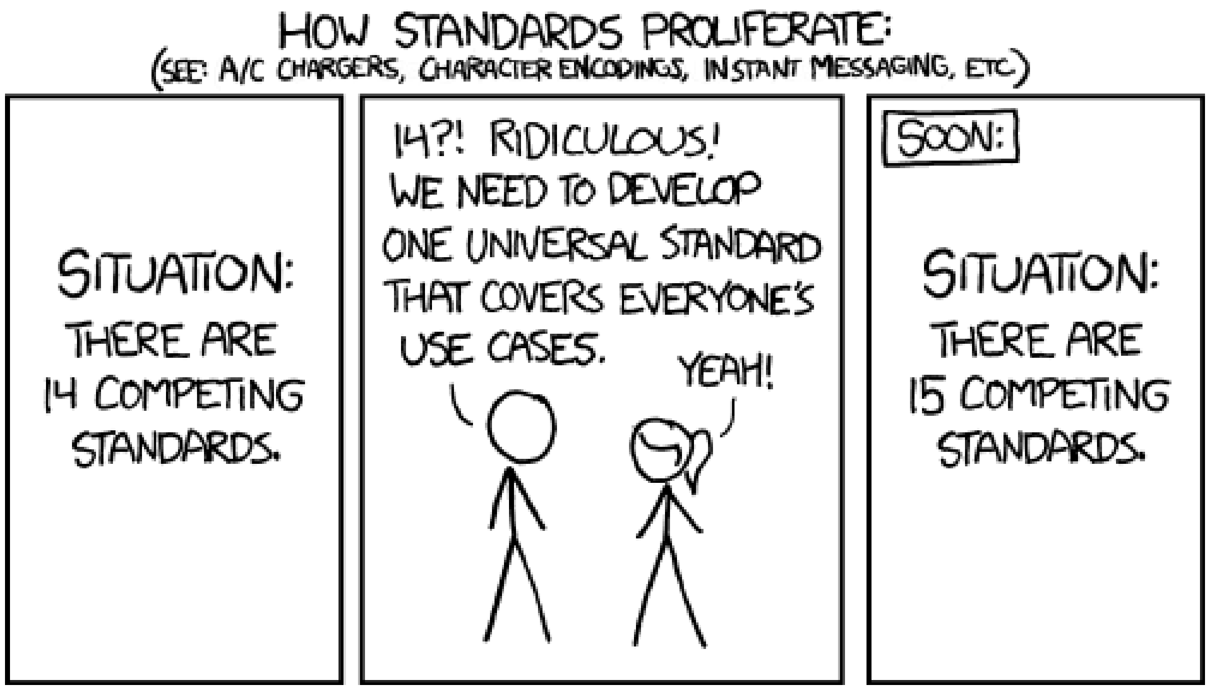
Figure 2: Cast Inconel 738 Creep Sample Data and Associated Test Points (Denoted by Green Accent), Heat Treat - 2050F, 2 hrs, AC +1550F, 24 hrs, AC (data taken from [8])







Specimen ID	Test Temper	Diameter (Inches)	Ultimate Strength	Yield Strength	Elongation (%)	Reduction Of Area (%)	Fracture Location
S1	1330	0.2507	162,000	113,000	17.5	27.1	Gage
S2	1330	0.2493	161,100	113,000	16.8	23.9	Gage
S3	1100	0.2498	190,600	111,600	15.4	23.5	Gage
S4	1100	0.2496	191,400	113,100	15.6	22	Gage
R1	1330	0.2507	161,300	114,300	21.6	34.1	Gage
R2	1330	0.2507	161,700	115,200	23.4	37.3	Gage
R3	1100	0.2509	185,800	113,600	15.2	23.1	Gage
R4	1100	0.251	185,700	112,800	14.6	22.1	Gage


HOW STANDARDS PROLIFERATE:
(SEE: A/C CHARGERS, CHARACTER ENCODINGS, INSTANT MESSAGING, ETC)
SITUATION: THERE ARE 14 COMPETING STANDARDS.
14?! RIDICULOUS! WE NEED TO DEVELOP ONE UNIVERSAL STANDARD THAT COVERS EVERYONE'S USE CASES.
YEAH!
SOON:
SITUATION: THERE ARE 15 COMPETING STANDARDS.

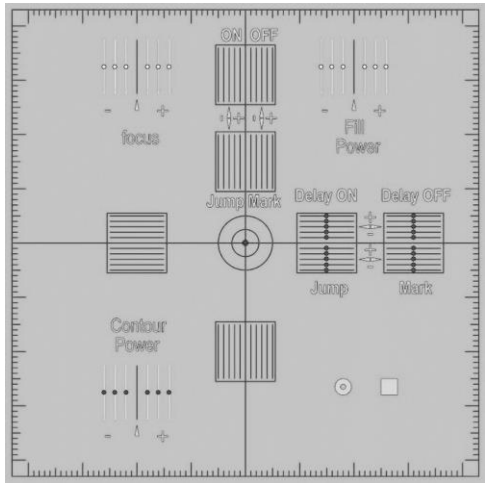
MSFC AM Flight Certification Standard

- 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.

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

Controlling document, requiring NASA approval.

Controlling document(s), not requiring NASA approval, but available for review.

Active database, not requiring NASA approval, but available for review.

Action or process.

Decisional action or process, with result available for review.

Part — Representation of part entering process.

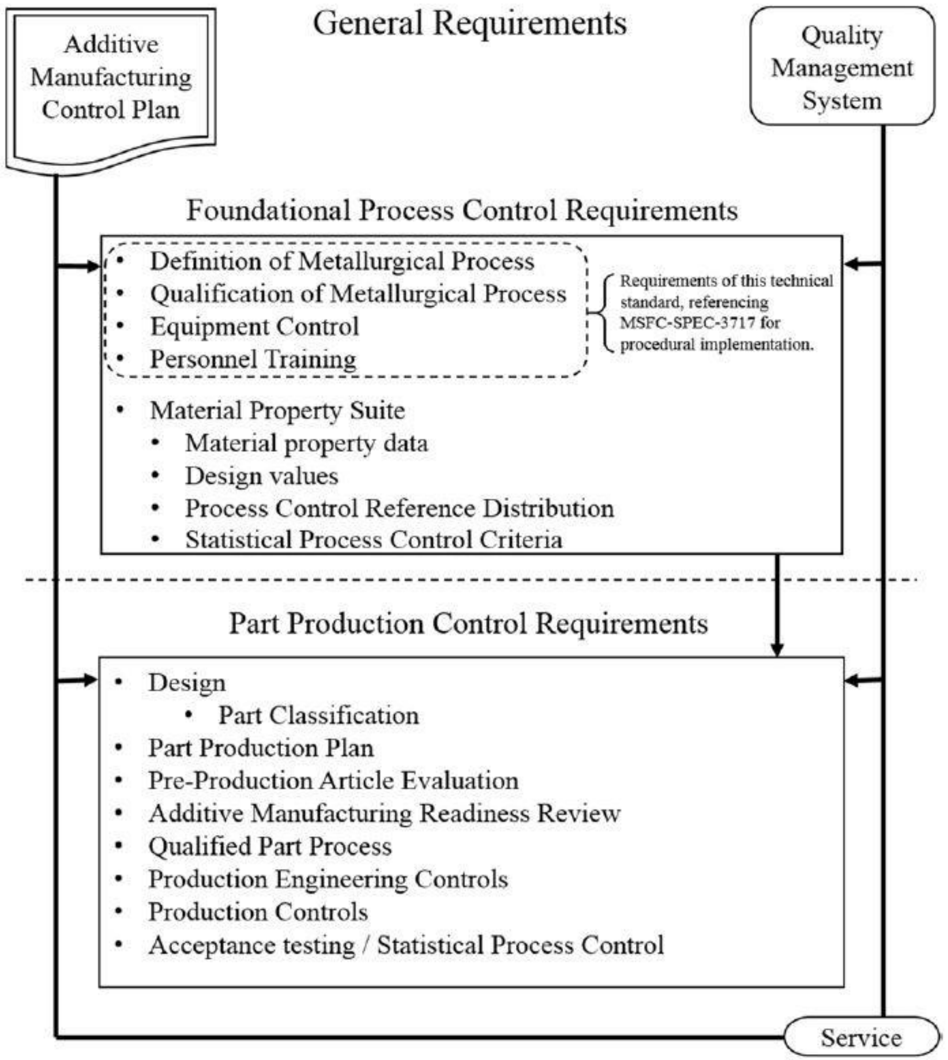
Requirements with procedural details contained in MSFC-SPEC-3717.

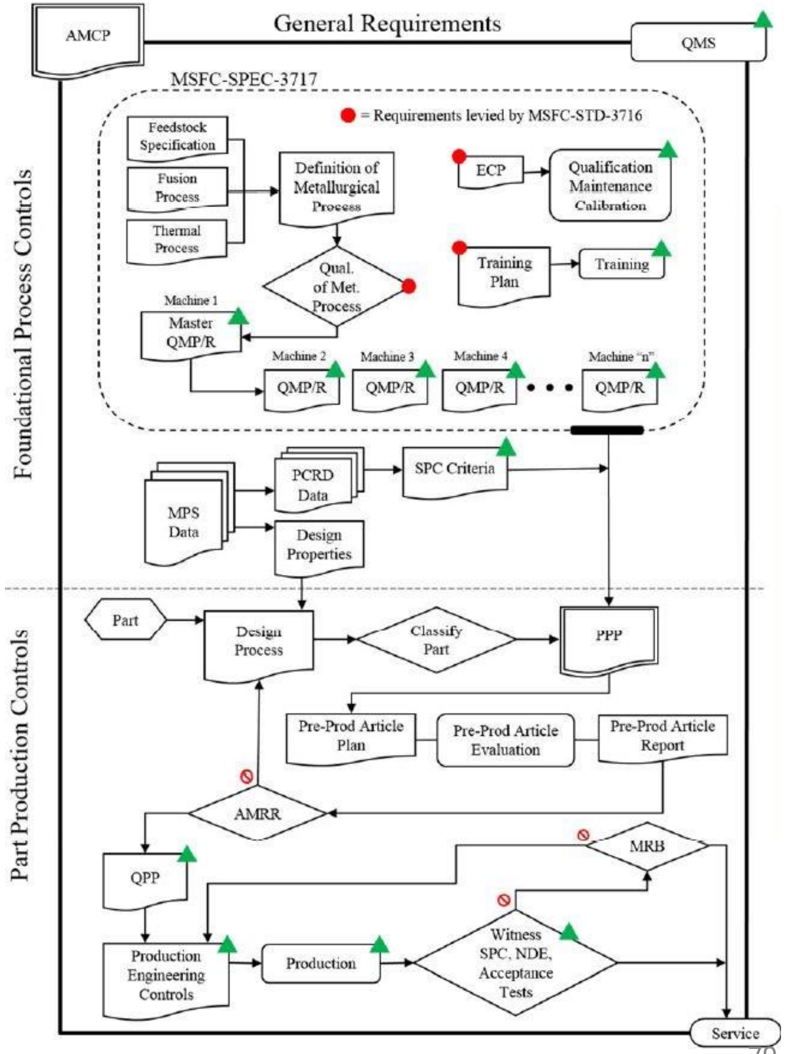
Service — Representation of part entering service.

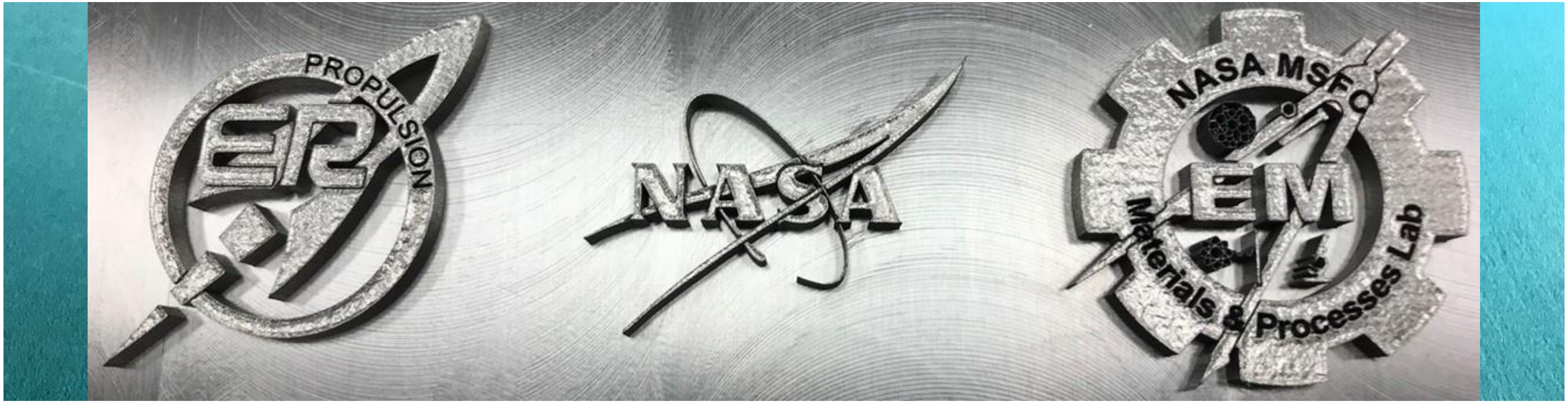
Identifies key points of QMS involvement.

Identifies PBF requirements levied by MSFC-STD-3716 with procedures in MSFC-SPEC-3717

Negative outcome of decisional action



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ER
NASA
NASA MSFC
EM
Materials & Processes Lab

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