Introduction to Additive Manufacturing for Propulsion Systems

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NASA

SwRI

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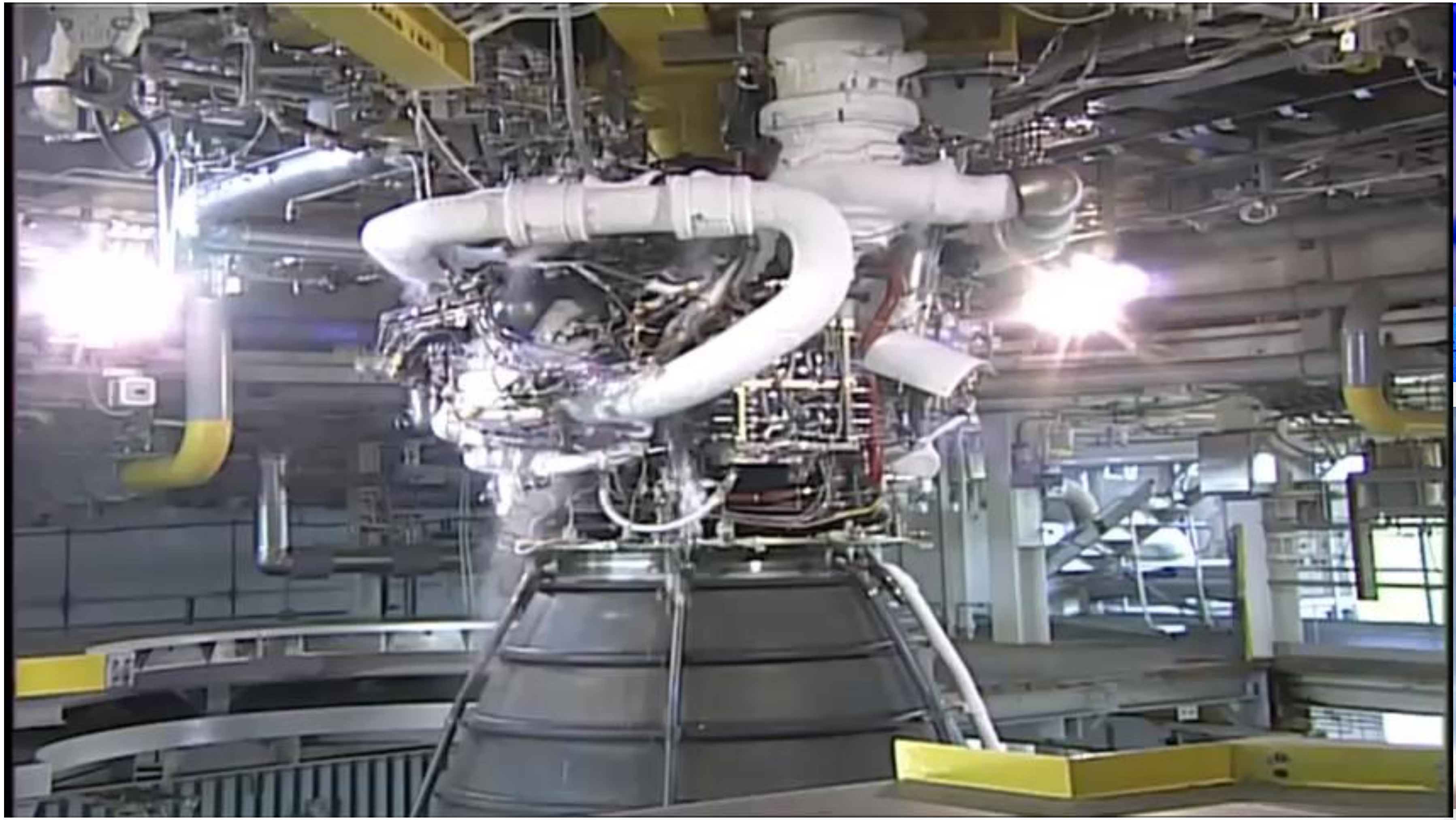
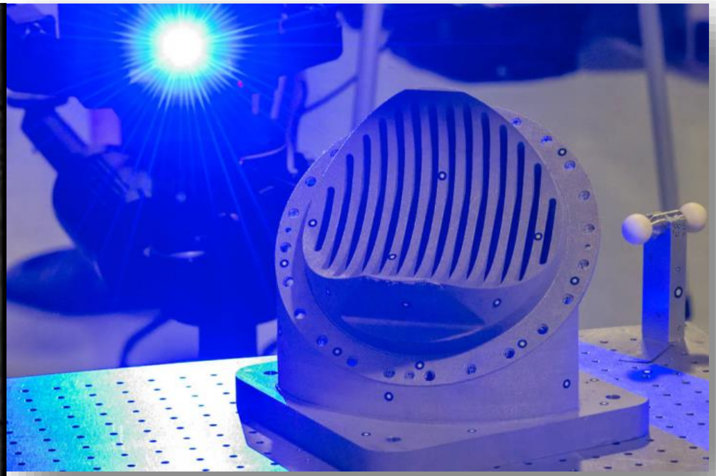
AIAA

Propulsion Energy and Forum 2019

Additive Manufacture is real…



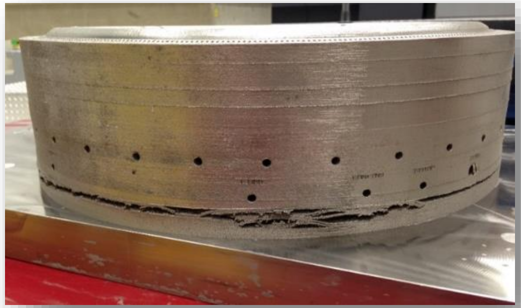


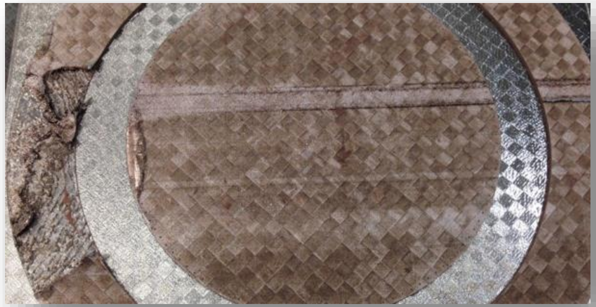
Successful hot-fire testing of full-scale additive part to be flown on NASA's Space Launch System (SLS)

RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from <u>127 welds to 4 welds</u>

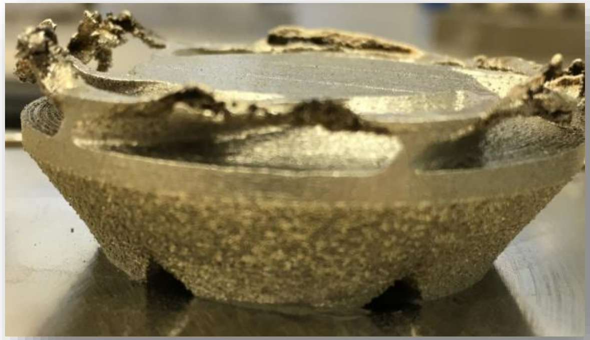
Ref: Andy Hardin, Steve Wofford/ NASA MSFC

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

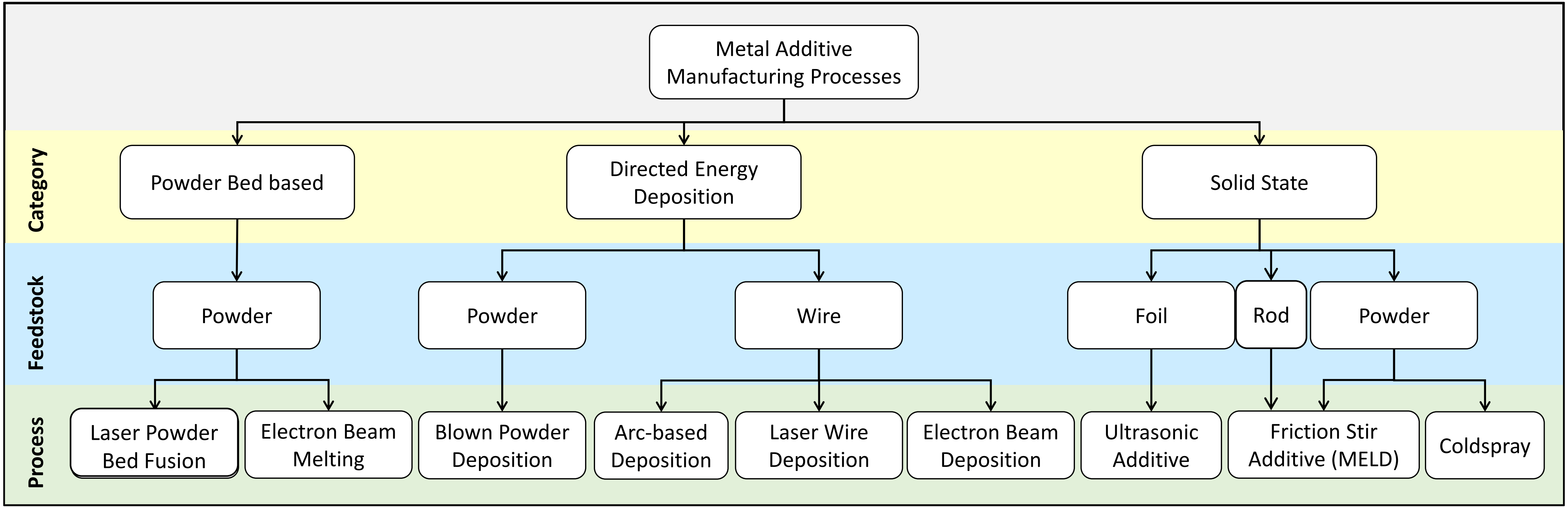
Design for AM and Detailed Fabrication Cases

- Details of Builds Process and Development – L-PBF
- How to Design for AM
- Build Failures
- Post-Processing
- Future Advancements

Introduction to Additive Manufacture (AM)

- Additive Manufacture (AM): The process of joining materials together to create objects from 3D models.
- AM is not the solve-all to manufacture. Trade AM with other manufacturing methods and implement *only* where appropriate.
- A complete understanding of design, build, and post-processing critical to utilization.
- AM takes practice!

Metallic Additive Techniques

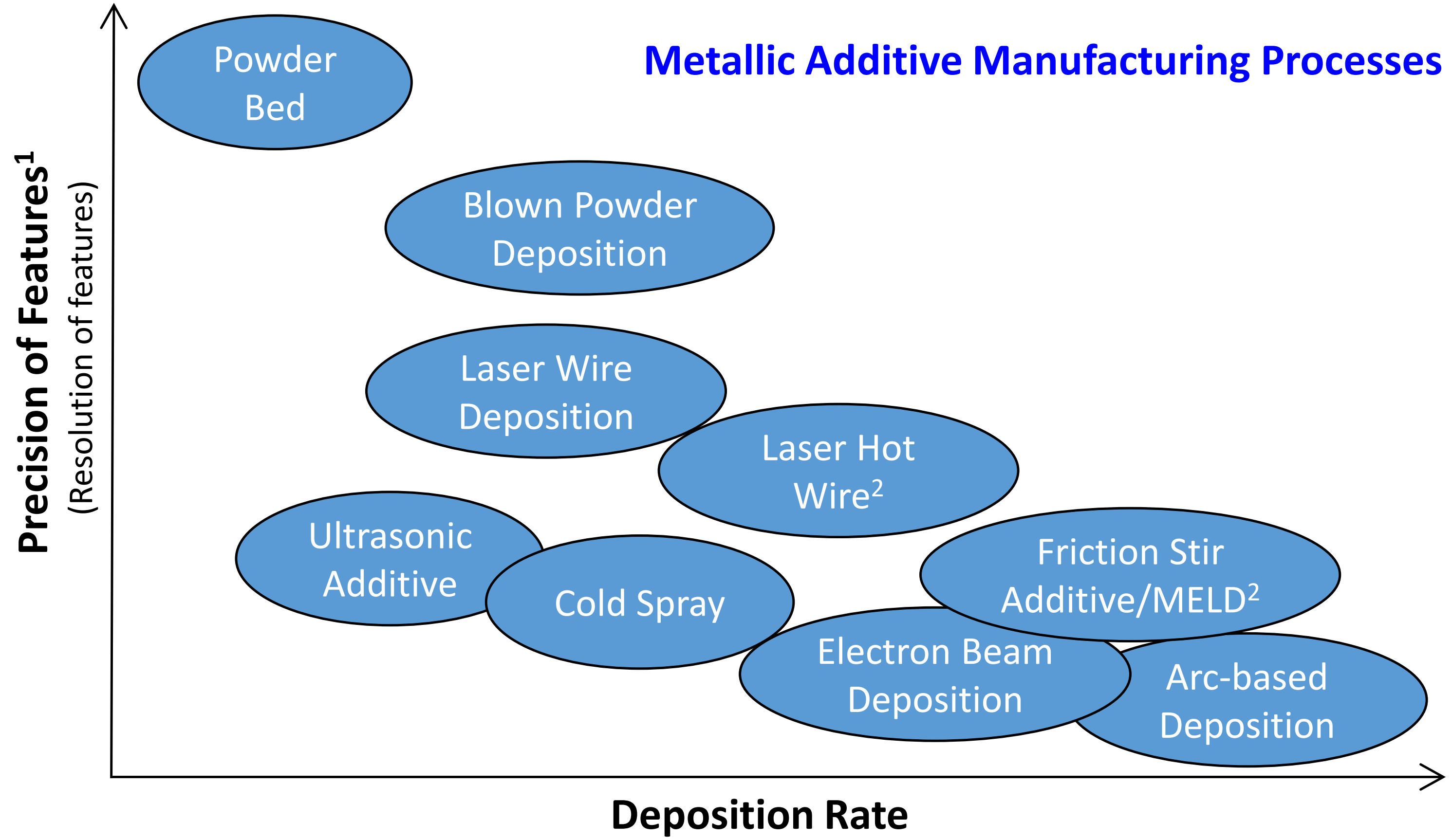


Other metal additive processes are being developed and exist such as binder-jet, material extrusion, joule printing, material jetting, vat photopolymerization, although public data limited at this time.

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).
- Gradl, P.R., Greene, S.E., Protz, C., Bullard, B., Buzzell, J., Garcia, C., Wood, J., Osborne, R., Hulka, J. and Cooper, K.G., 2018. Additive Manufacturing of Liquid Rocket Engine Combustion Devices: A Summary of Process Developments and Hot-Fire Testing Results. In *2018 Joint Propulsion Conference* (p. 4625).

Why use one AM technique over another?



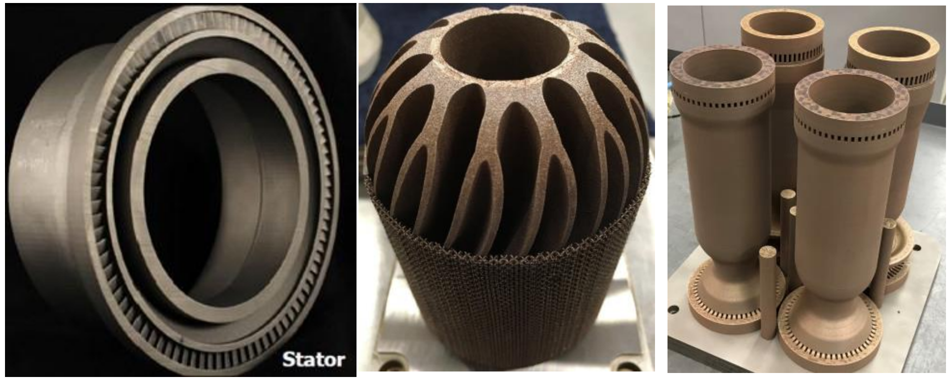
[1] Precision refers to the as-built state and does not encompass hybrid techniques and/or interim machining operations that would increase resolution. There are a lot of other factors not considered in this chart, including heat inputs to limit overall distortion.
[2] Technology still under development

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

Advantages and Disadvantages of AM

Advantages:

- Components that are highly complex and low production rate.
- Features that could not be fabricated by other methods.
- Increased design freedom and customization.
- High feature resolution.
- 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.



Disadvantages:

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

Examples of AM Metallic Alloys

Materials developed for L-PBF, E-PBF, 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-41Re
Mo-47.5Re
C103
Ta

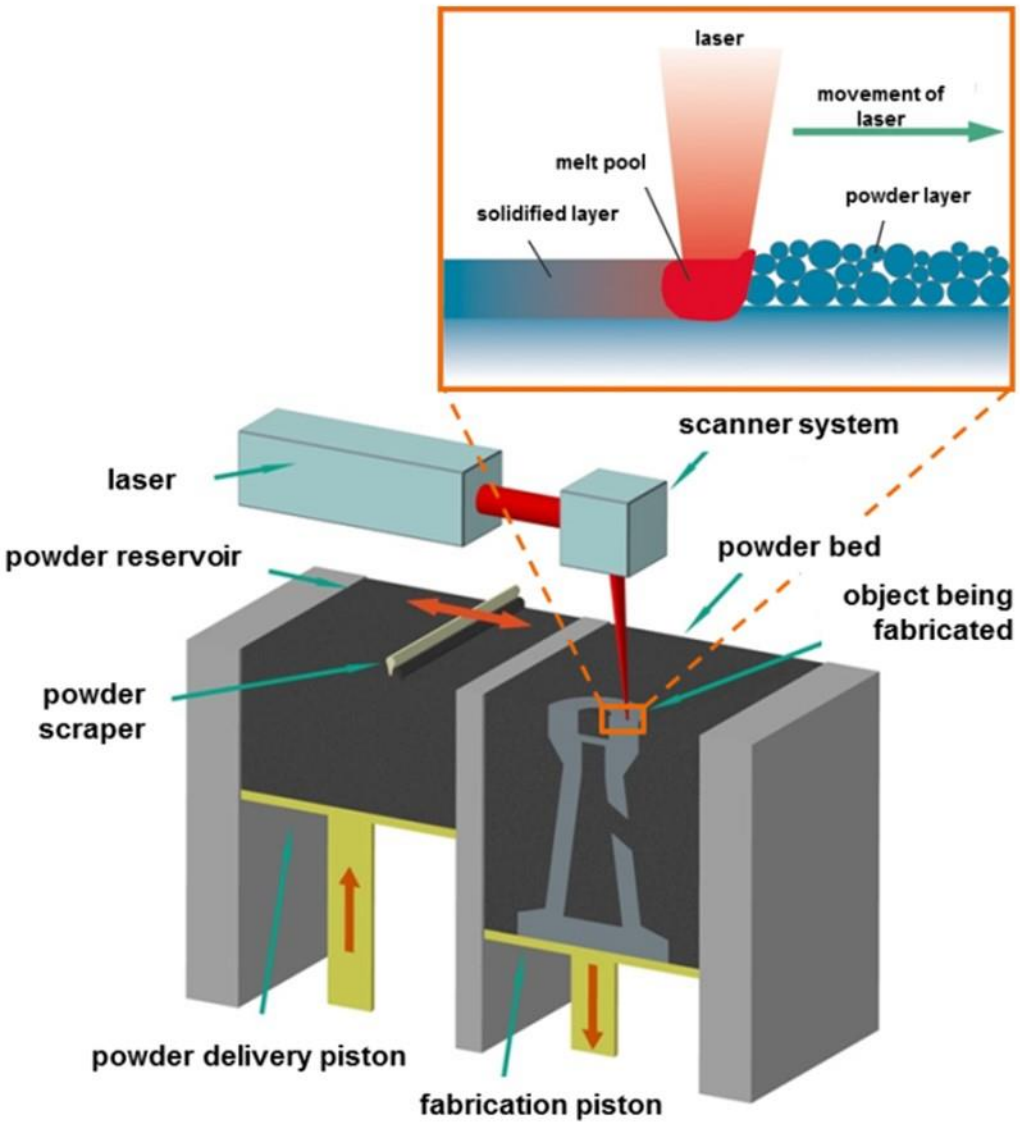
Bimetallic
GRCop-84/IN625
C-18150/IN625

MMC
Al-base
Fe-base
Ni-base

Powder Bed Fusion

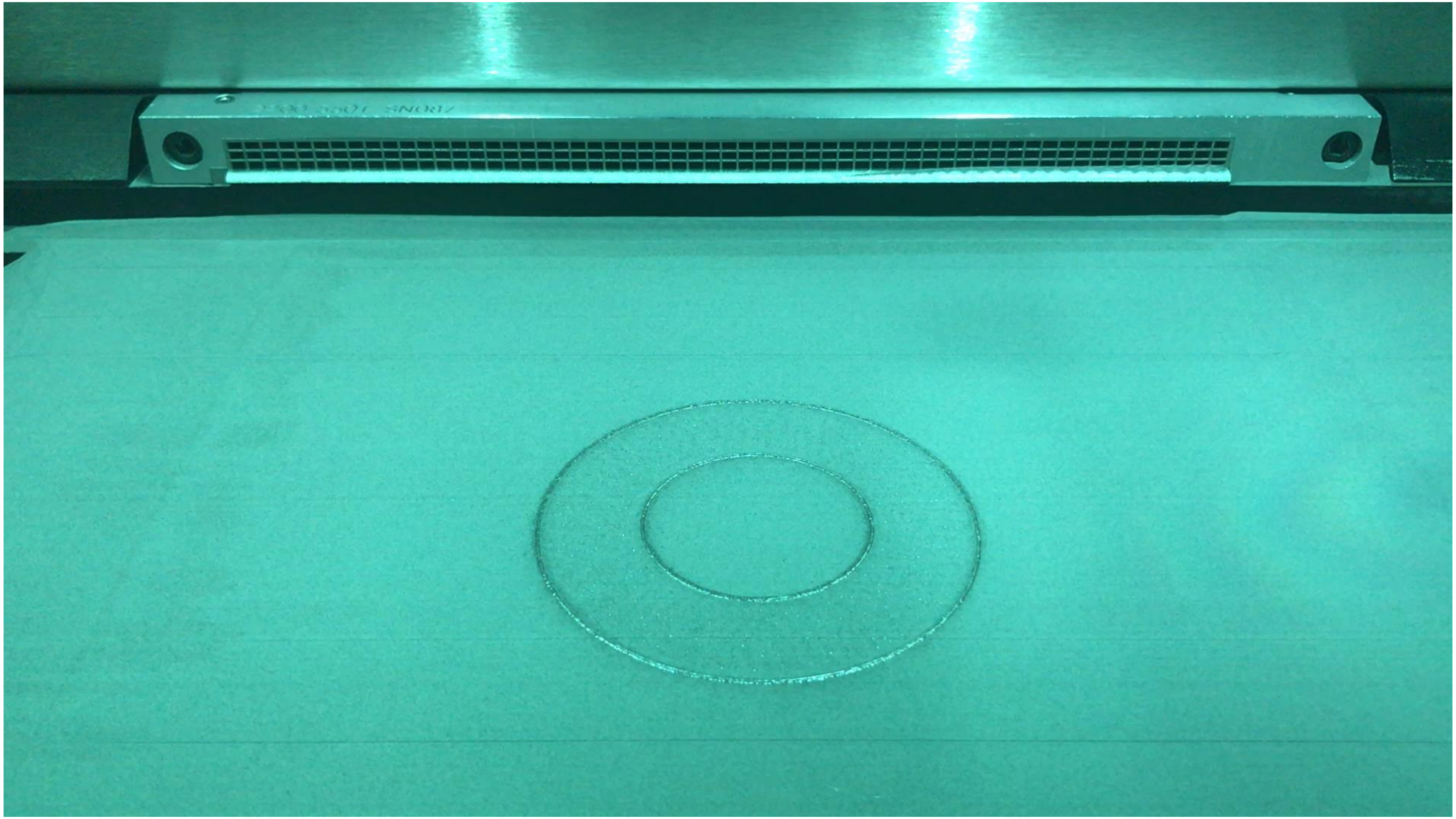
- **Laser Powder Bed Fusion (L-PBF)**
  - Basic Process: Layer-by-layer powder-bed approach where desired features are melted using a laser and solidify.
  - Advantages: High feature resolution, complex internal designs such as cooling channels.
  - Disadvantages: Scale limited and does not provide a solution for all components.

- **Electron Beam Melting**
  - Basic Process: Similar to L-PBF, but uses an electron beam.
  - Advantages: Performed in-near vacuum, which is useful for reactive materials such as Ti6A4V.



Process Illustration. Image courtesy Simufact.

L-PBF Operations

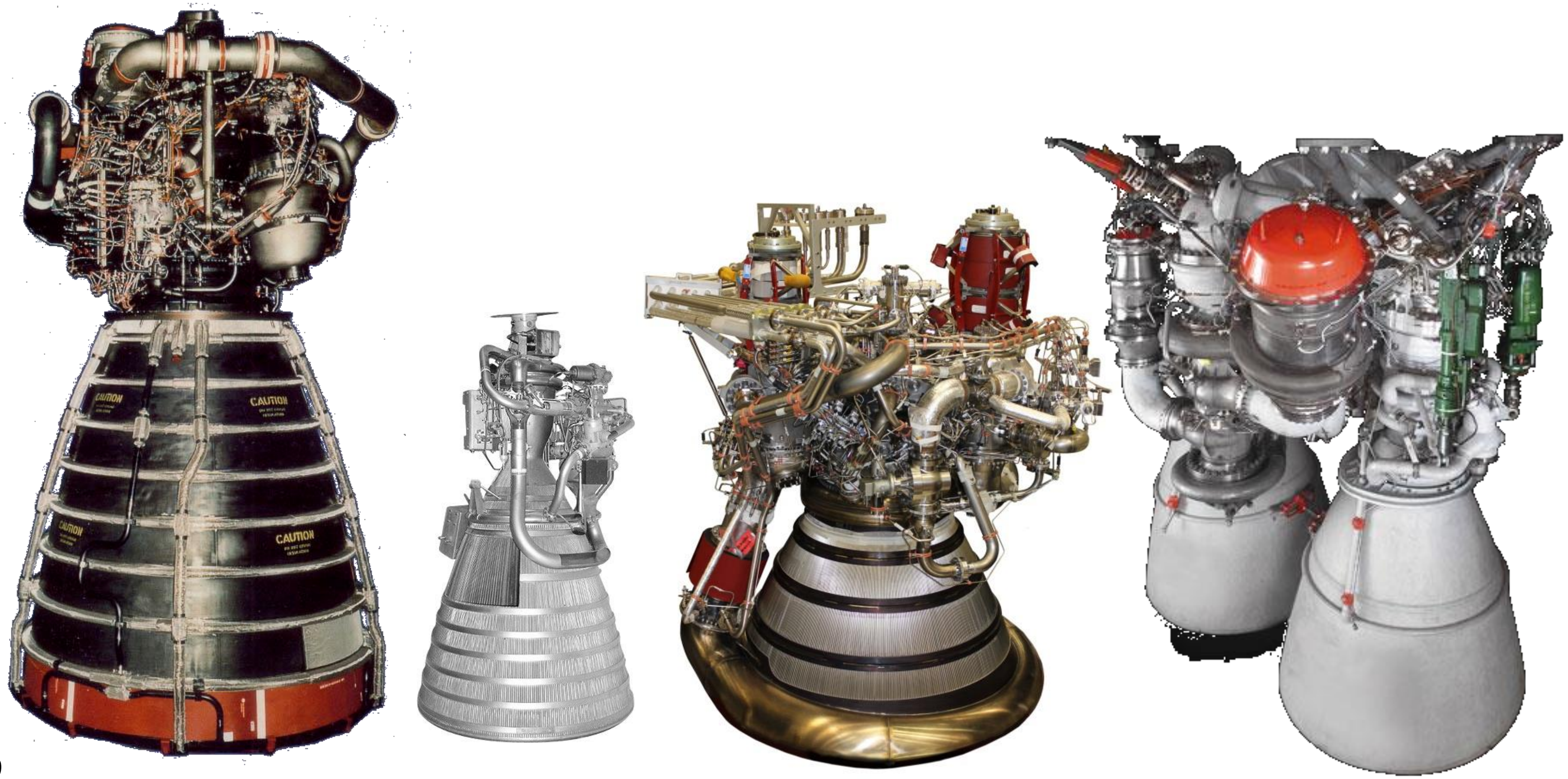


EOS M290, IN718

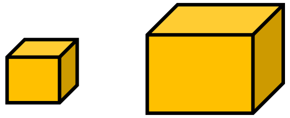
L-PBF Scale vs. Engine Scale

Engine

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



L-PBF Build Boxes



10x10x10 15.5x24x19
(inches)

90″ 46″ 70″ 56″

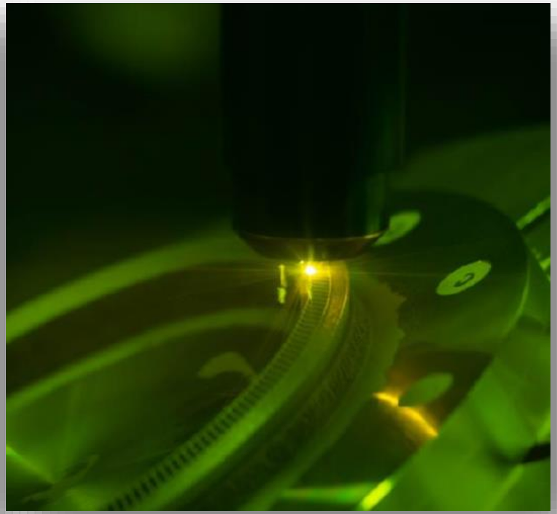
Nozzle Exit Dia.

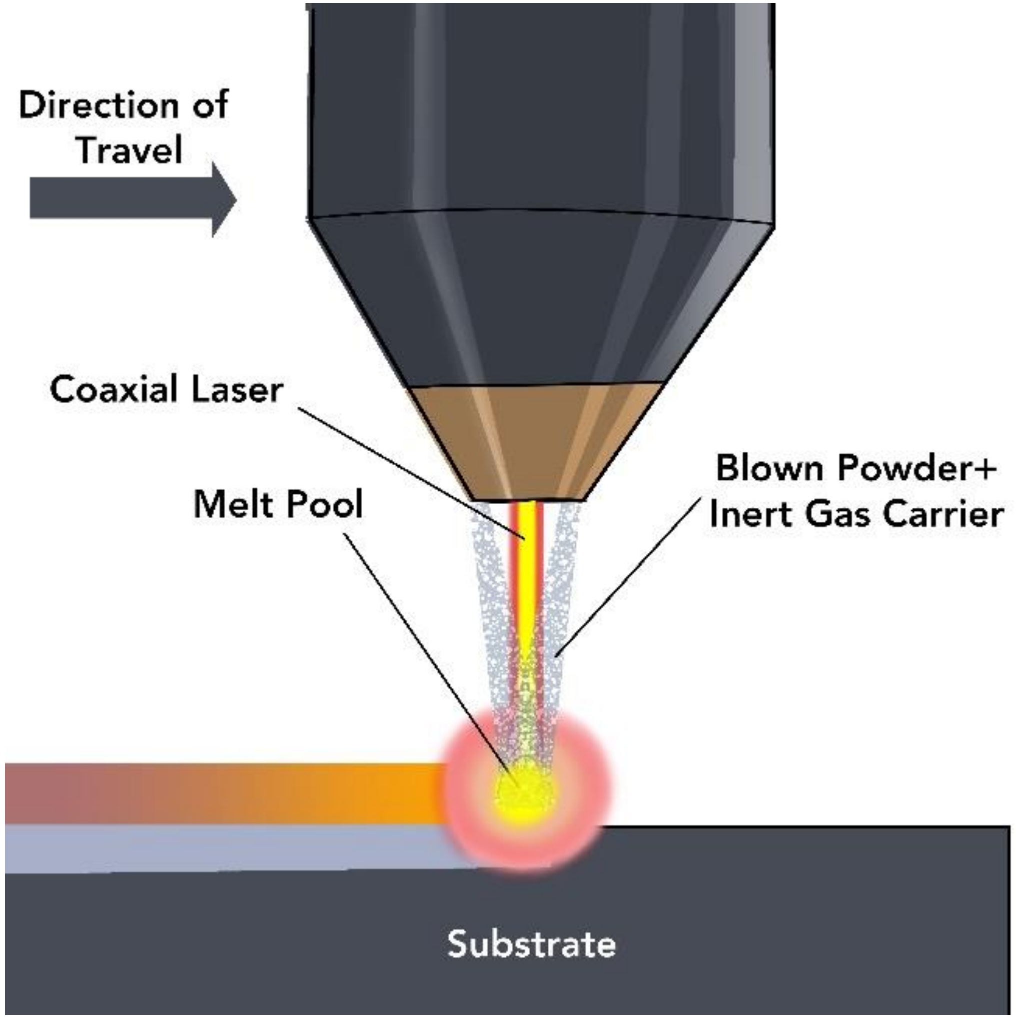
Gradl, P.R., Brandsmeier, W. Alberts, D., Walker, B., Schneider, J.A. **Manufacturing Process Developments for Large Scale Regeneratively-cooled Channel Wall Rocket Nozzles**
Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

Directed Energy Deposition (DED)

Blown Powder Directed Energy Deposition (DED)

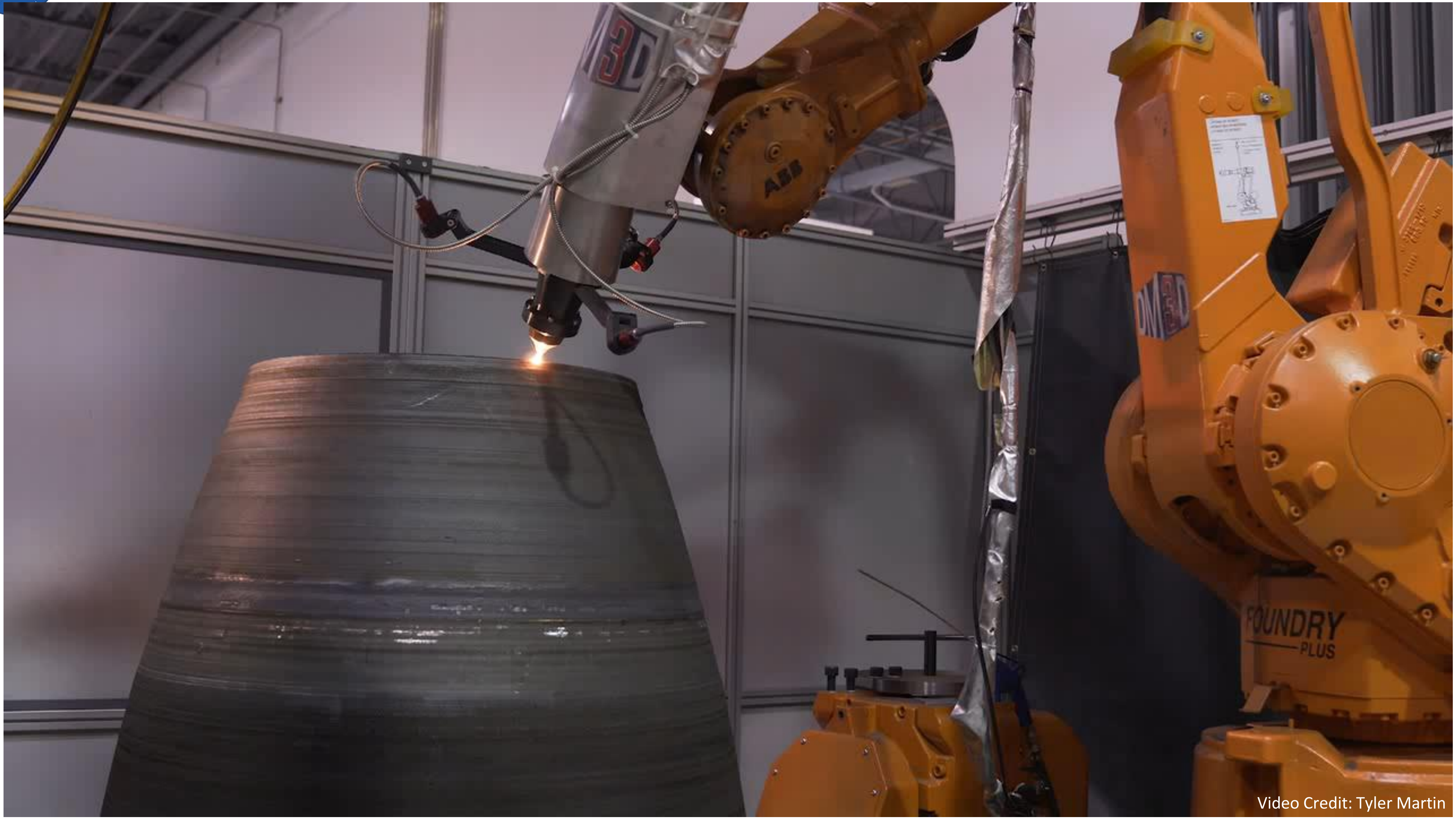
- Basic Process: Coaxial laser energy source with surrounding nozzles that inject powder (within inert gas) fabricating freeform shapes or cladding
- Advantages: Large scale (only limited by gantry or robotic system), multi-alloys in same build, high deposition rate
- Disadvantages: Resolution of features, rougher surface that L-PBF, higher heat input





*Process pictures courtesy RPM Innovations and DM3D (photo credit: Tyler Martin)

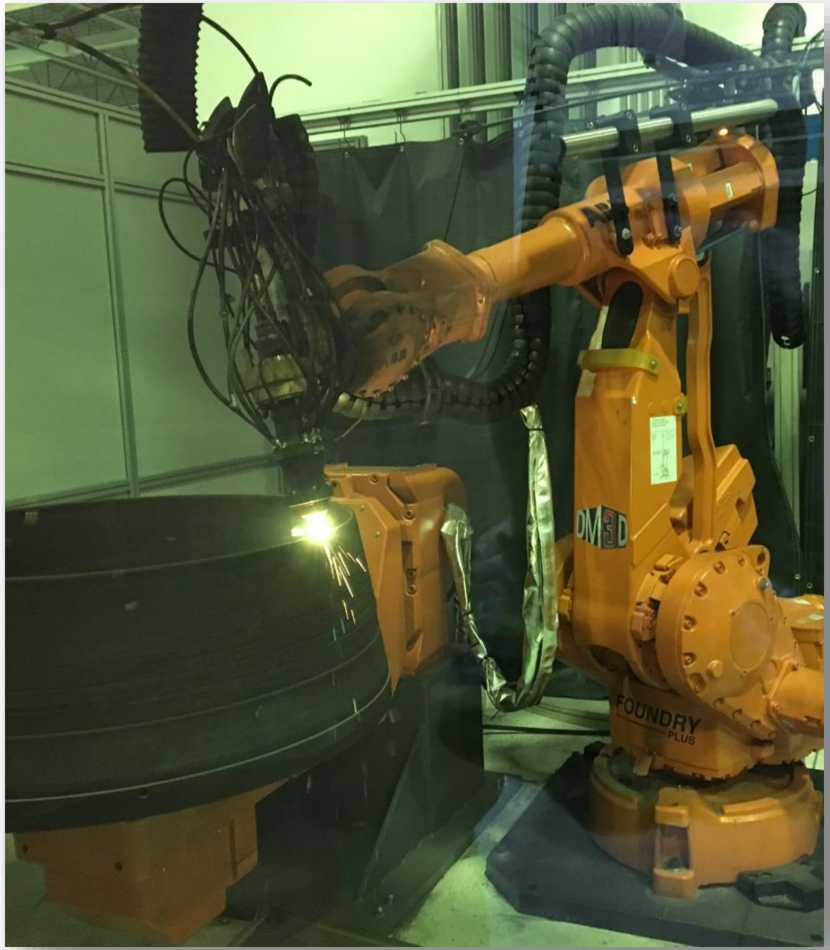
Directed Energy Deposition (DED)



Video Credit: Tyler Martin

Large Scale Example of DED

Rapid fabrication using blown powder Directed Energy Deposition (DED) of channel wall nozzle liners to reduce lead time and cost >50%



1/2 scale RS25 channel wall nozzle liner (without coolant channels)

Various Directed Energy Deposition (DED) Technologies

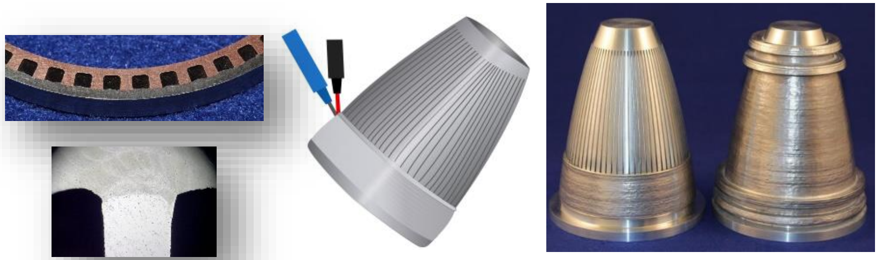
Freeform fabrication technique focused on near net shapes as a forging or casting replacement and also near-final geometry fabrication. Can be implemented using powder or wire as additive medium.

Blown Powder Deposition / Hybrid

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

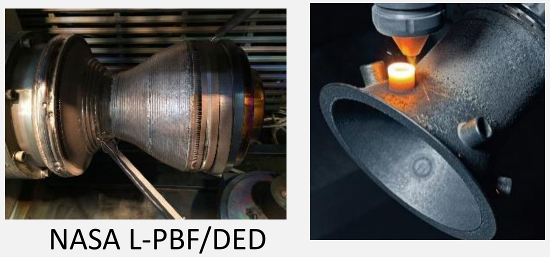
Laser Wire Deposition

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 L-PBF/DED
- Combine AM with subtractive
- Wrought and DED

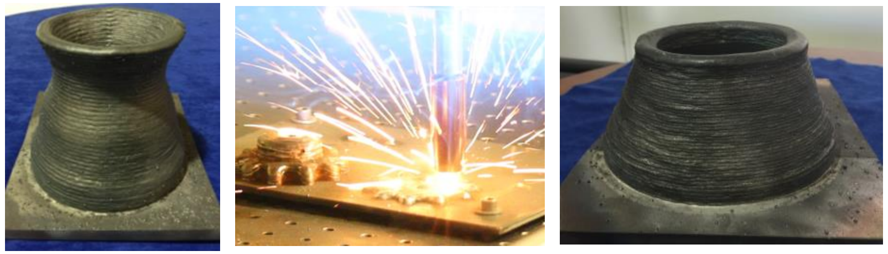


NASA L-PBF/DED

*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

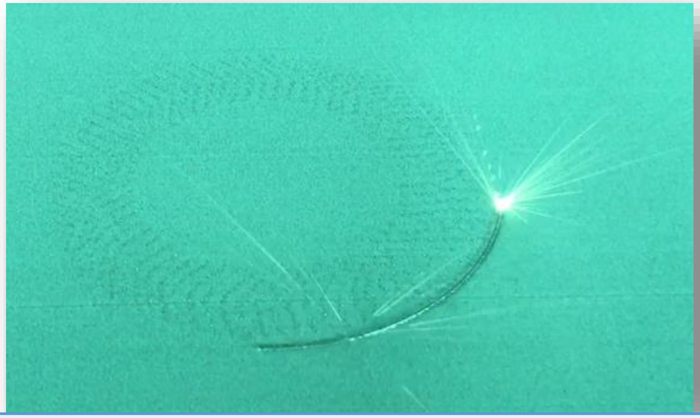
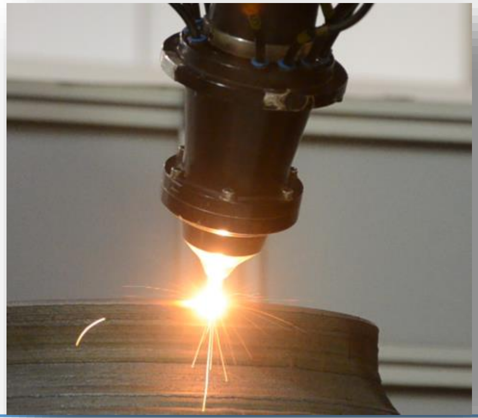


Electron Beam Deposition (wire)

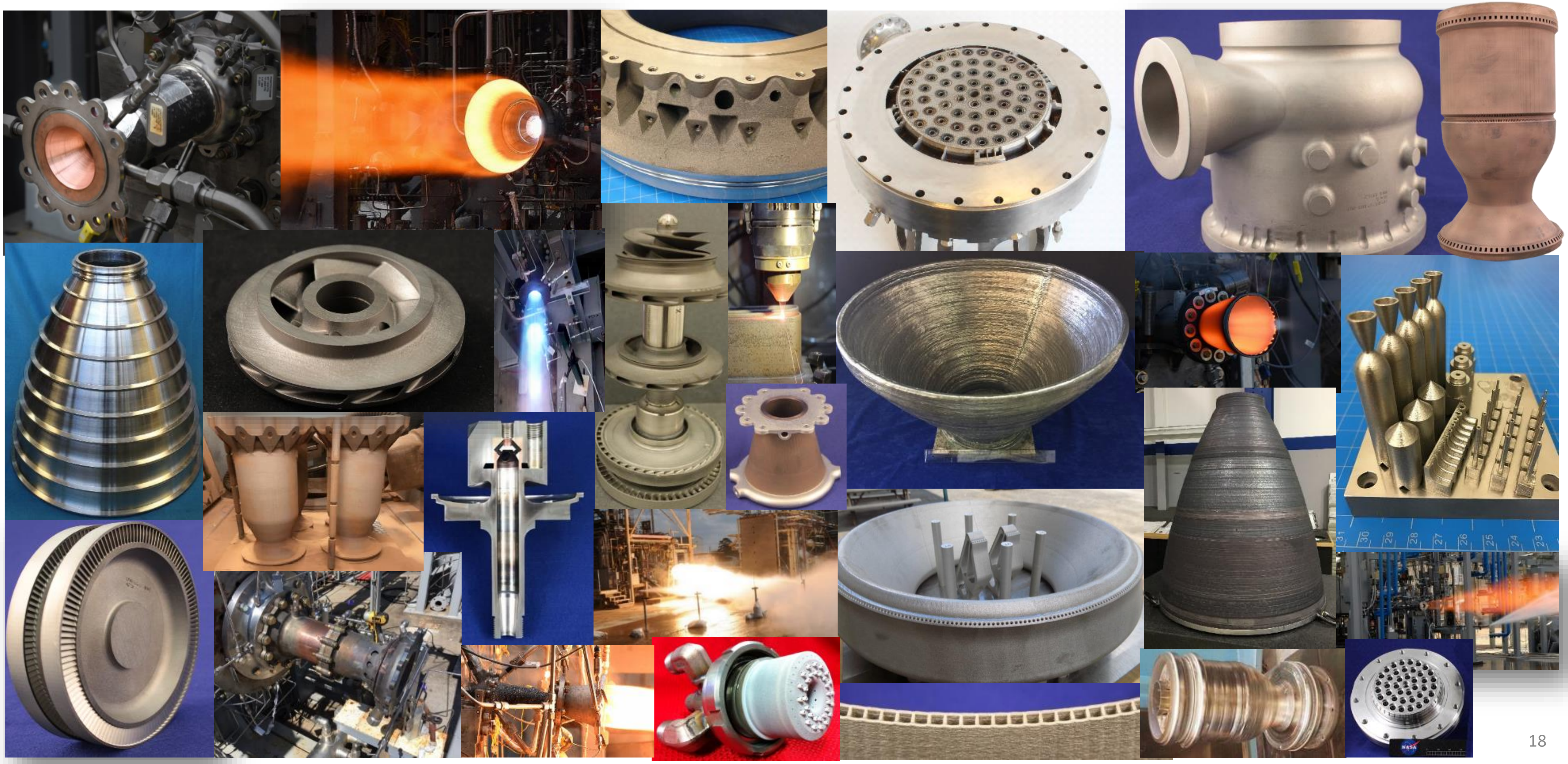
An off-axis wire-fed deposition technique using electron beam as energy source; completed in a vacuum.

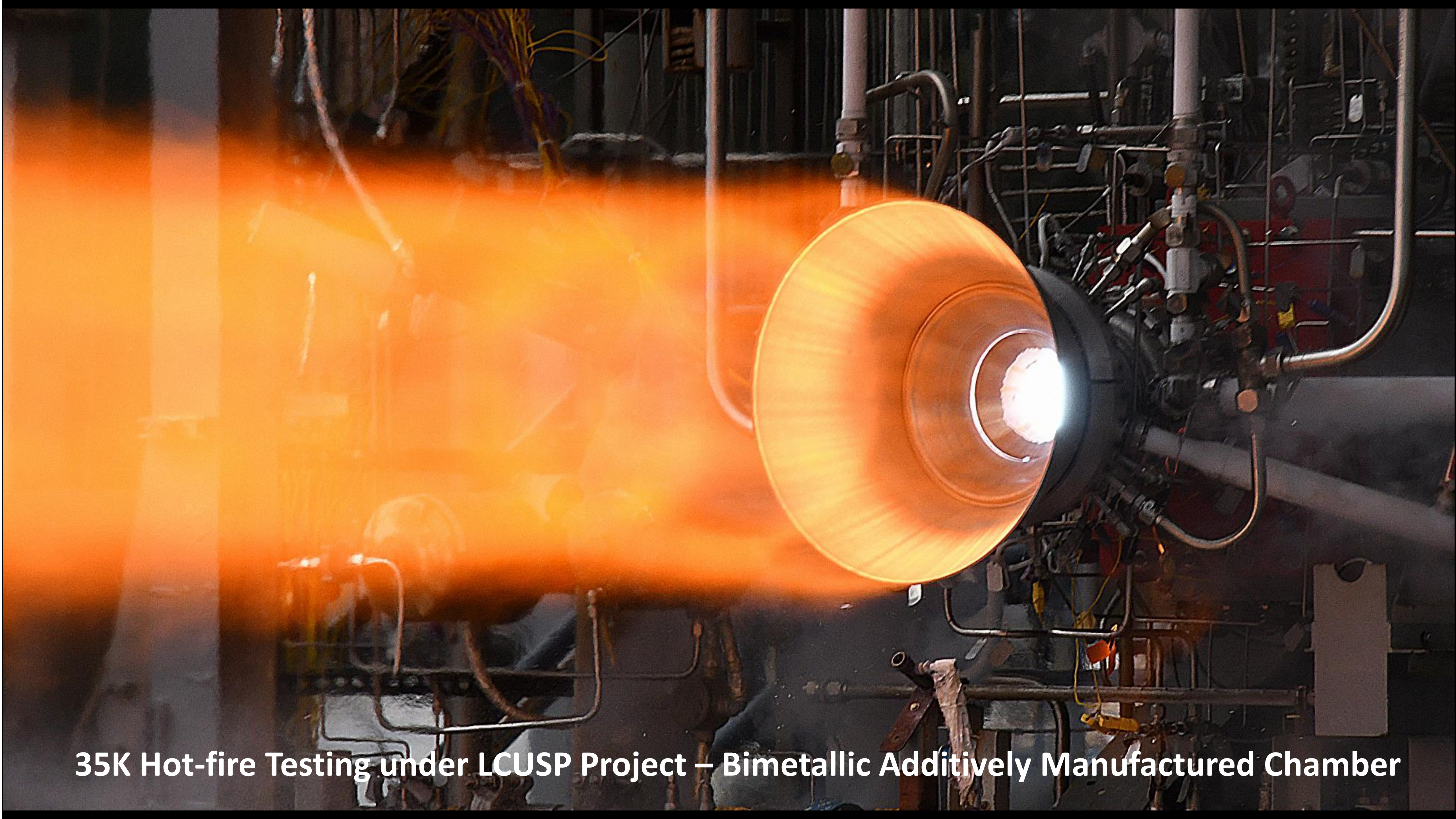
Comparison of L-PBF with DED

Different methods for different components!

	Laser Powder Bed Fusion (L-PBF)	Directed Energy Deposition (DED)
		
Feature Resolution / Complexity	High resolution of features Wall thicknesses and holes <0.010” ✚	Medium resolution of features Walls >0.040” and limited holes
Deposition Rate	Low build rates <0.3 lb/hr	✚ High Build rates lbs per hour (some systems >20lb/hr)
Multi-alloys / Gradient Materials	Monolithic materials in single build	✚ Option for multi-alloys or gradients within single build
Materials Available	High number of materials available and being developed ✚	✚ High number of materials available and being developed
Production Rates	Higher volume with several parts in a single build ✚	Generally limited to single builds; longer programming/setup time
Scale / Size of components	Limited to existing build volumes <15.6” dia or 16”x24”x19”	✚ Scale is limited to gantry or robot size
Added Features / Repair	No (limited) ability to add material to existing part	✚ Can add material or features to an existing part

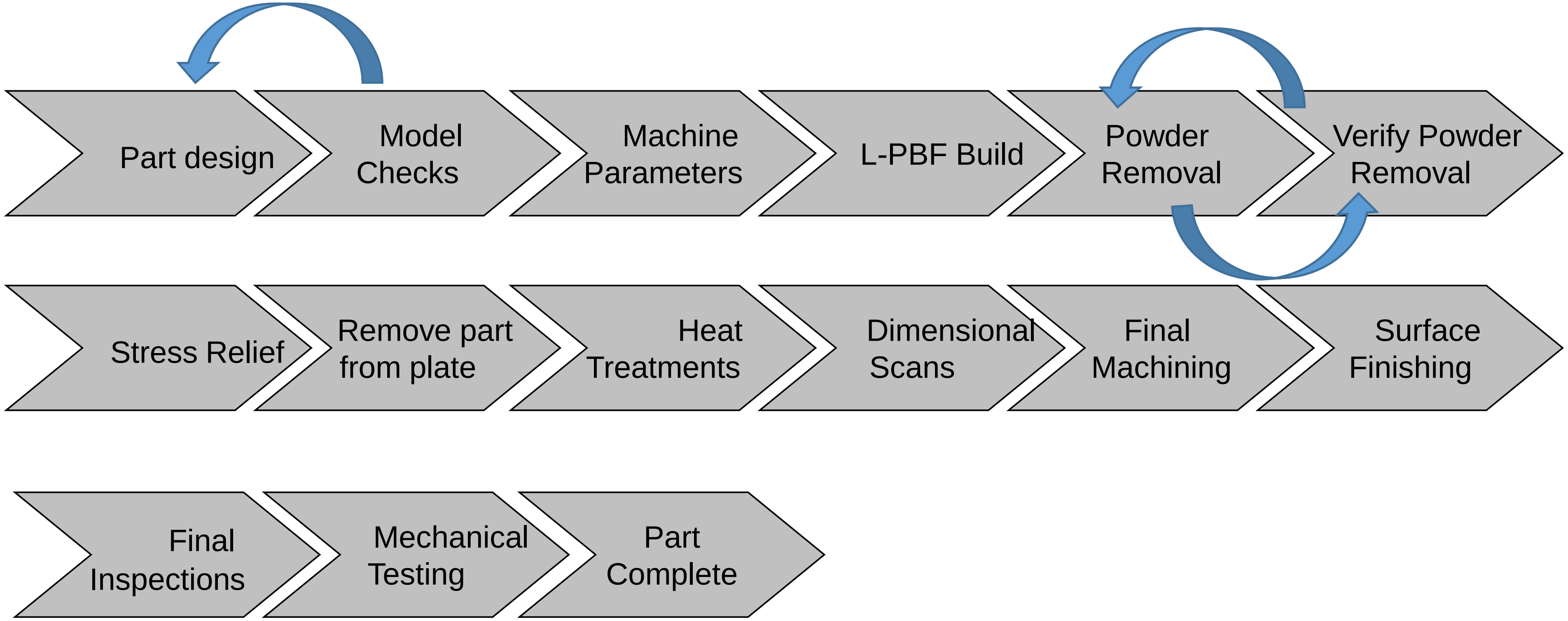
Examples of Additive Propulsion Components





35K Hot-fire Testing under LCUSP Project – Bimetallic Additively Manufactured Chamber

AM Process Flow

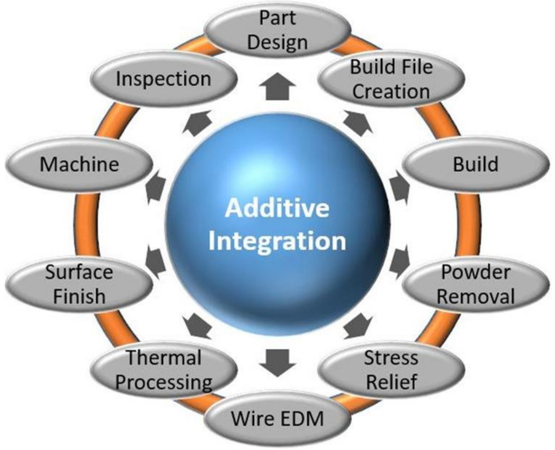


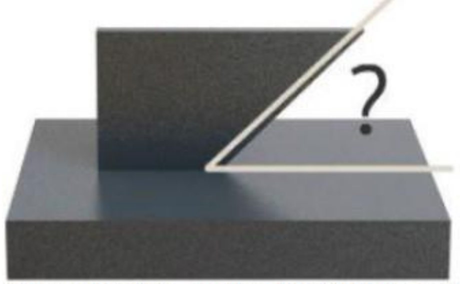
Each process step also includes a series of additional tasks in order to properly design, build, or complete post-processing

Holistic AM Design Flow & Considerations

Courtesy Melissa Orme, Morf3D

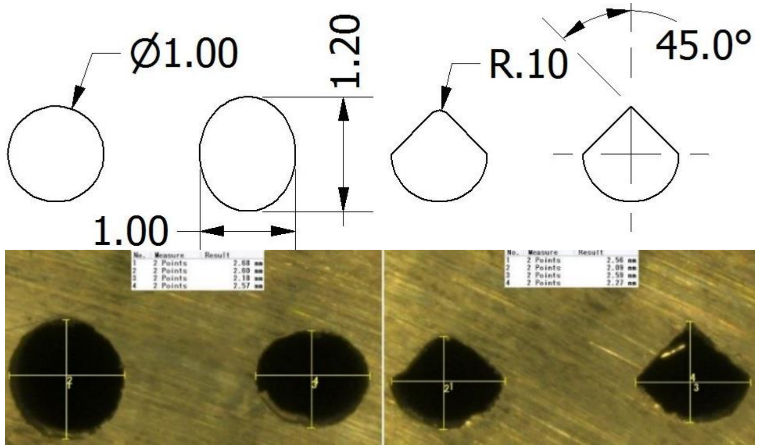
- Holes & Passages
  - Size limits (Horizontal: Min: 0.4 mm, Max: 8 mm; Vertical: Min: 0.4 mm, Max: unlimited).
  - Channel surface roughness variable on size: powder sintering for smaller OD and overhang angle for larger OD.
  - Hole sag in the Z-axis: circular hole becomes a horizontal ellipse, vertical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



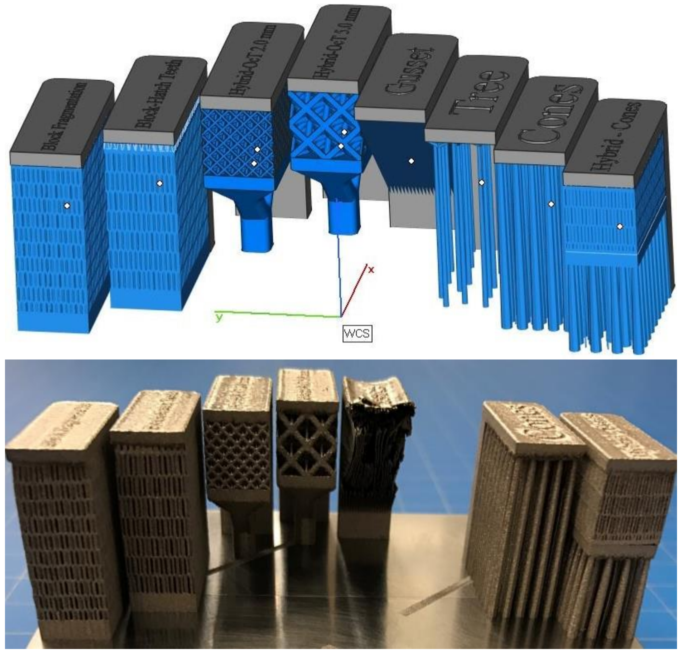
1 mm hole array micrographs (45°)

Hole size & surface roughness

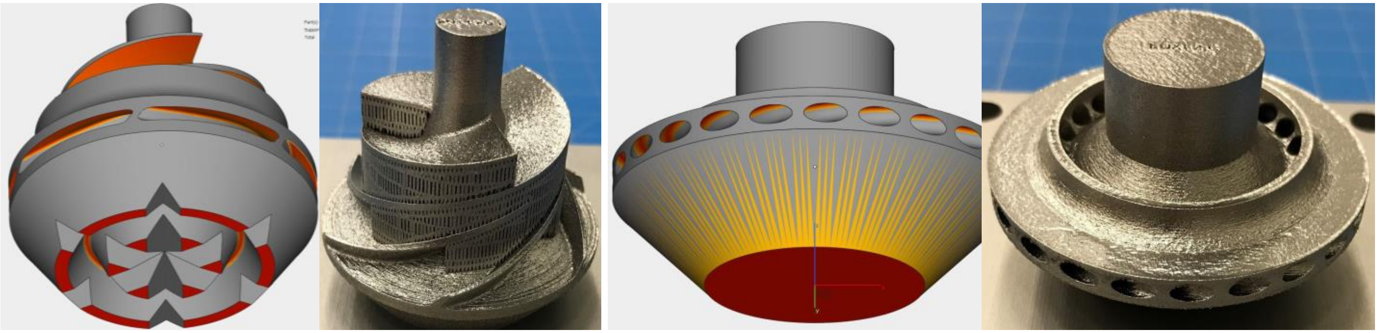
The design engineer of the 21st century is successful if parts can be repeatedly and economically manufactured.

Part Orientation, Supports, Slicing

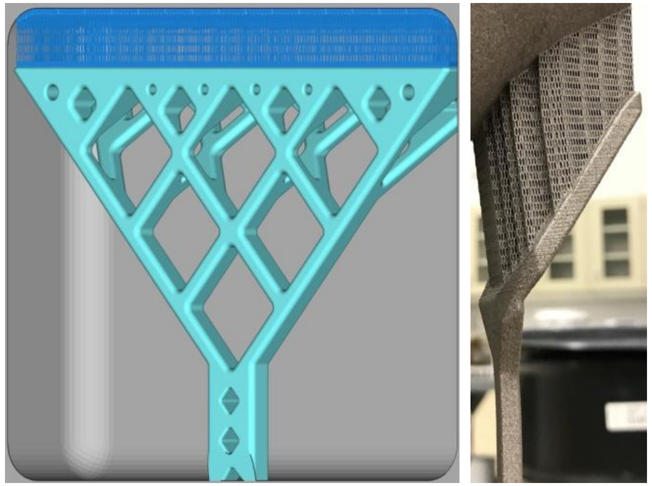
The purpose of support structures in metal AM are to hold down the part to the build plate, preventing upward distortion. Supports are sacrificial and are built less dense and thin.



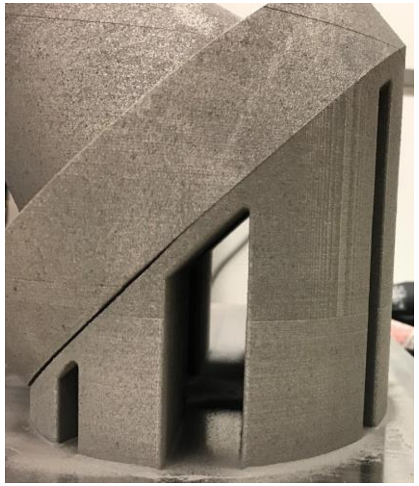
Supports examples



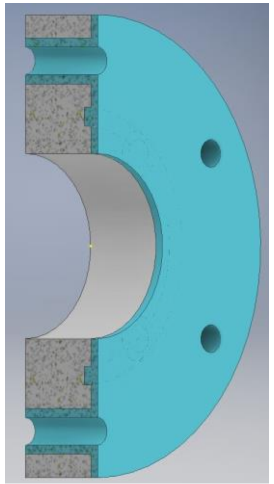
AMPed LOX Impeller Iterations vs. overhang surfaces. Courtesy Marty Calvert.



Hybrid crown & perforated block support

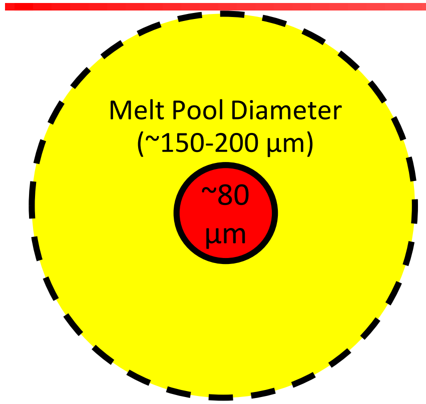


Sacrificial powder removal features

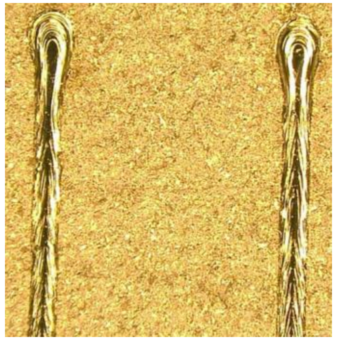


Sacrificial features- interfaces

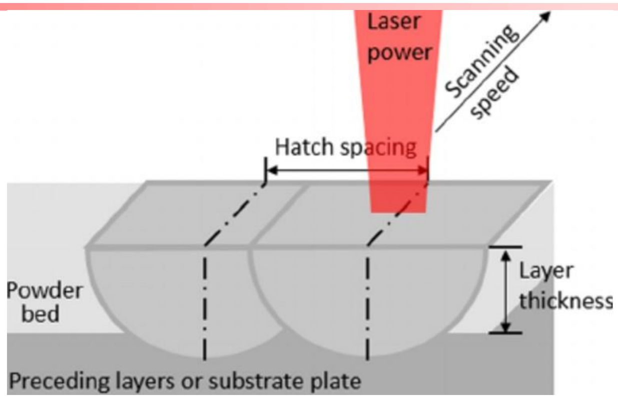
Build Process



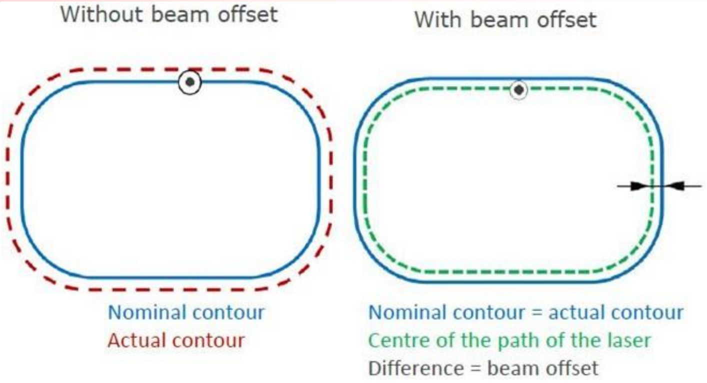
Laser Focus Diameter. Courtesy EOS.



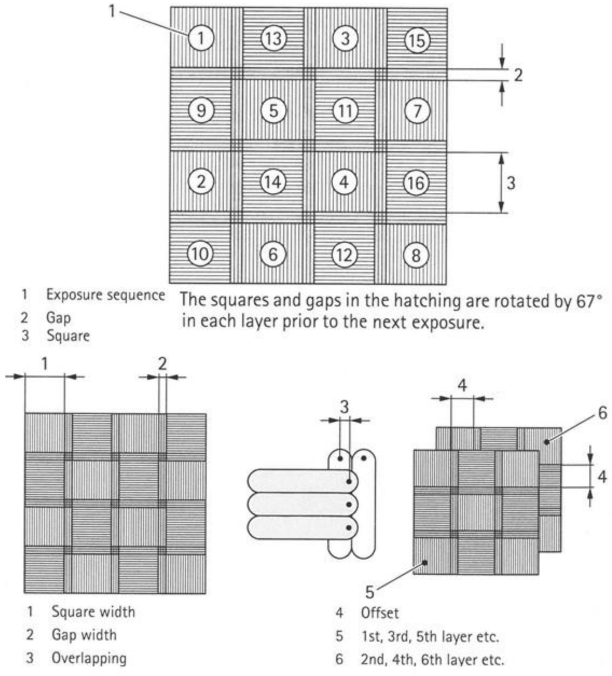
Melt Pool Track



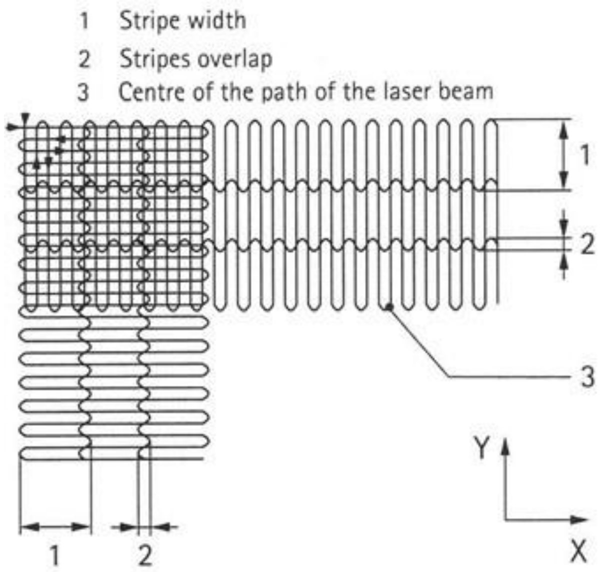
Hatch spacing



Beam Offset. Courtesy EOS.



Chess Rotated Exposure Strategy. Courtesy Concept Laser.

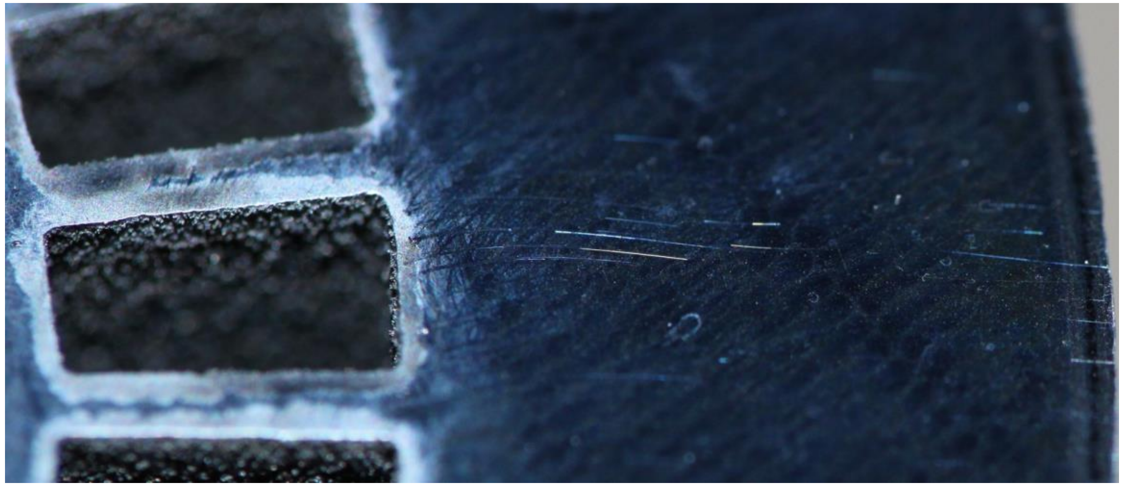


Stripe Exposure Strategy. Courtesy EOS

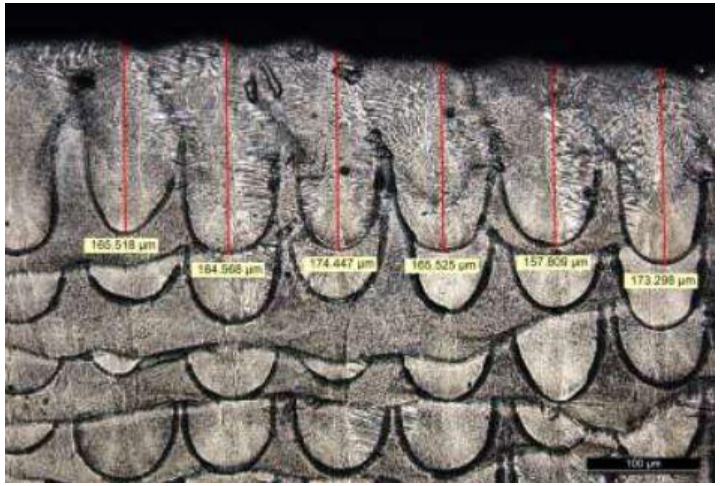
Parameter	Description
Thickness (t)	Powder layer thickness (mm)
Power (P)	Laser power set-point (W)
Speed (V)	Laser scan speed (mm/s)
Hatch Distance (D)	Distance between centerlines of weld pools (mm)
Overlap	Melt pool overlap (%)
Beam Offset (BO)	Compensates for melt pool size to part (mm)
Scan Pattern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

Scan Strategy & Microstructure

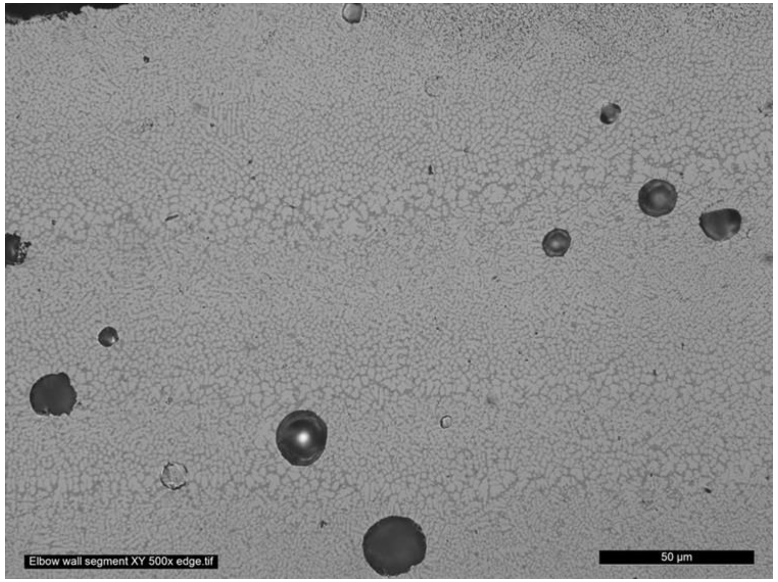
Porosity & melt pool path in AlSi10Mg



Melt pool path in AlSi10Mg



Melt 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.

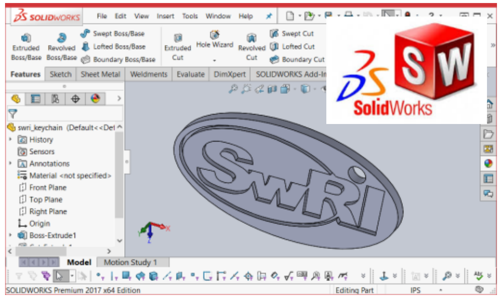
Shrinkage (keyhole) porosity in IN718 results from high laser power or fast scan speed.

Printing Exercise #1

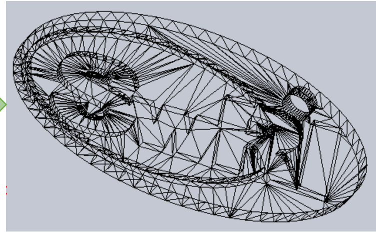
Your widget will change the world……..how can you print it?

Printing Exercise #1

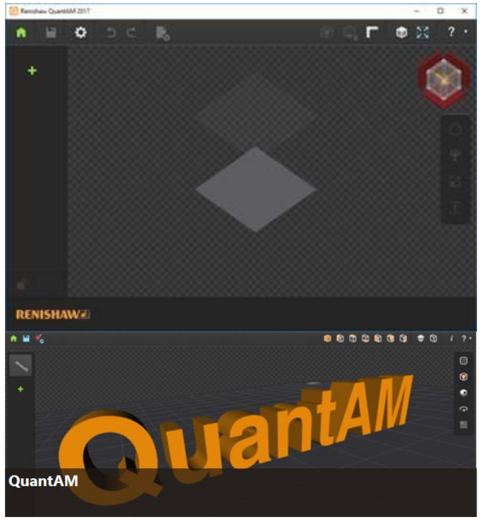
Create CAD



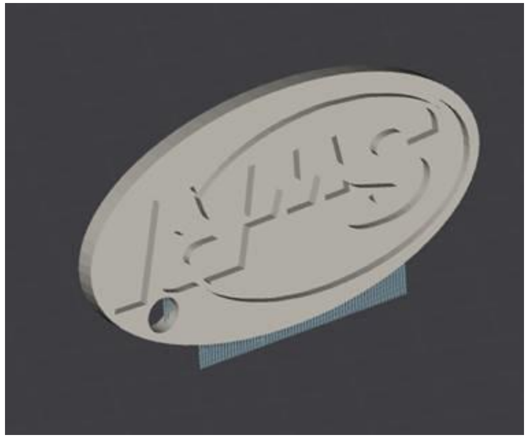
Generate STL



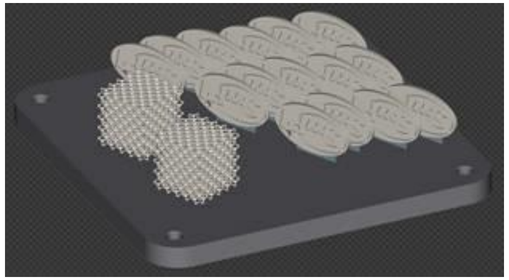
Build Software



Create Single Part Layout

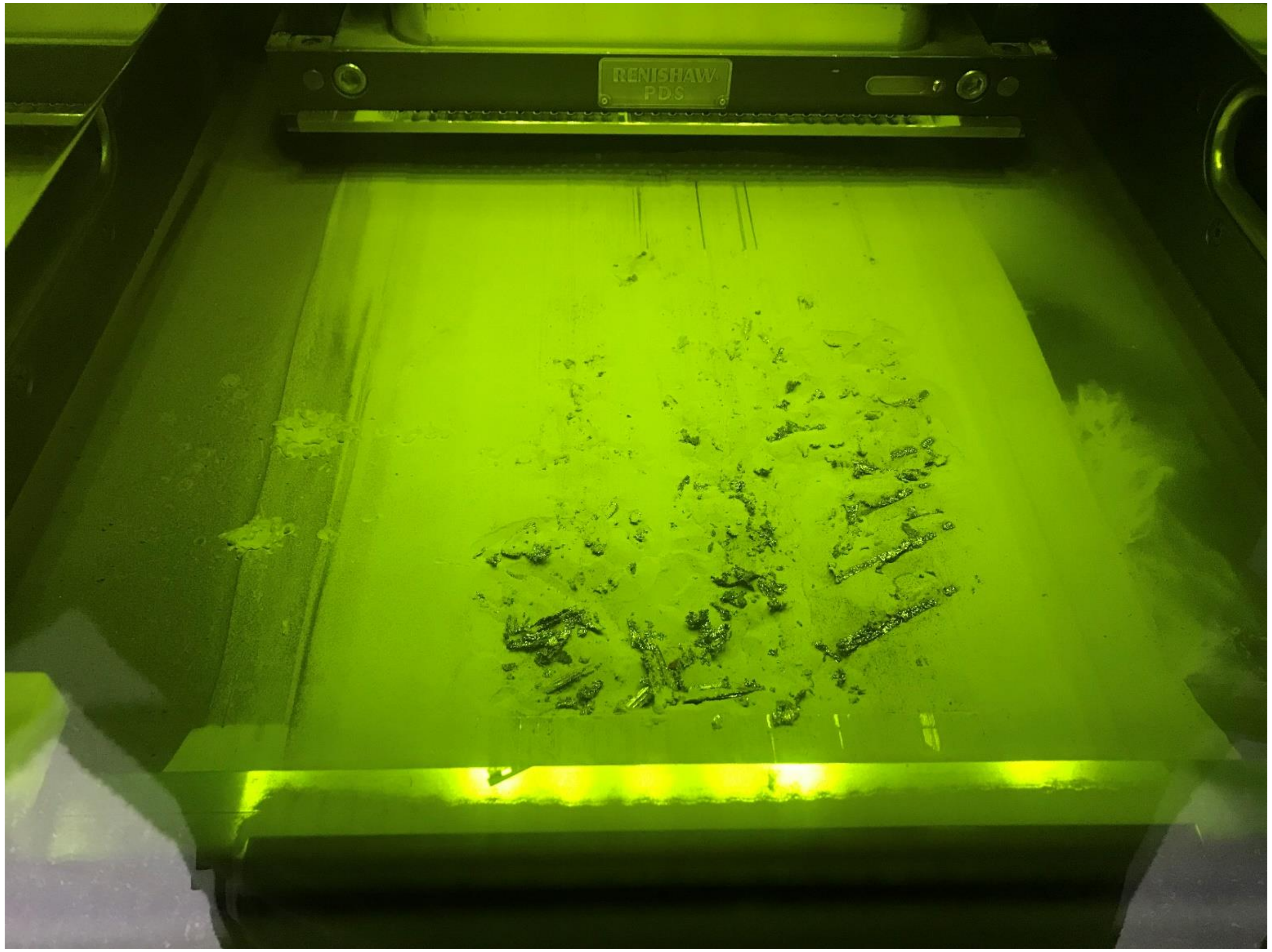


Create Build Layout

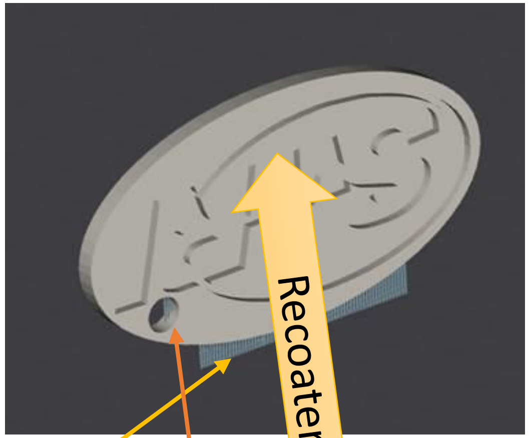


Off to the Machine!

Printing Exercise #1



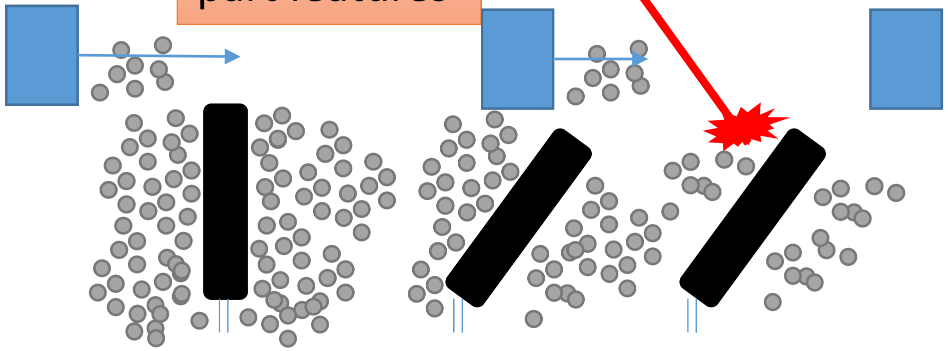
What happened?!?!



Weak supports

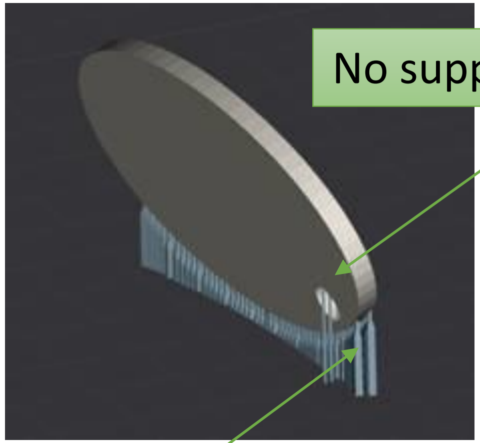
Supports on part features

Thin keychain was straight up and down. Large lever arm with recoater

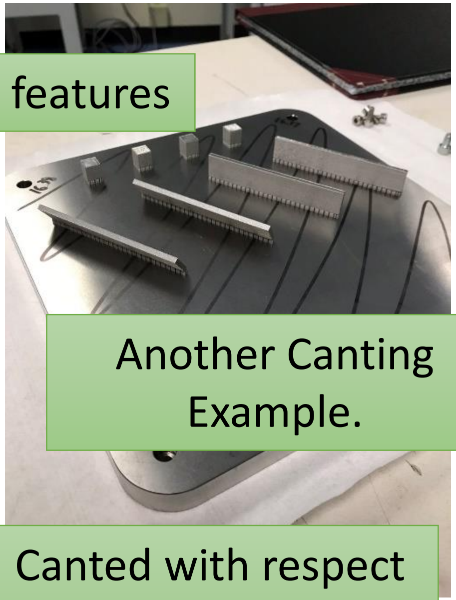


Printing Exercise #1

Improvements to build plan.

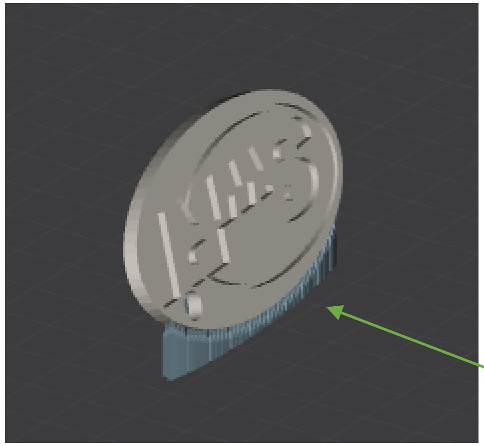


No supports on features

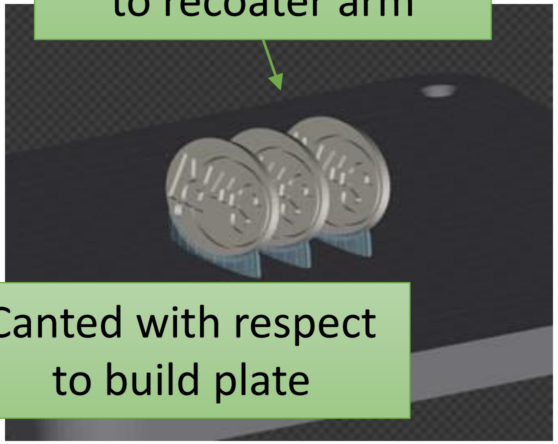


Another Canting Example.

Stronger supports



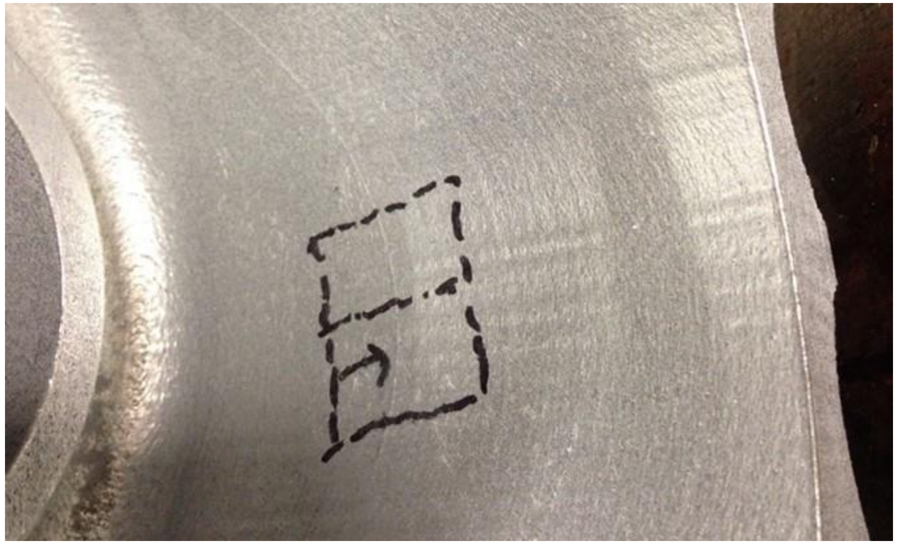
Canted with respect to recoater arm

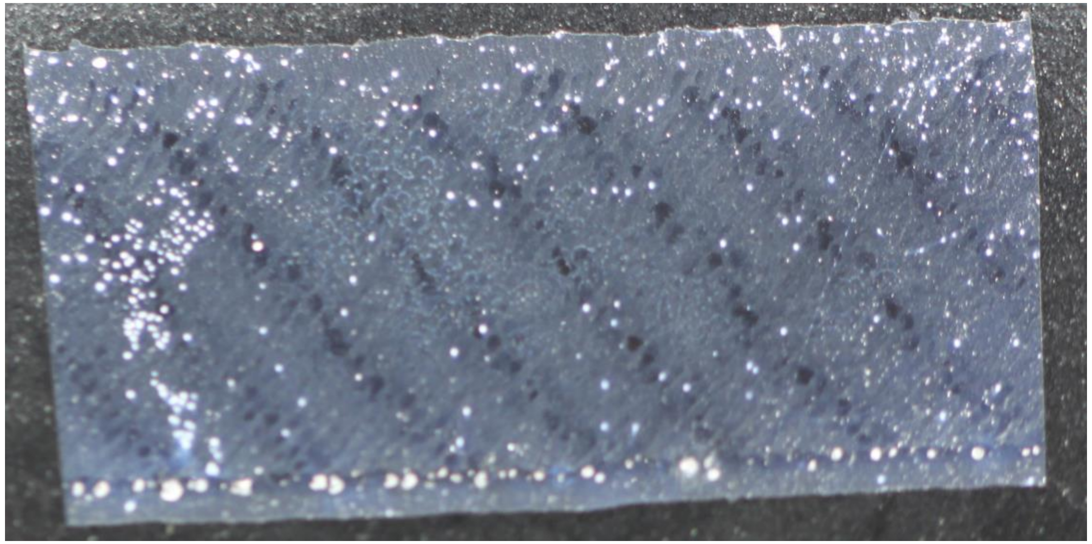


Canted with respect to build plate

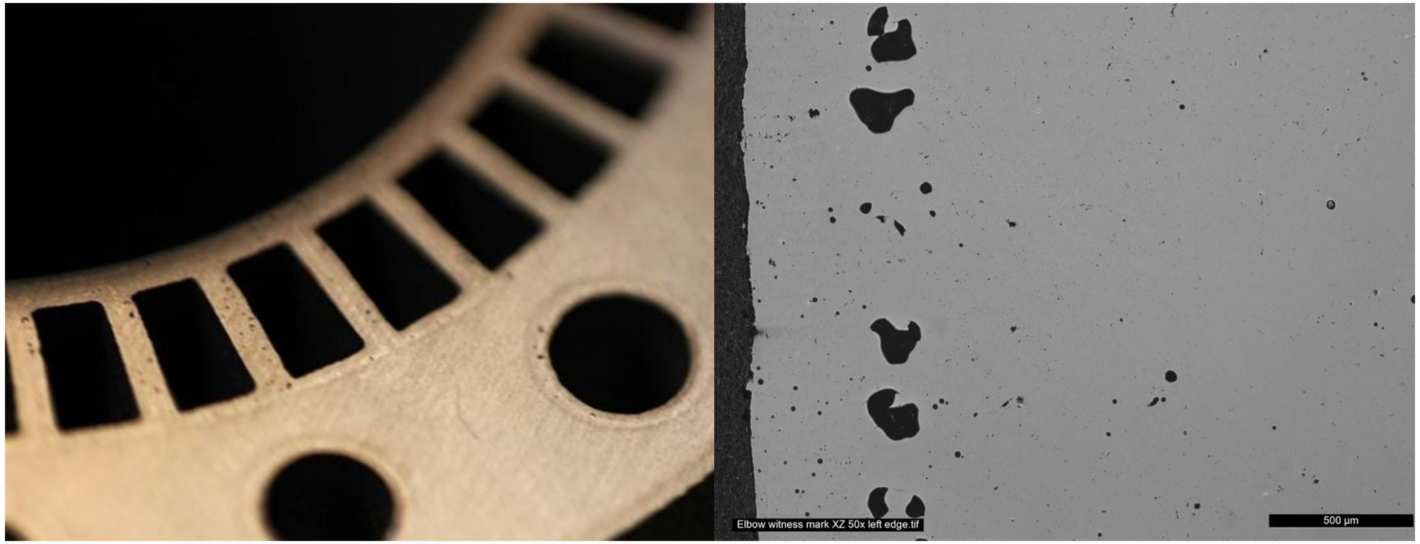
Successful build!

Build Artifacts

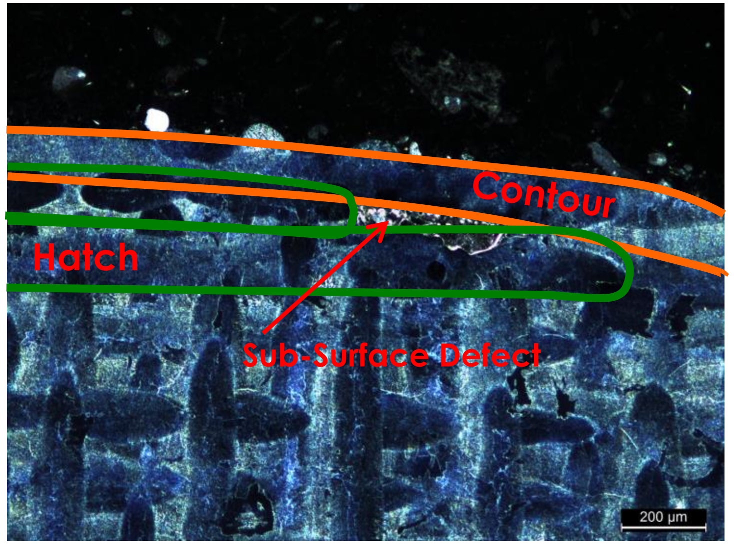




Witness marks on the surface and interior



Edge Porosity



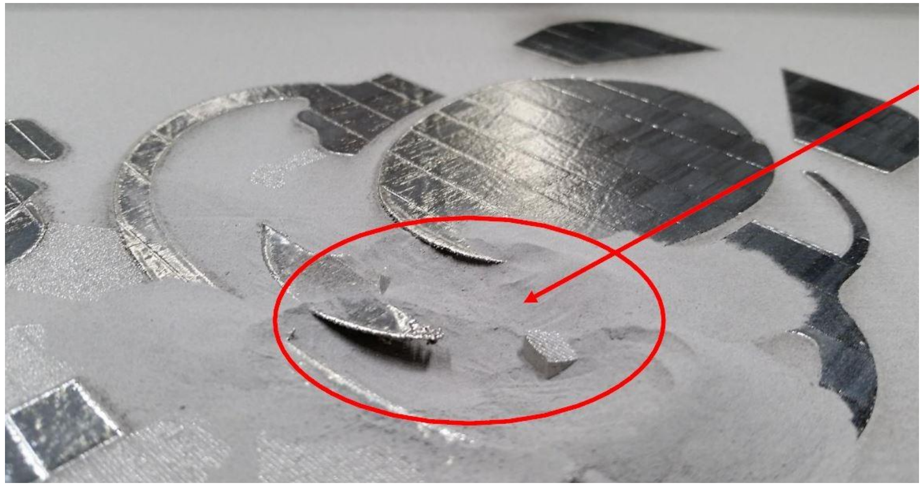
Edge Porosity can result from an excessive beam offset.

Build Failure Examples

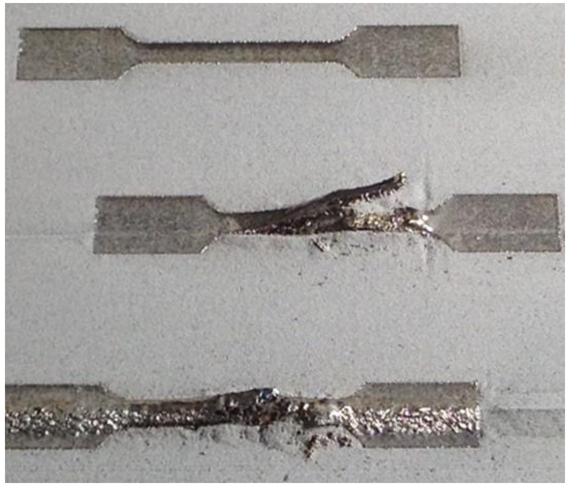
Short feed where insufficient/non-uniform powder distribution occurs. Over time the powder layer will be excessively thick when corrected and the laser melt pool will not be sufficiently deep to bond the thick layer to substrate underneath. The re-coater blade is eventually damaged by curling.

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

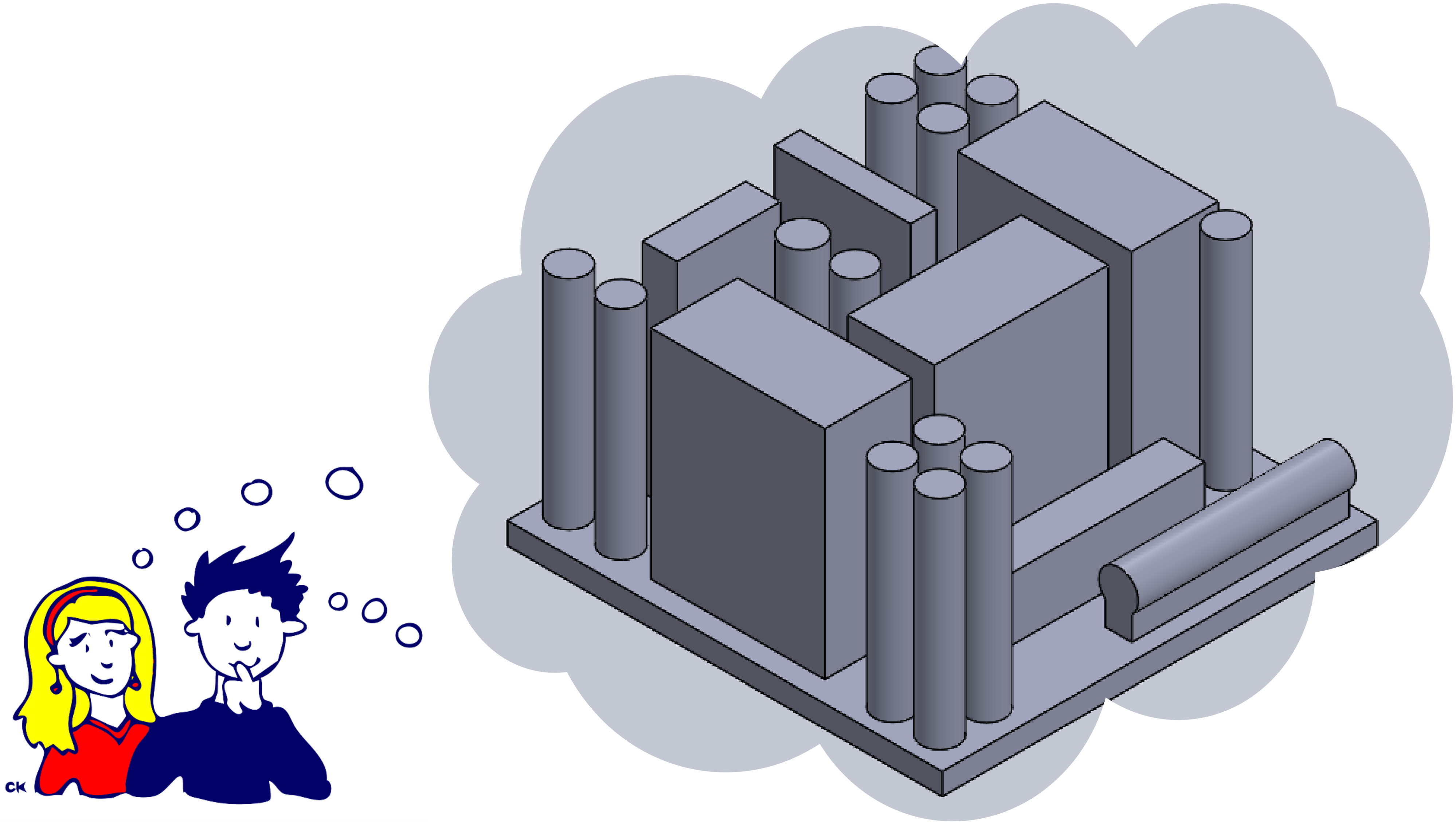
Machine to machine variation

Damaged re-coater blade

Stray vectors

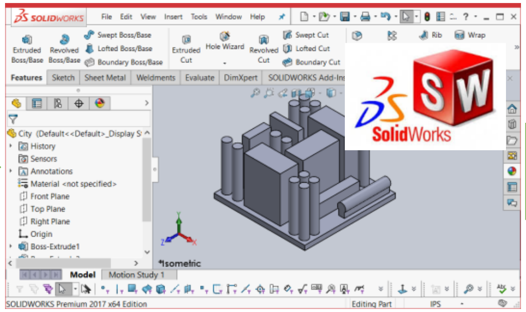
Printing Exercise #2

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

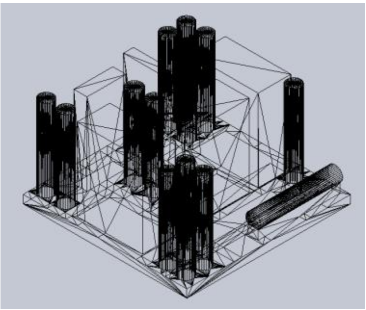


Printing Exercise #2

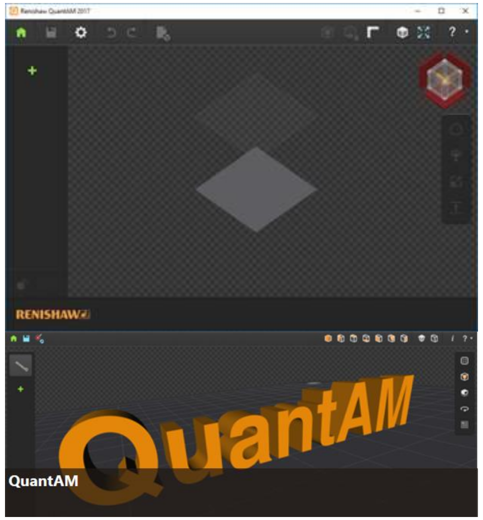
Create CAD



Generate STL



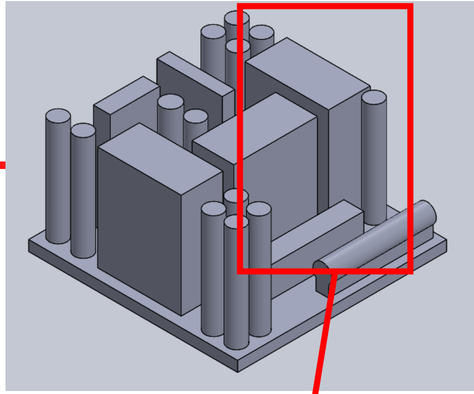
Build Software

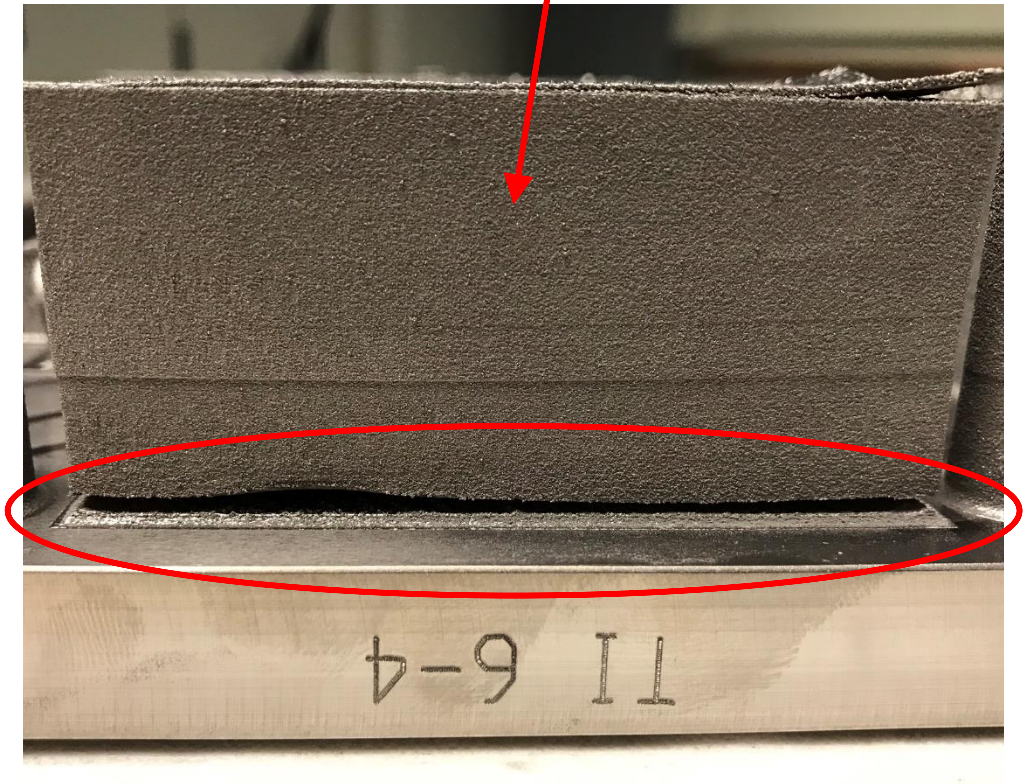


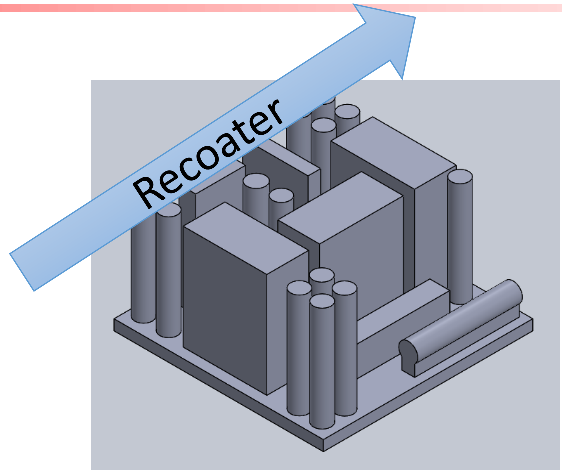
Set Machine Build Parameters

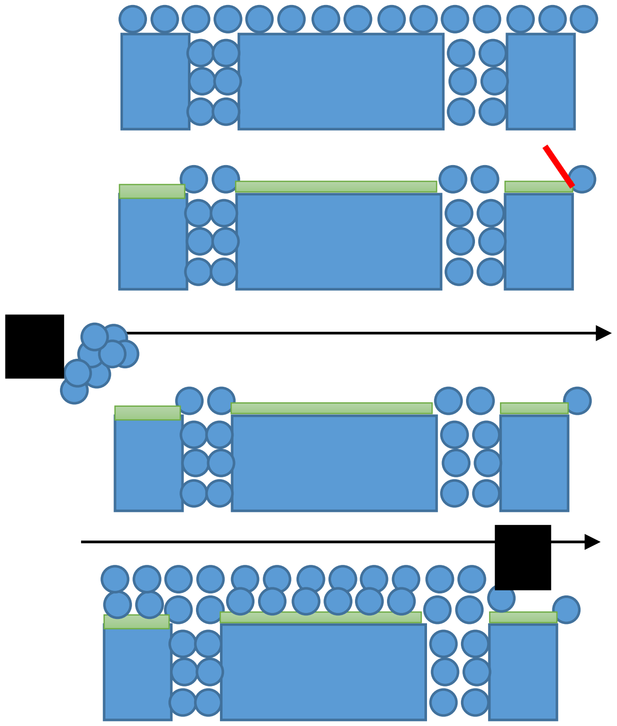
Off to the Machine!

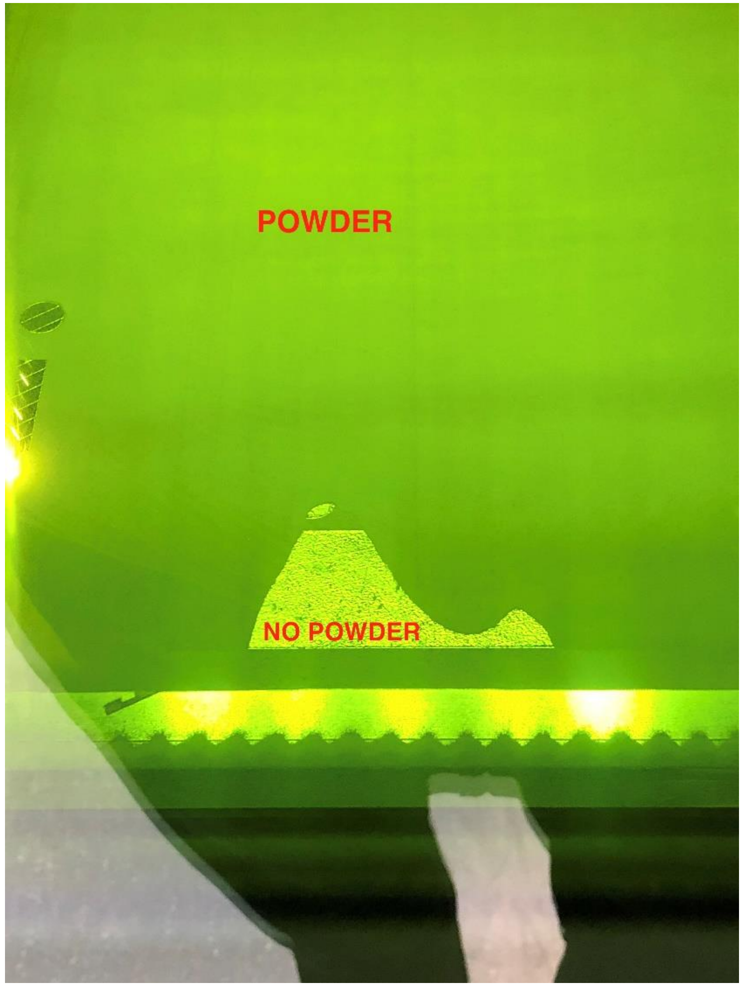
Printing Exercise #2





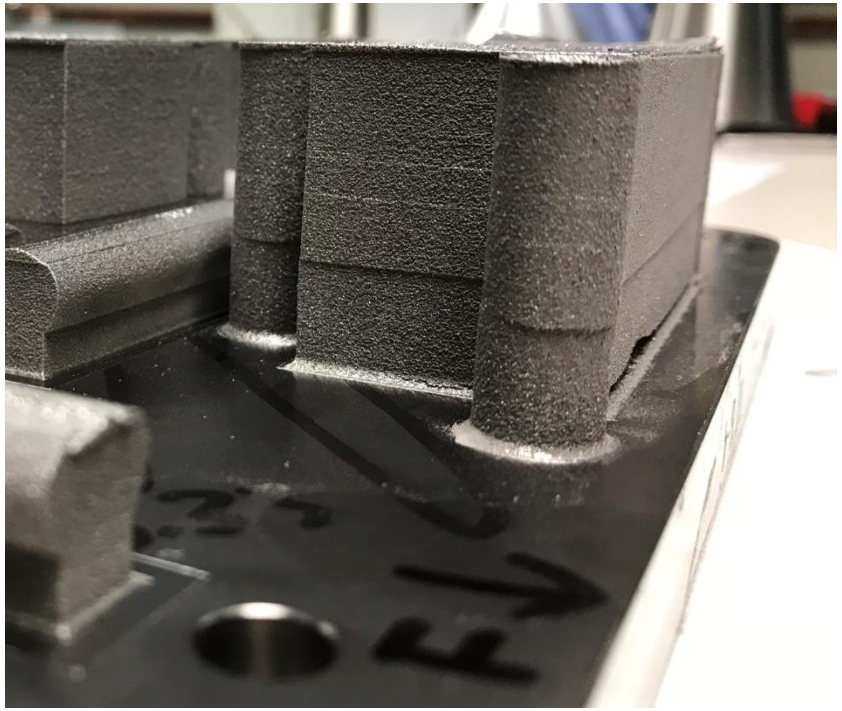


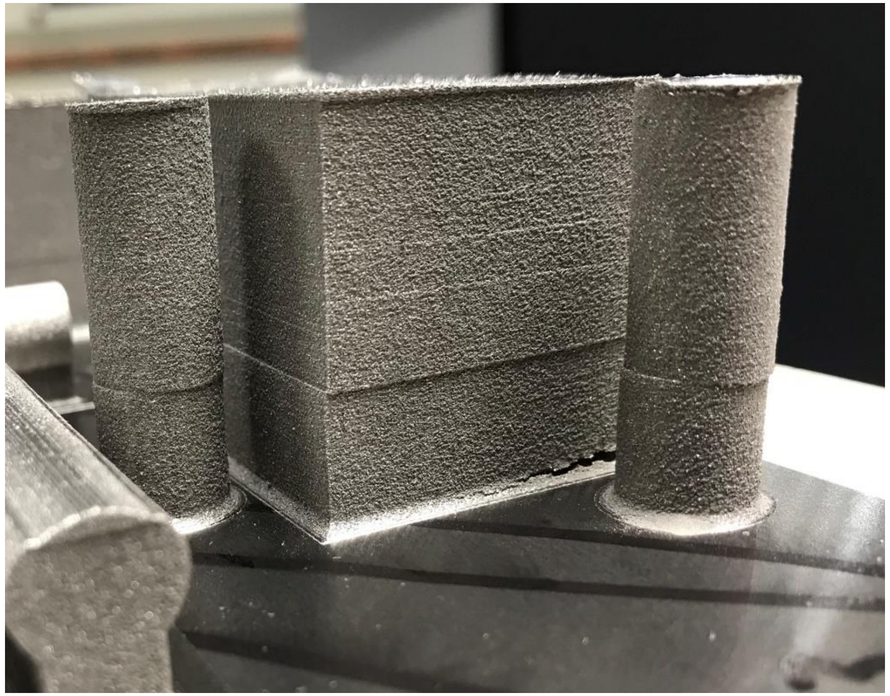




What happened?!?!

Printing Exercise #2





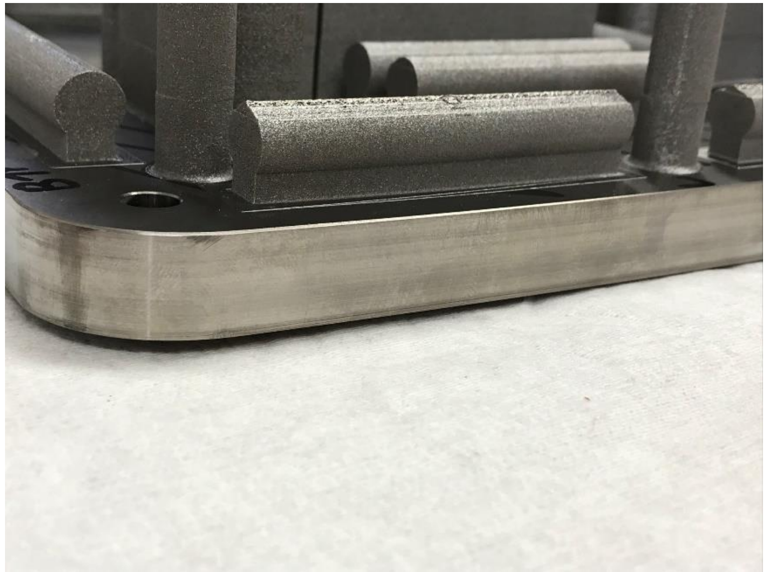
What happened?!?!

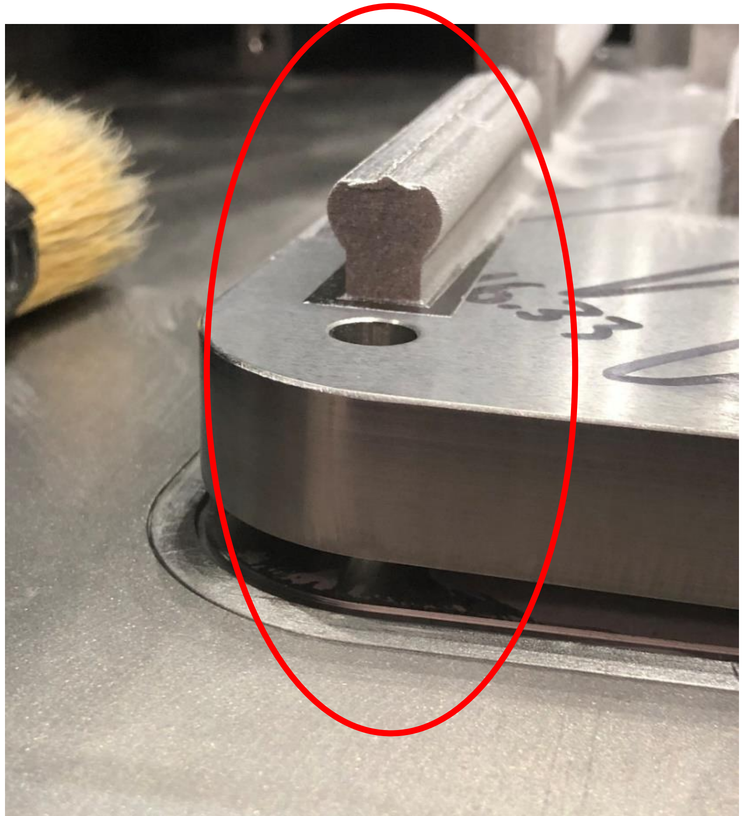
Printing Exercise #2

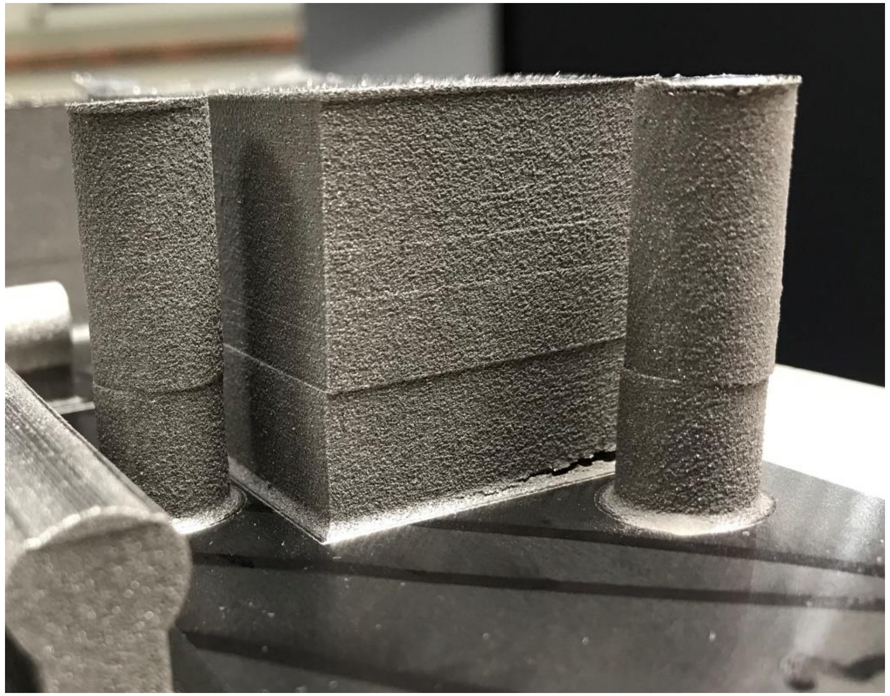
What happened?!?!...Another Clue

Printing Exercise #2

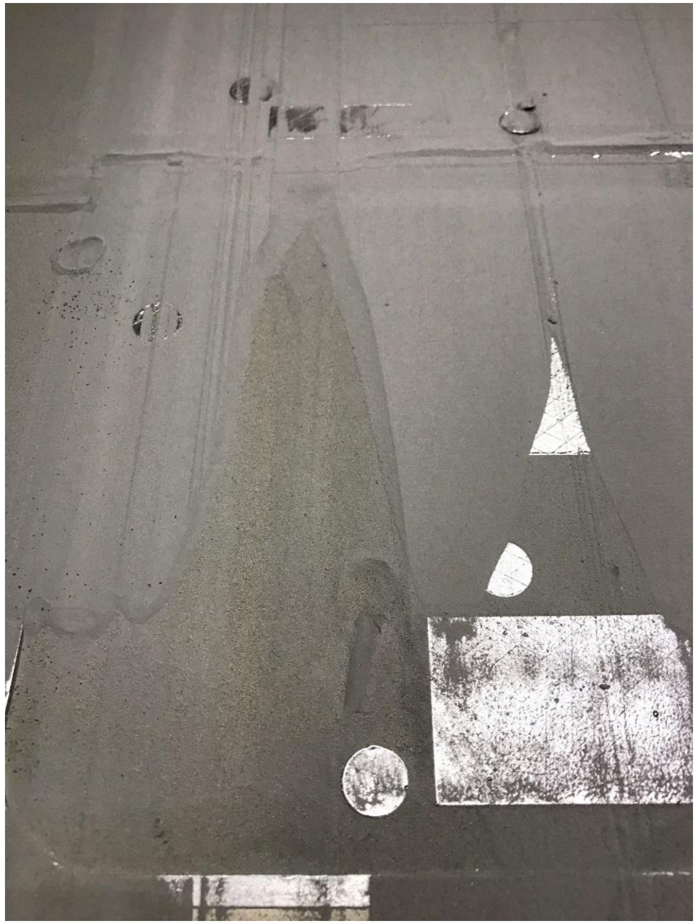
- Large amounts of sintered material -> Thermal stresses in build plate
- Bolt broke
- Corner elevated resulting in offset of parts
  - Laser doesn’t know (or care) so it keeps printing original coordinates onto “new shifted datum”

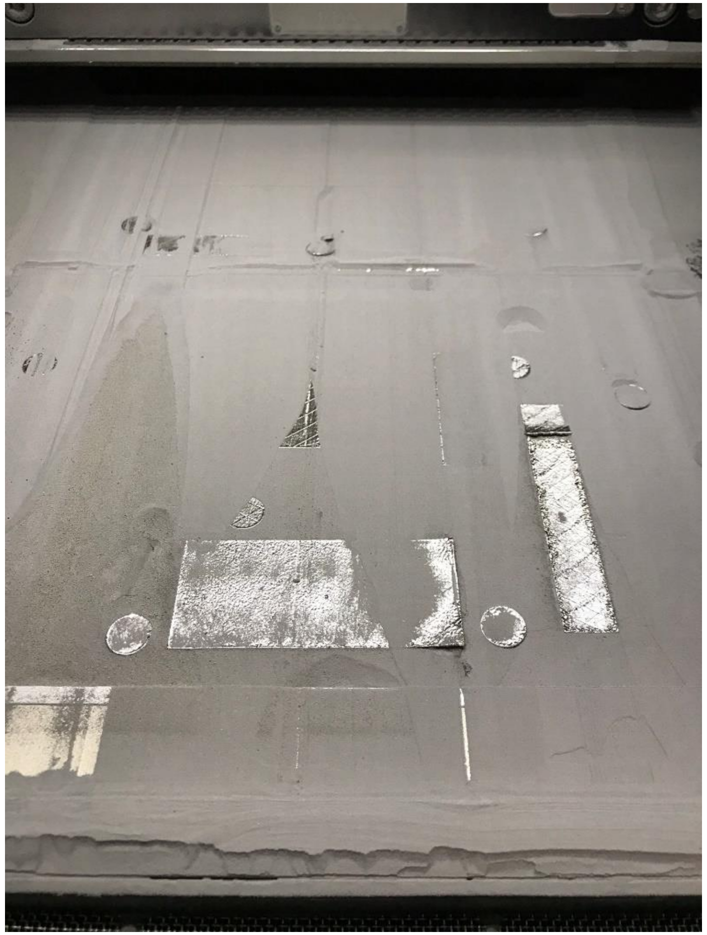






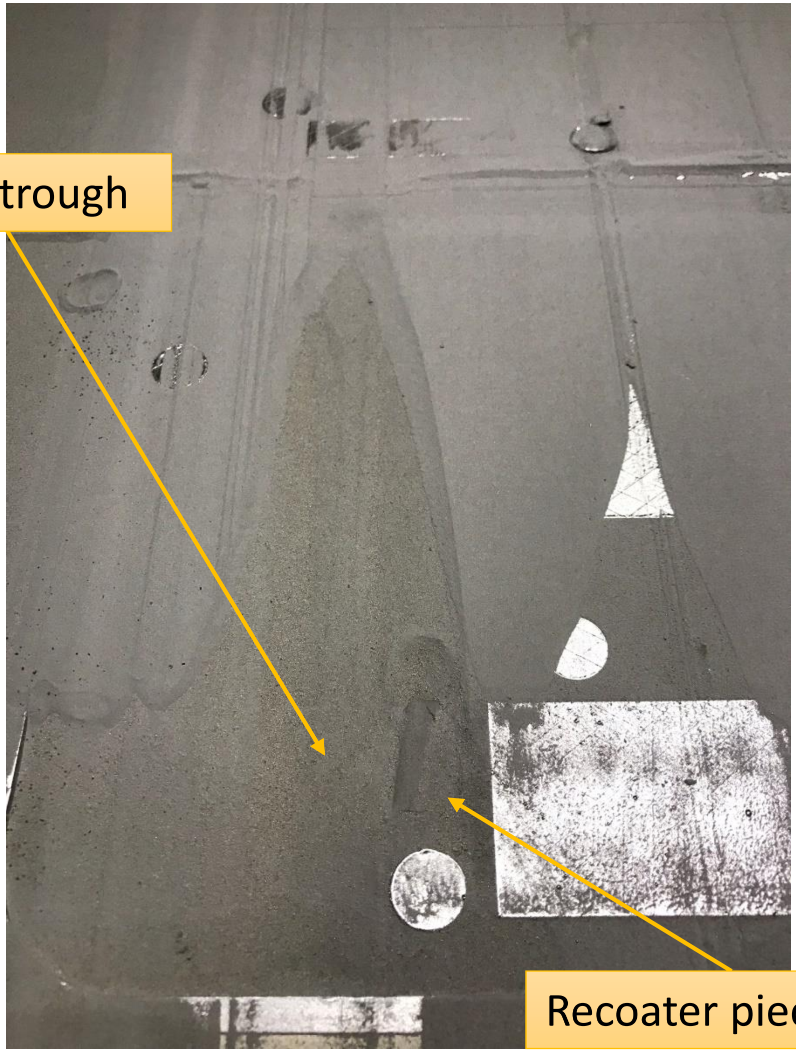
Printing Exercise #2





What happened?!?!

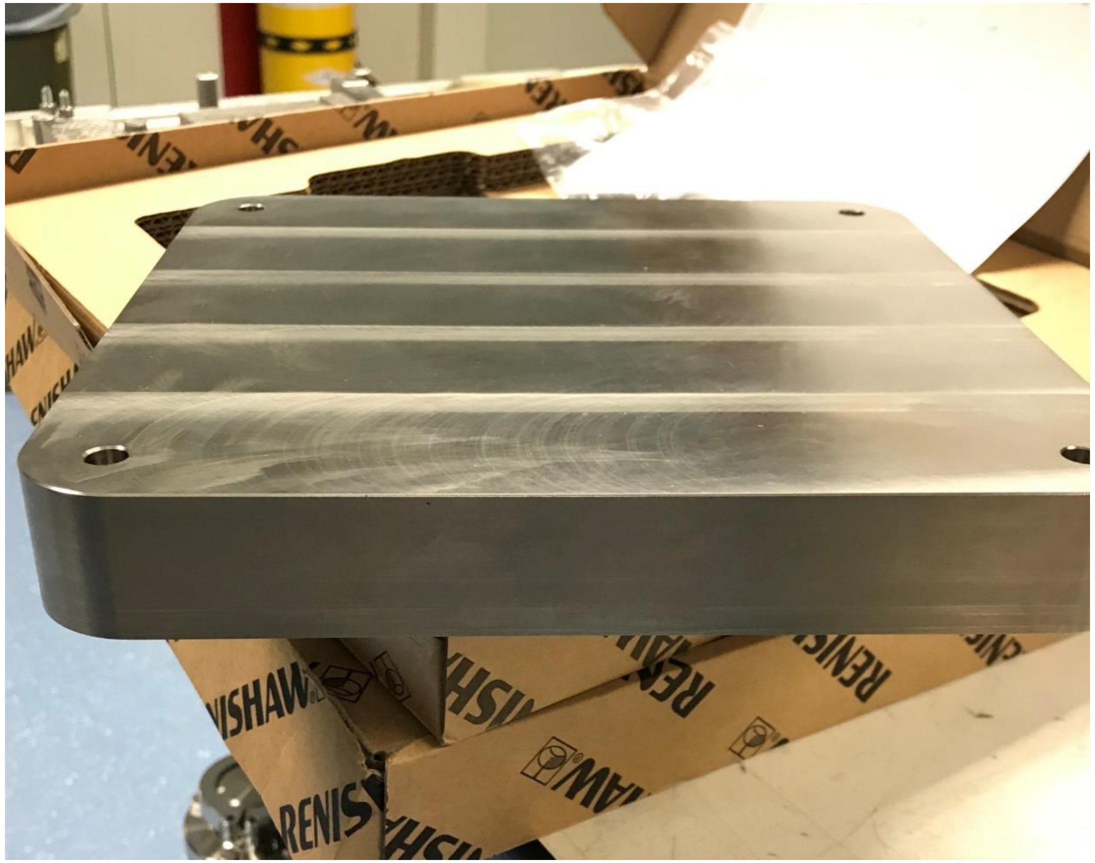
Printing Exercise #2



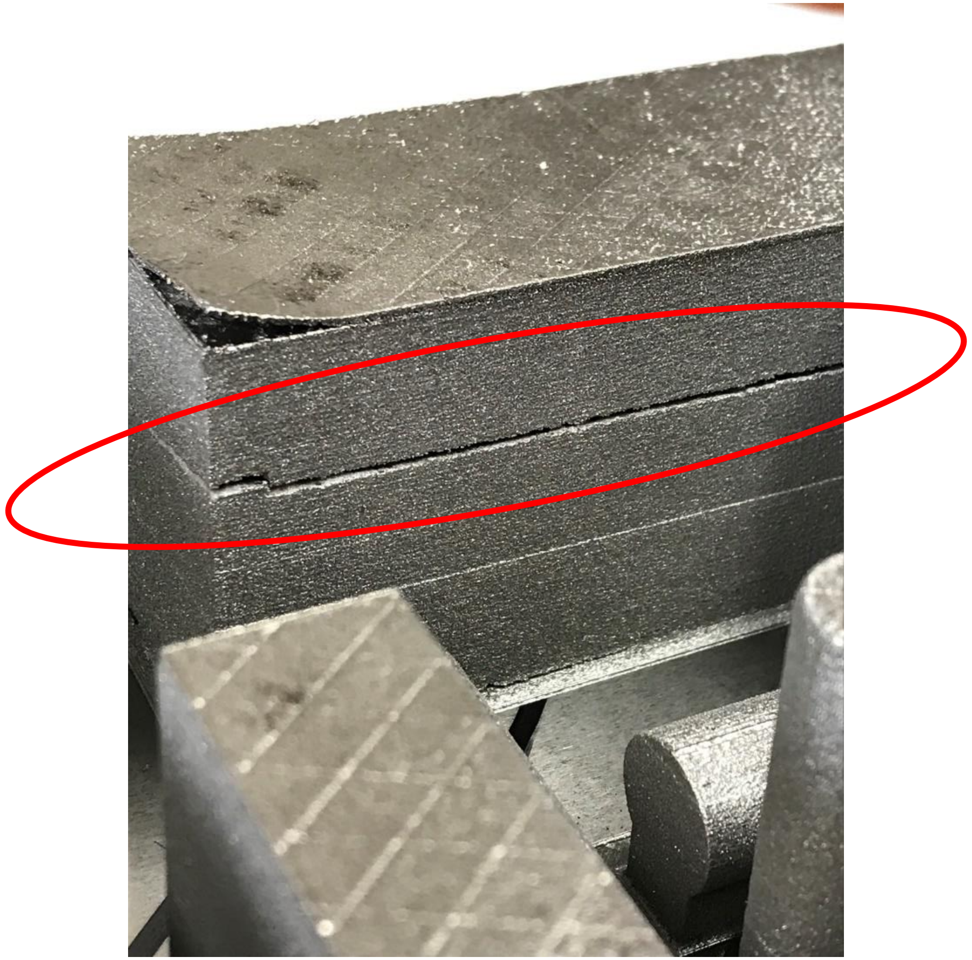
- Root Cause: Second bolt broke causing an additional shift in build plate
    - Symptom 1: Offset in laser/part datum
    - Symptom 2: Newly created layers now "overhung" and were able to curl and separate
    - Symptom 3: Recoater blade strikes deformed layers and is damaged
    - Symptom 4: Complete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

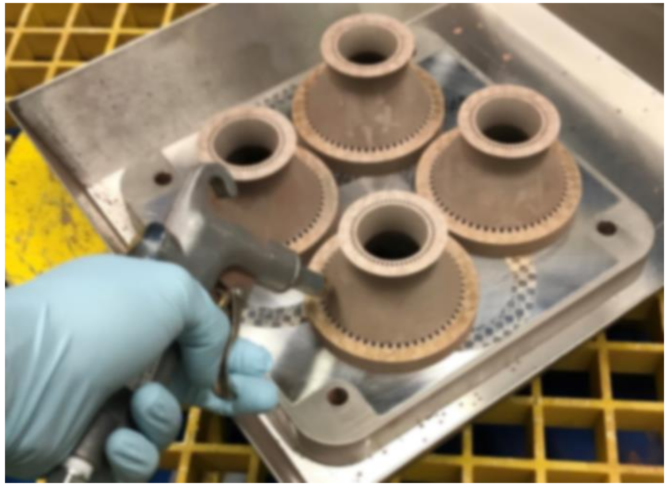
What happened?!?!

Post-Processing

Unpack & Vacuum

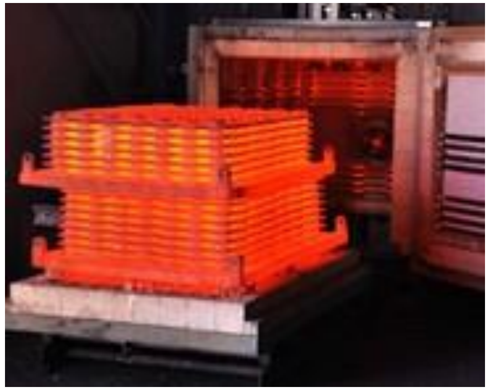
Vibration & Mechanical Removal

Downdraft Table



Compressed Air

Sintered Powder



Stress Relief

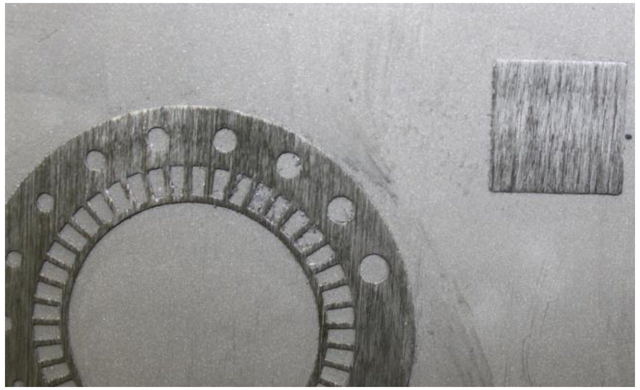


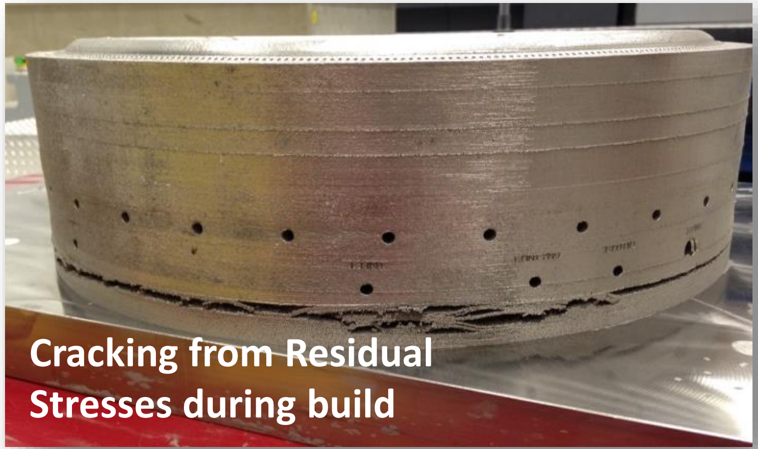
Plate removal (band saw or wire EDM)

Support Removal

Sieve Powder

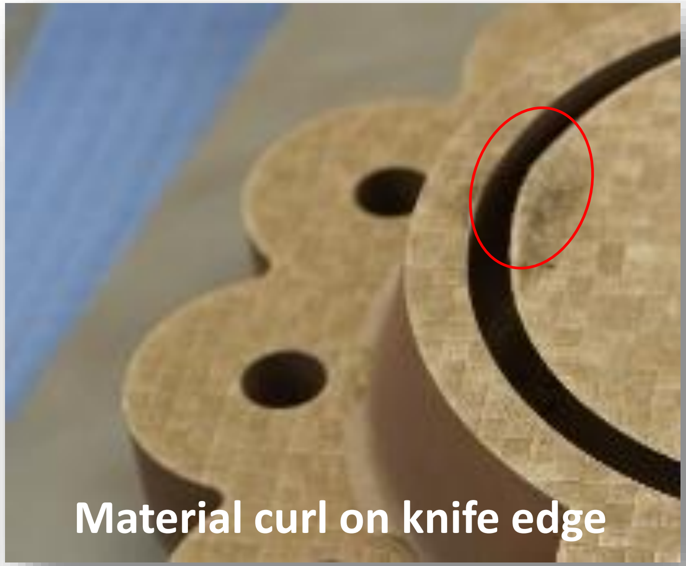
Distortion, Curl, Re-start Marks

- 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 witness lines
  - Refill of powder in dose chamber
  - Issue observed that requires visual



Cracking from Residual Stresses during build

Restart line observed post-build



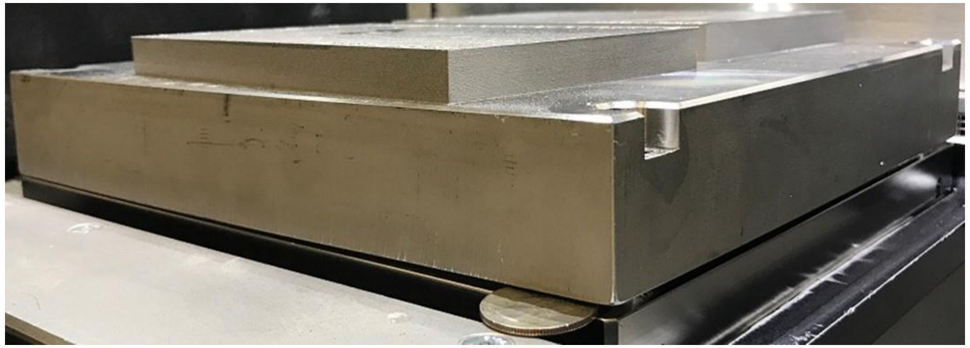
Material curl on knife edge

Stress Relief Heat Treatment

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

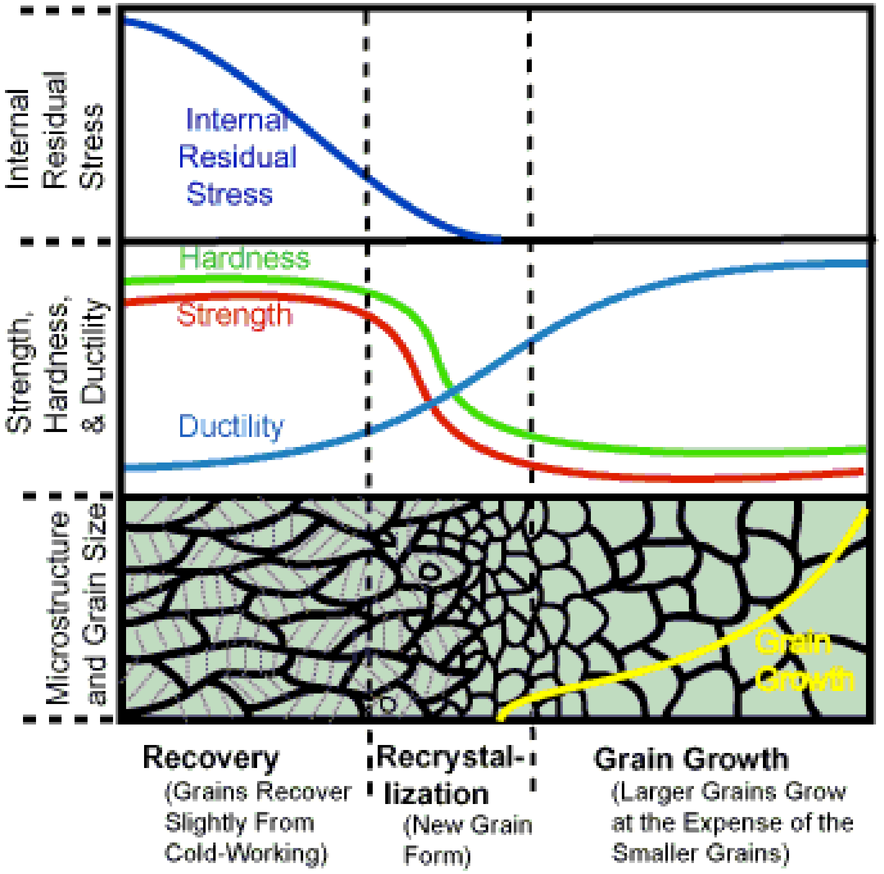
- *Recrystallization* – Microstructure change from dendritic (stressed) to equiaxed grains (stress free).

Cooling shrinkage behavior.



L-PBF induced residual stress of IN718 distorting 316L build plate

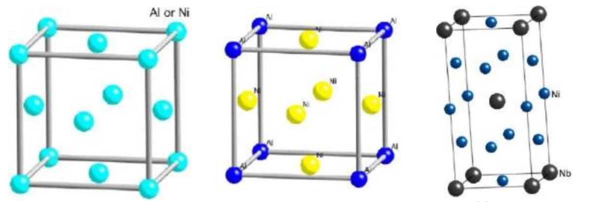
Residual stress induced failure.



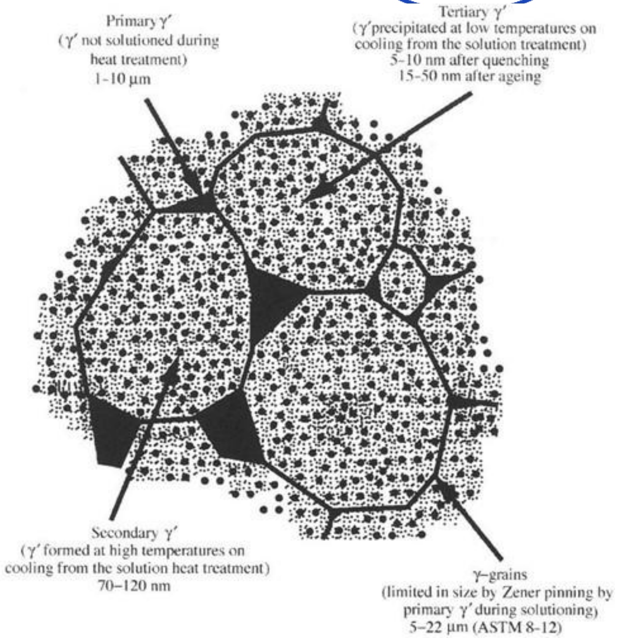
Nucleation, Recrystallization & Grain Growth

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.

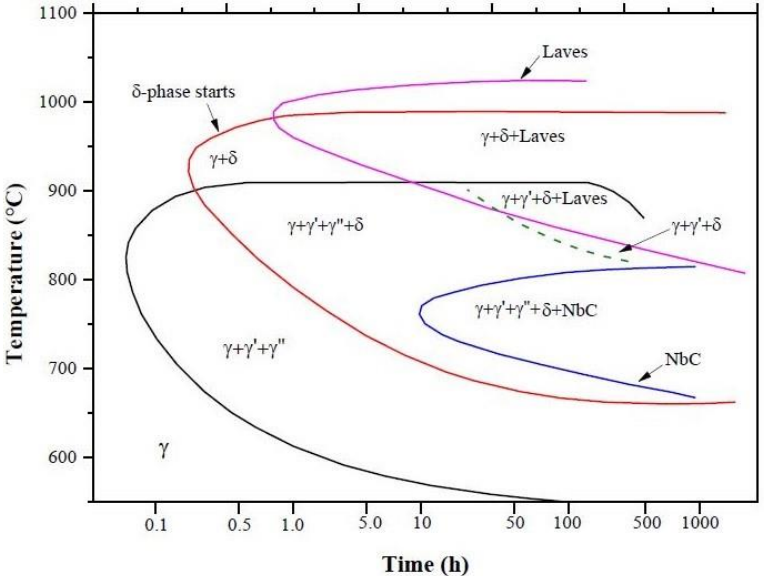


γ FCC structure[3] | γ' FCC structure[3] | γ'' BCT structure[3]

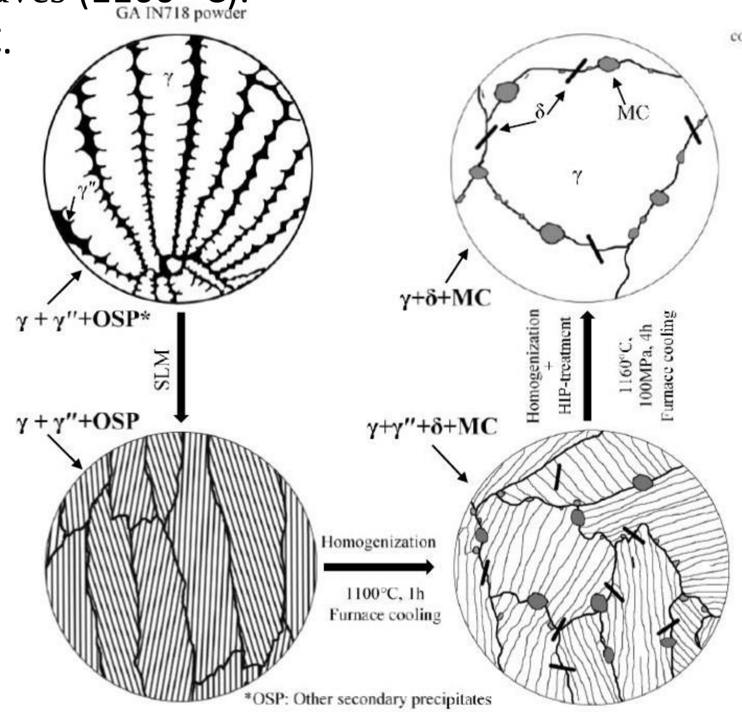


IN718 Microstructure. Courtesy Reed.

- Solidification sequence[1,2]
  - $L \rightarrow L + \gamma$ (1359 °C), $L \rightarrow \gamma + MC$ (1289 °C), $L \rightarrow \gamma$ + Laves (1160 °C).
  - δ phase precipitate (solid state reaction) at 1145 $\pm$ 5 °C.
  - γ' and γ'' phases precipitate at 1000 $\pm$ 20 °C.



Time-Temperature Transformation Diagram-IN718[1].

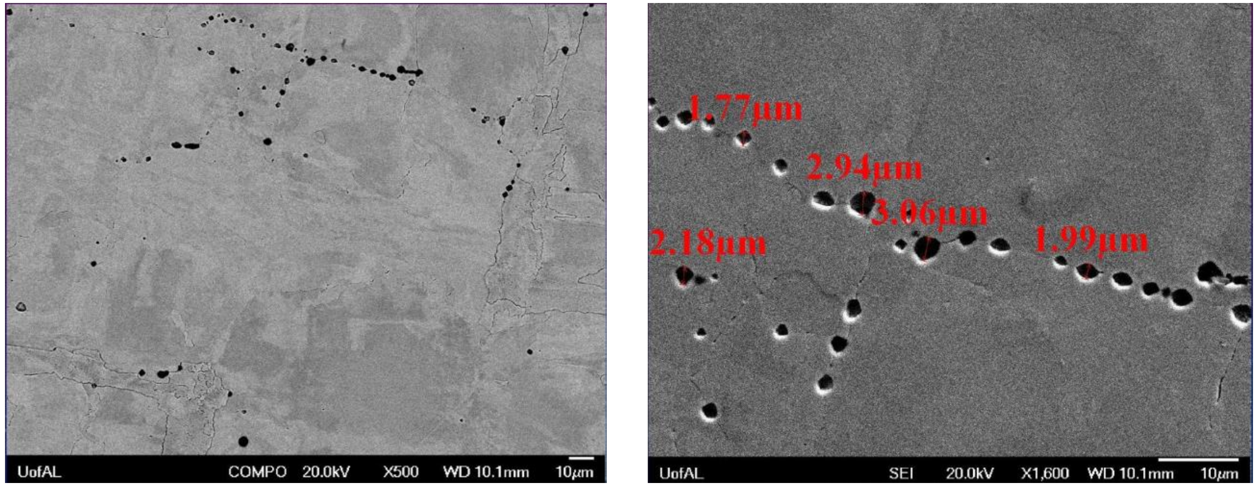


Microstructural change & phase evolution of IN718[1].

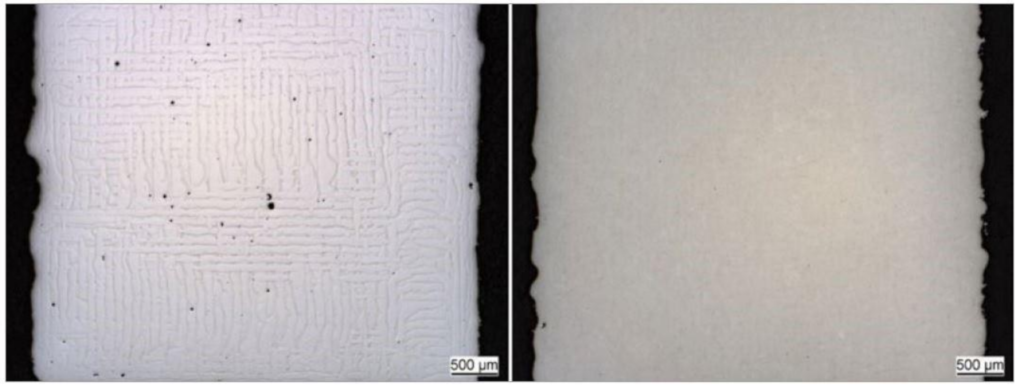
[1]Courtesy Mostafa et. al, 2017.
[2]Manikandan, 2015.
[3]Courtesy Bhadeshia, 2018.

Hot Isostatic Press (HIP)

HIP – Closeout porosity and potential to heal defects.

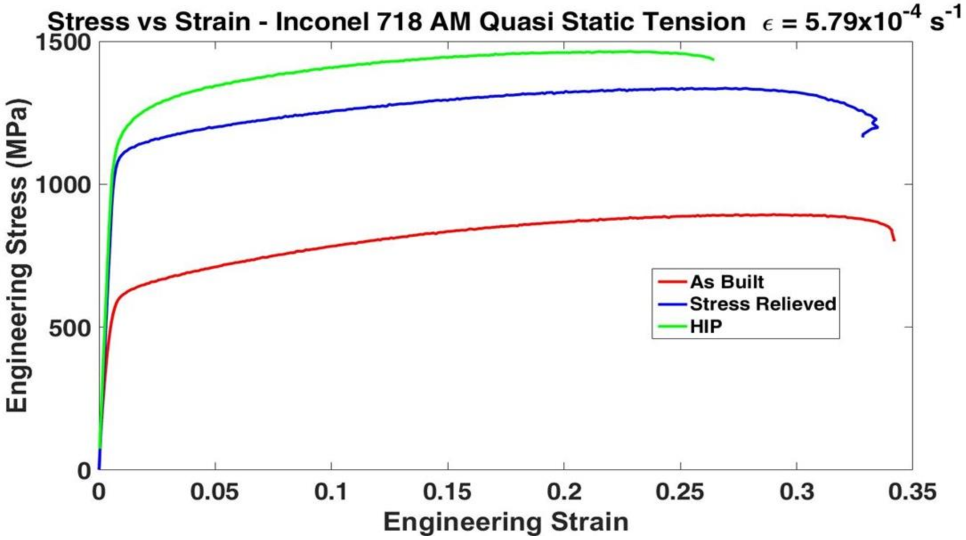


Monel K500 SEM BSE micrographs 500x (L) and 1600x (R) showing porosity along grain boundaries. Courtesy UA Senior Materials Team.



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

MSFC HIP Furnace

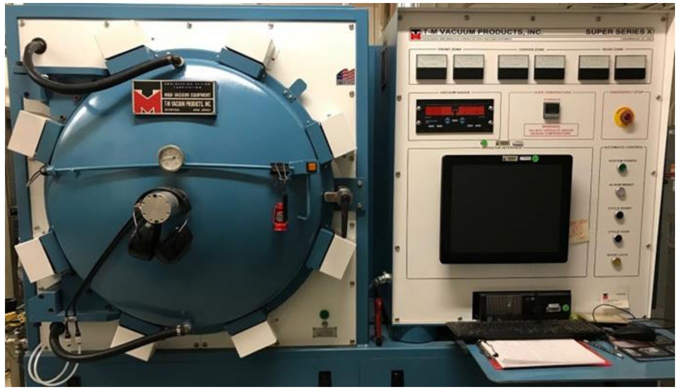


L-PBF IN718 Tensile Strength vs. Condition. Courtesy Hazeli.

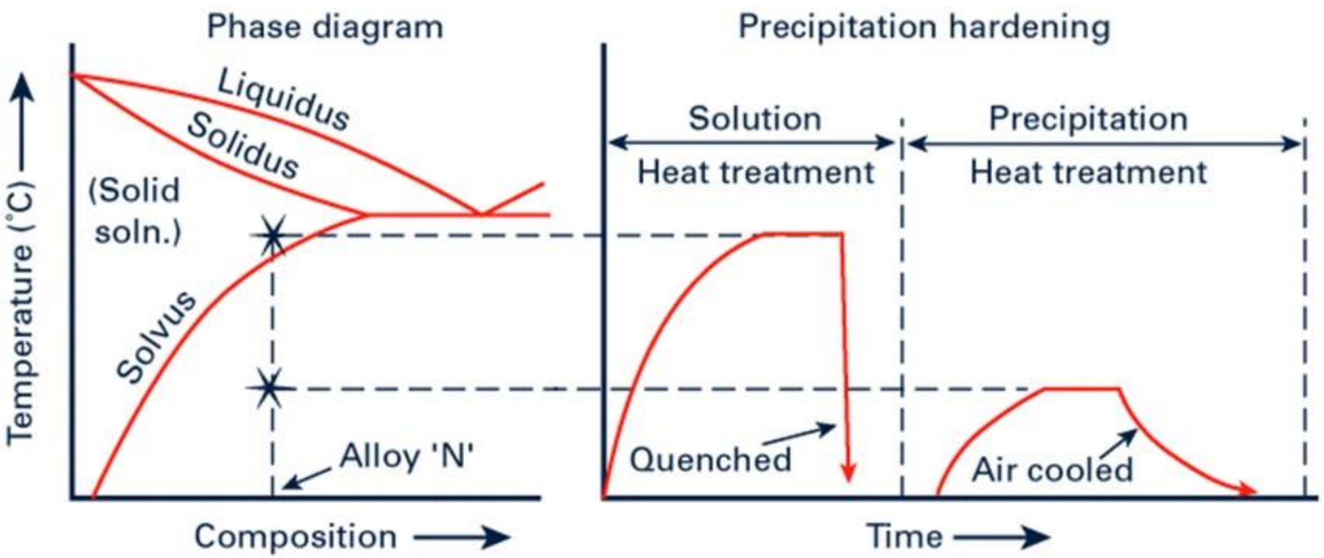
Solutionize & Age Heat Treatment

- *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.

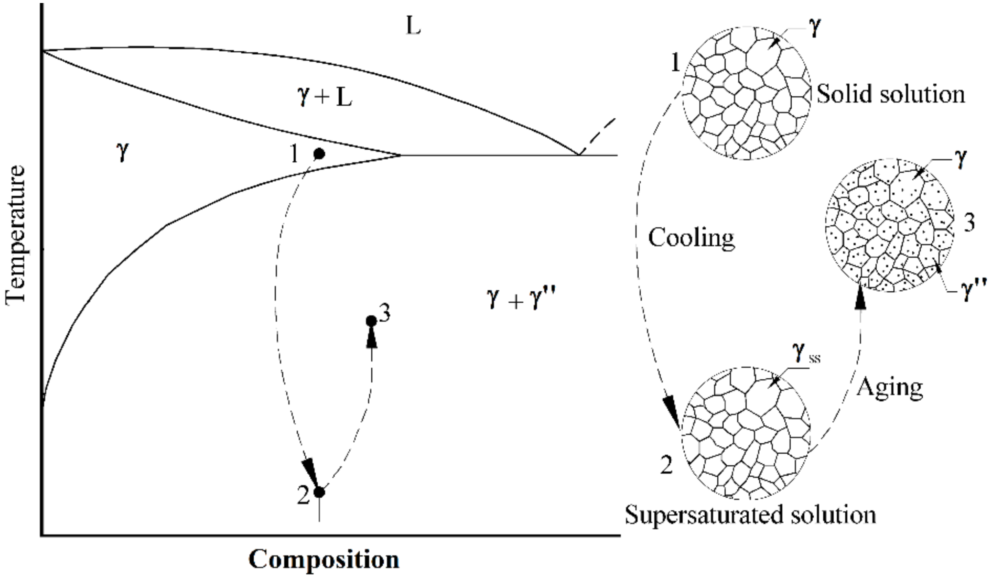
- *Age*: γ'' nucleate uniformly in the microstructure and grown to an optimal size.
  - AMS 5664: 760°C for 8h (γ'' forms), cool to 650°C, hold for 20 h (γ'' grow), air cool.



MSFC Vacuum Furnace



General phase diagram showing heat treatments.



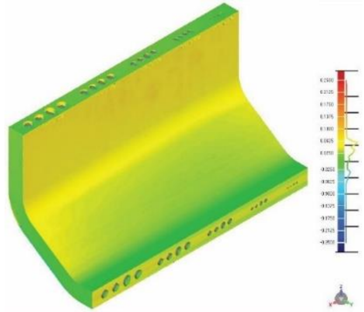
Notional Phase Diagram- IN718

NDE

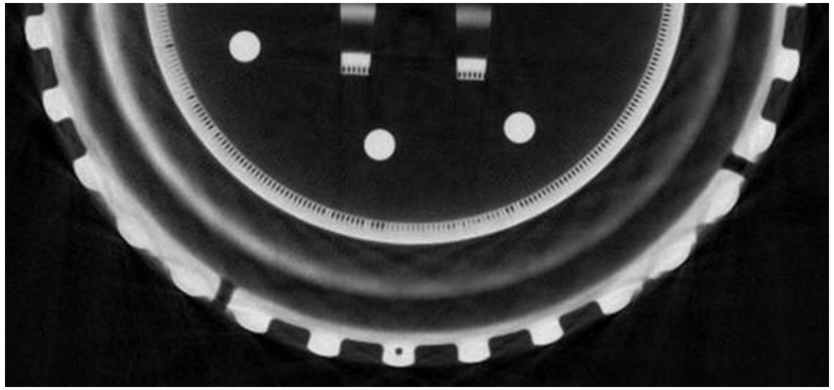
- Structured Light Scanning
  - Surface mapping
  - Geometric distortion/deviation
  - Limited spatial resolution
  - Equipment expensive but operation relatively inexpensive
- X-ray radiography & CT
  - Detect trapped powder
  - Large flaws
  - Limited spatial resolution (excludes micro-focus CT)
 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

Visual Borescope

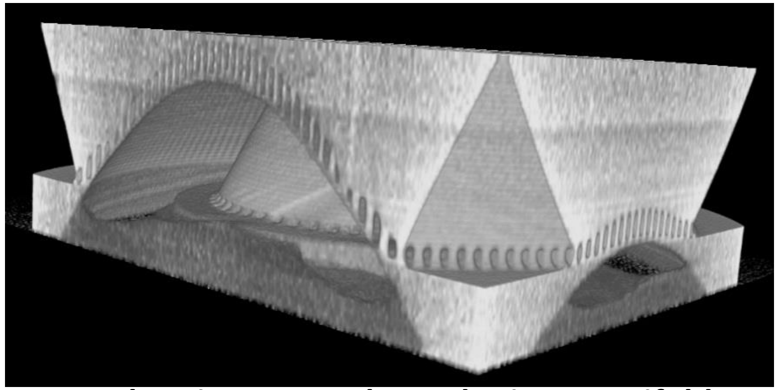
Structured Light Scanning



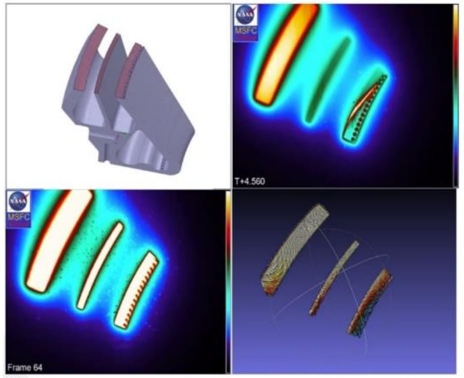
CAD-scan data comparison



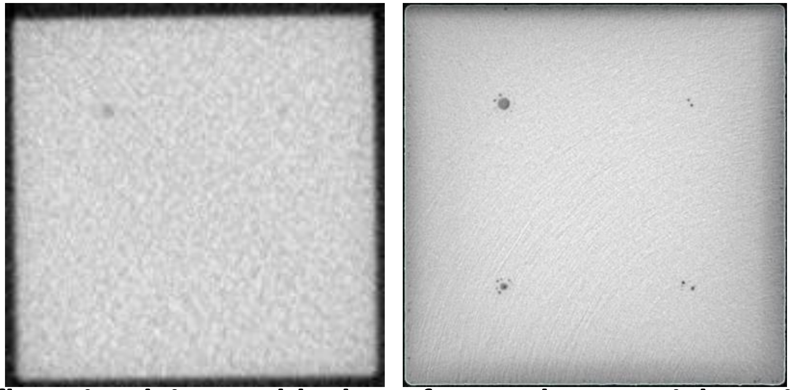
Radiograph showing powder filled channels



CT showing trapped powder in a manifold



In-situ Inspections

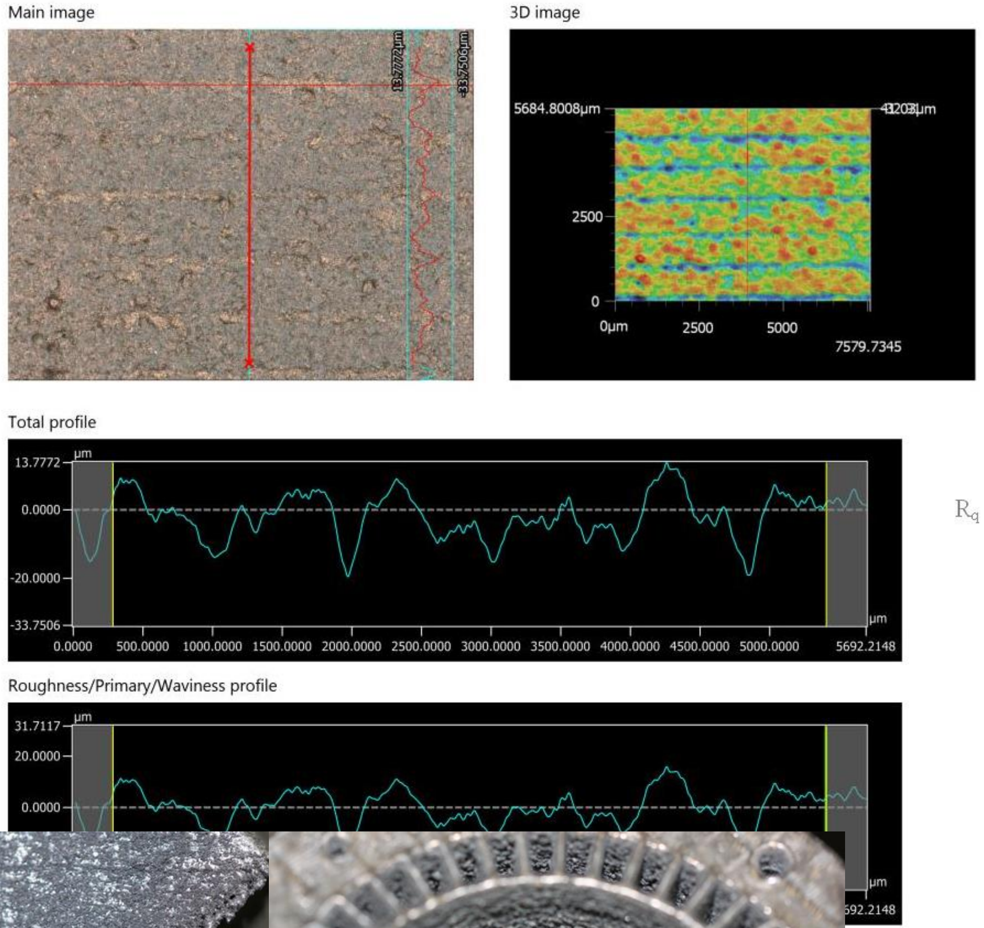


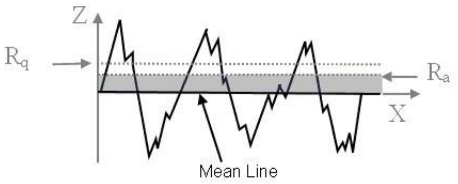
Known flaws in AlSi10Mg block. Left: Regular CT. Right: Micro-CT

Surface Finish Modification

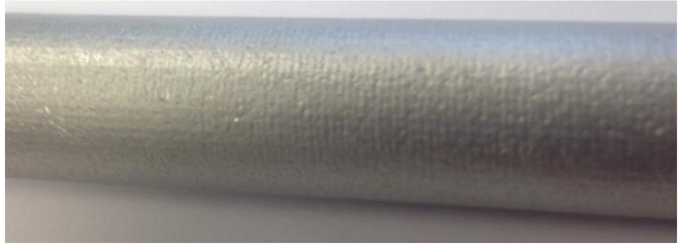
- As built roughness
  - PSD & parameters influence Ra.
  - High cycle fatigue (HCF) knock down due to near-surface porosity.

- Surface finish modification
  - Shot peen
  - Tumble
  - Machine
  - Extrude/slurry hone
  - Chemical etch
  - MicroTek (removes 0.05 mm)
  - Electro-polish





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



Software induced tesselation

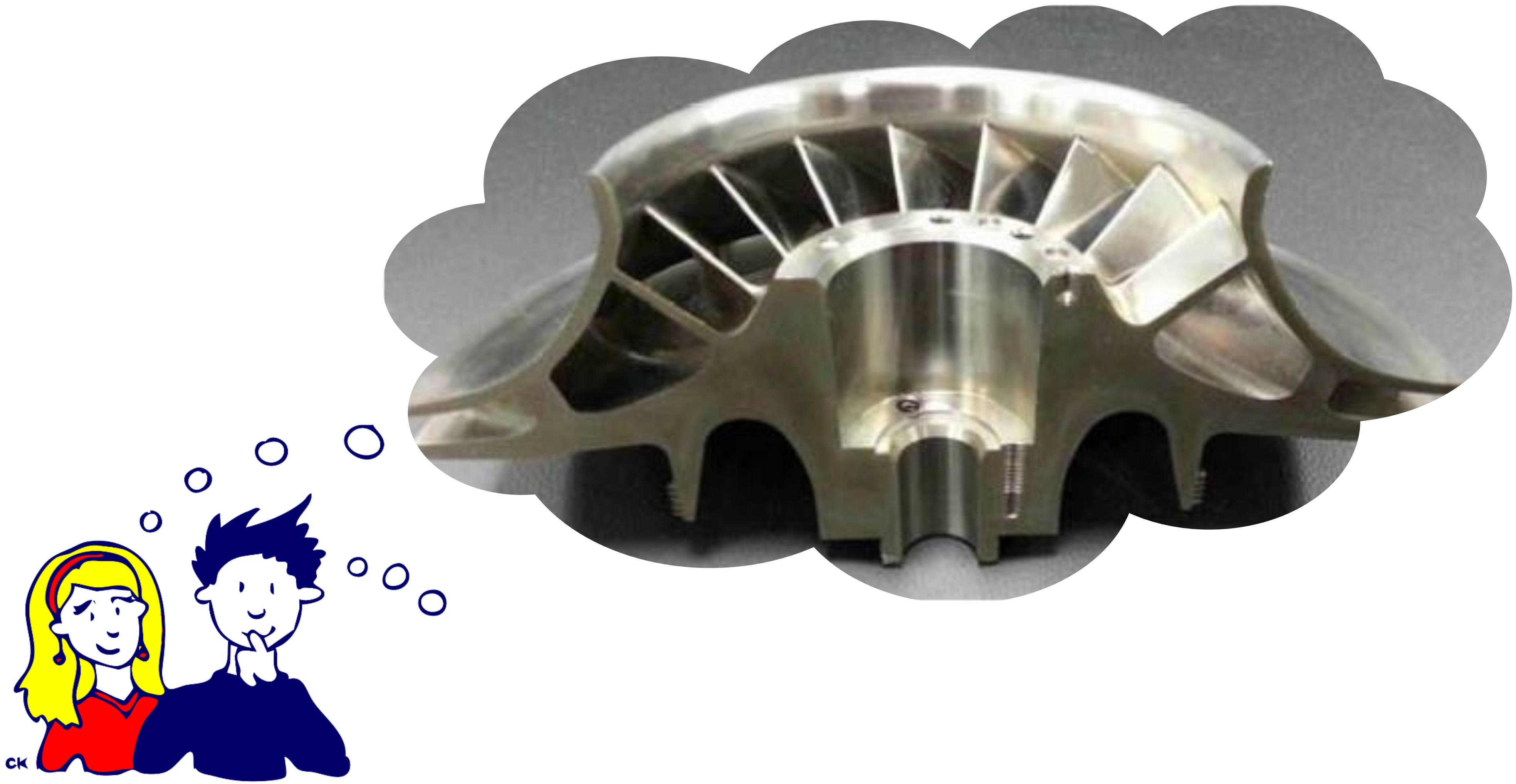
As-built surfaces of AlSi10Mg on Concept Laser X-Line.

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

Typical as-built surface roughness (L-PBF)

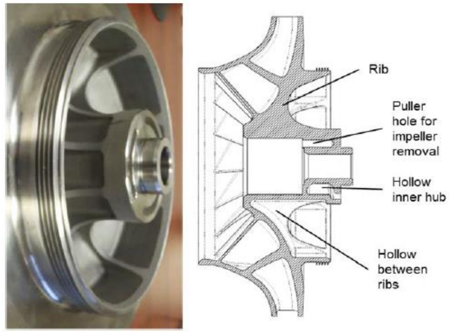
Printing Exercise #3

I want to try something I'd actually use…



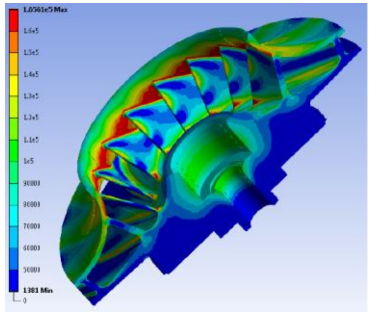
Printing Exercise #3

Design for AM

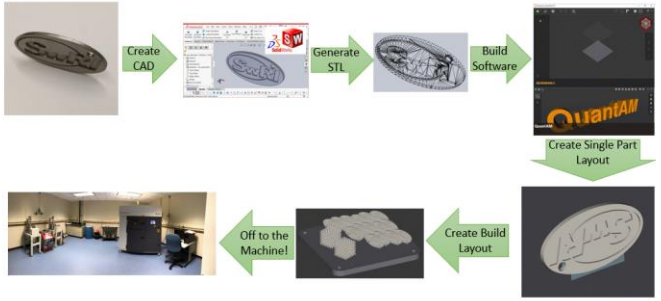


Closed Centrifugal Compressor Impellors

Material:
SS 17-4 PH

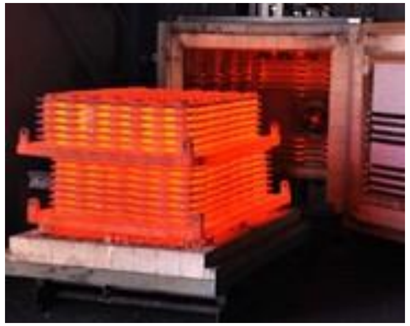


Prepare for Printing

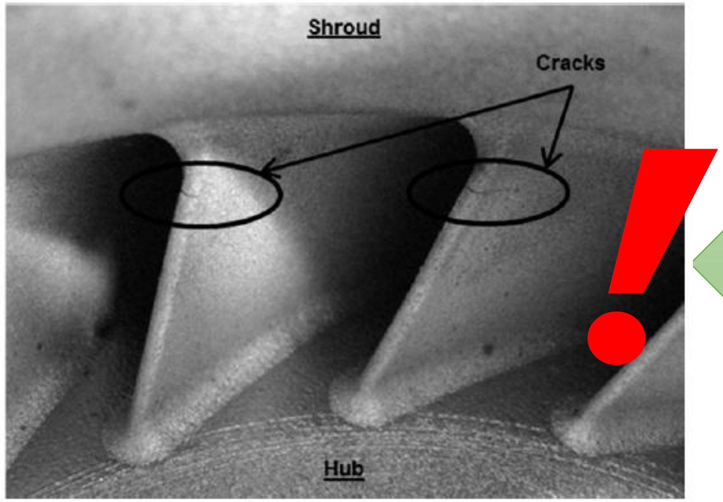


Print and Remove Part

Post Process



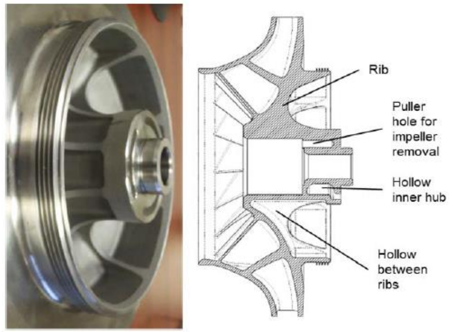
Inspect



What happened?!?!

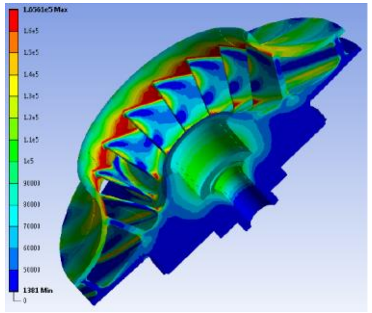
Printing Exercise #3

Design for AM

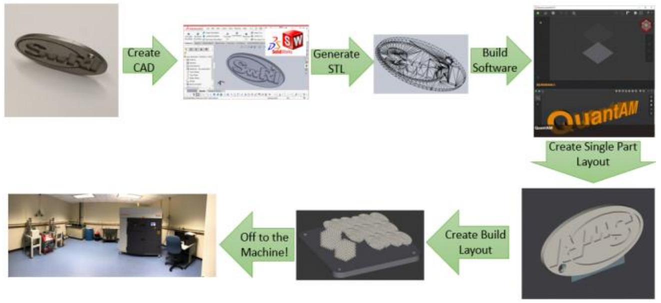


Closed Centrifugal Compressor Impellors

Material:
Inconel 718
Ti-6Al-4V

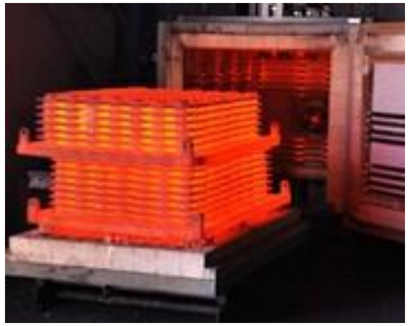


Prepare for Printing



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

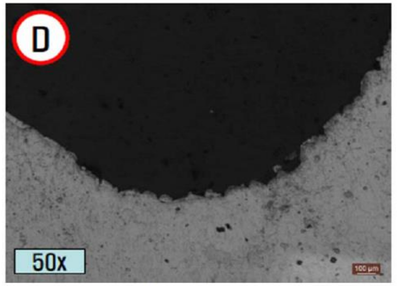


Figure 12. Magnified View of Fillet Region Between Impeller Blade and Shroud

Destructive Evaluation

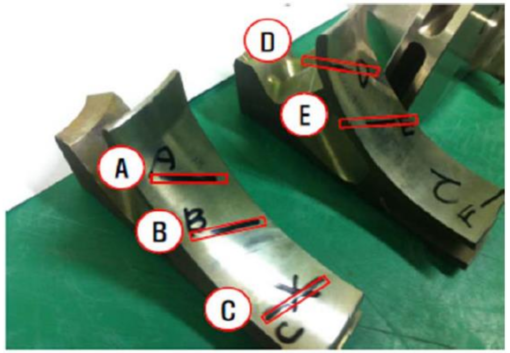


Table 2. Dimensional Accuracy of Manufactured Impellers

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

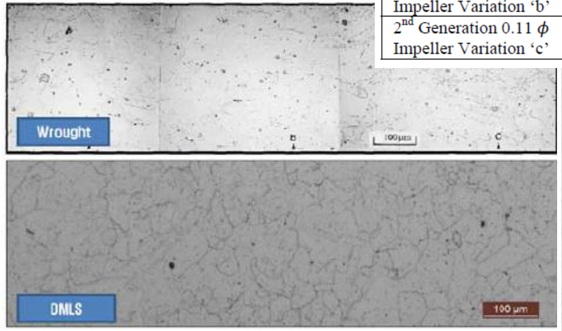


Figure 13. Comparison of Grain Size Between Wrought Inconel 718 and DMLS Inconel 718

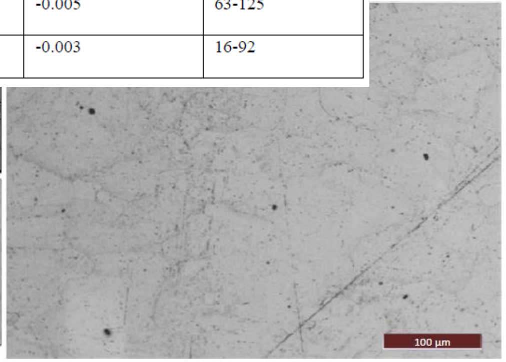


Figure 14. Magnification of DMLS Inconel 718 Sample Showing Micro-Porosity

Application Testing

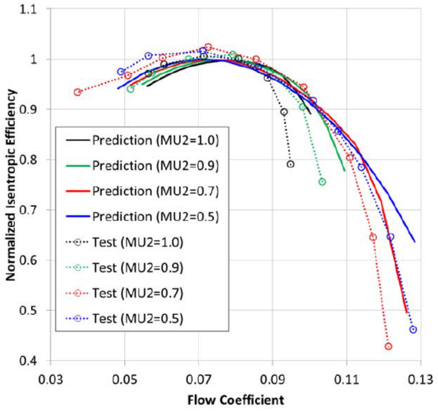


Figure 18. Comparison of Predicted and Tested Normalized Isentropic Efficiency vs. Flow Coefficient

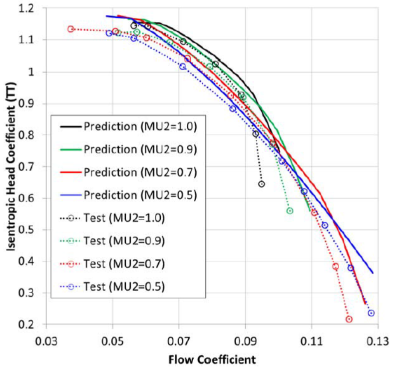


Figure 17. Comparison of Predicted and Tested Head vs. Flow Coefficient

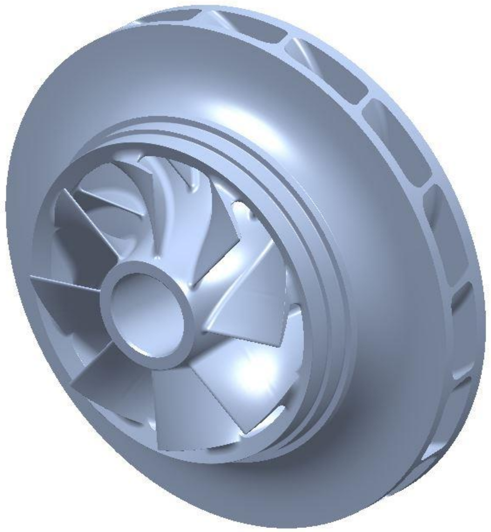
Allison, T.C., Moore, J.J., Rimpel, A.M., Wilkes, J.C., Pelton, R., Wygant, K., "Manufacturing and Testing Experience with Direct Metal Laser Sintering for Closed Centrifugal Compressor Impellers," *Proceedings of 43rd Turbomachinery Symposium*, Houston, TX, September 2014.

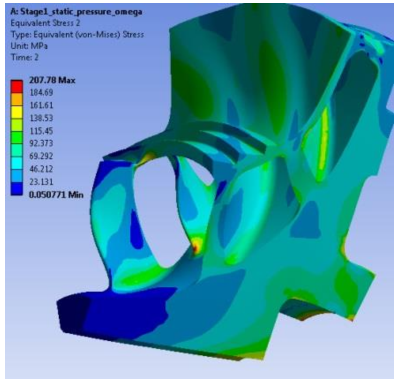
Printing Exercise #3

- 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

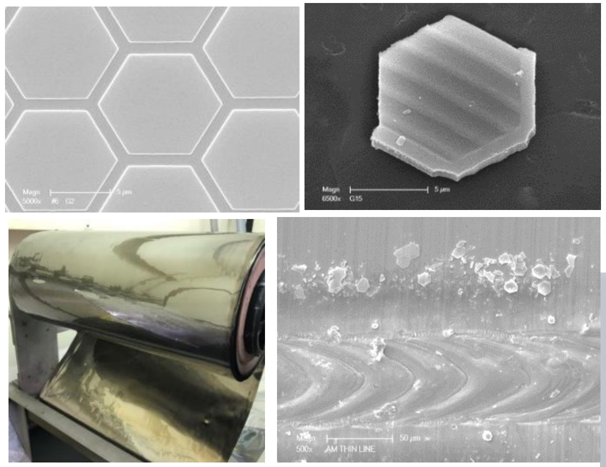




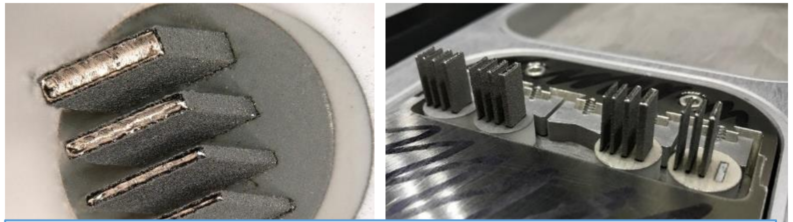
3D Printed Part (Unfinished)

3D Printed Part (Finished)

Advances in Additive Manufacturing

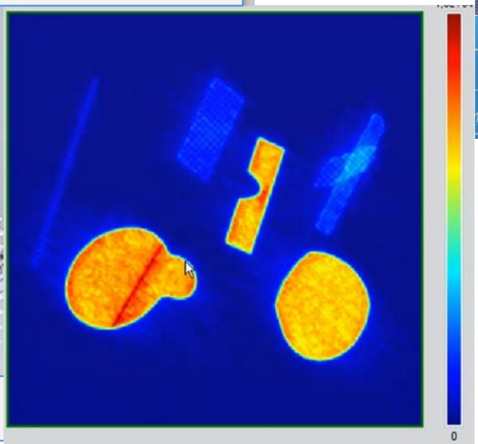


Engineered platelets to replace powders. Courtesy SwRI

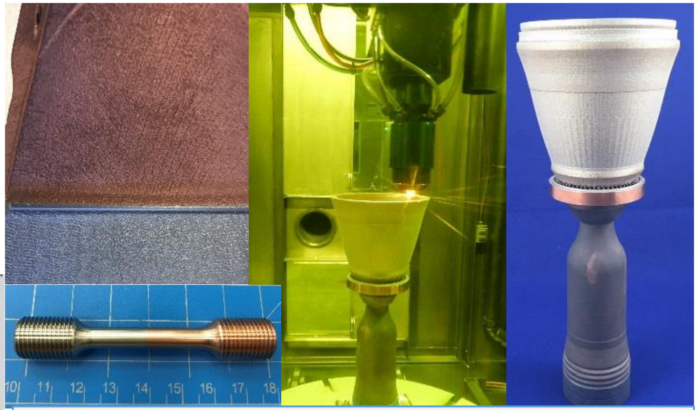


Hermetic metal-ceramic bonds. Courtesy SwRI

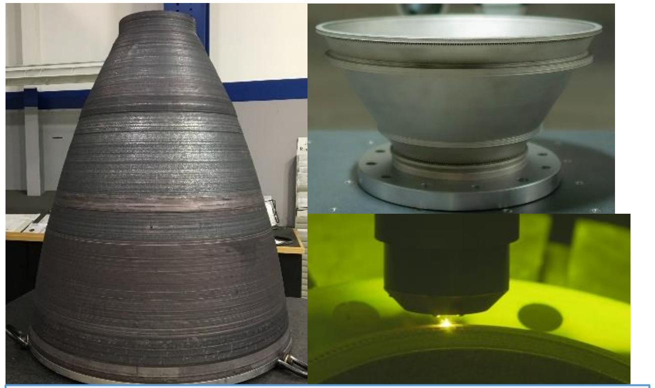
High density ceramic AM. Courtesy Lithoz.



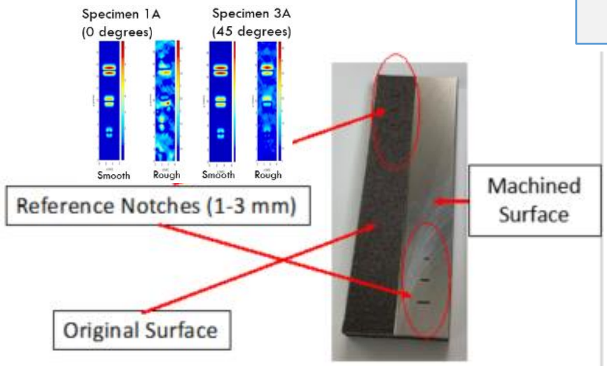
In-Situ Process Monitoring. Courtesy EOS.



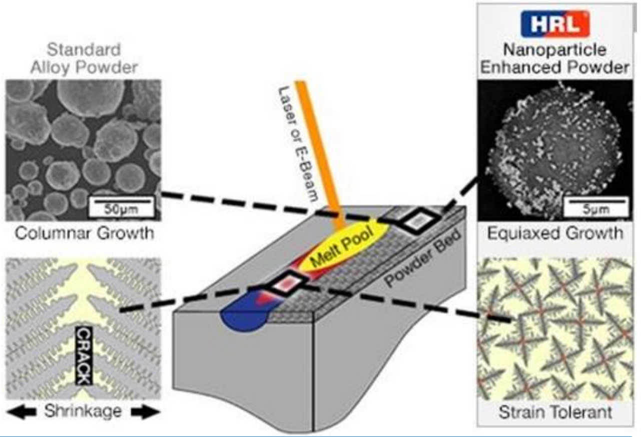
Multi-alloys and hybrid techniques



Increased scale and resolution



Advanced NDE application for qualification (Eddy Current Testing shown). Courtesy SwRI



Non-weldable alloys. Courtesy HRL.

Support structure etching. Courtesy CO. School of Mines.

LPBF of shape memory alloys. Courtesy SwRI

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- MSFC EM42
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- Cynthia Sprader
- MSFC Test Stand 115 and 116 Crews
- MSFC ET10
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- Mike Kynard
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- Jason Wilkes
- Kevin Hoopes
- John Helfand
- Carl Popelar
- Aaron M. Rimpel
- J. Jeffrey Moore
- Natalie Smith
- Robert Pelton
- Karl Wygant
- Sewoong Jung
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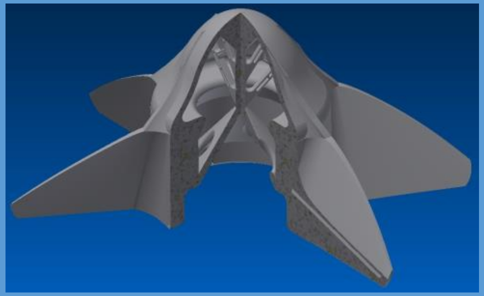
AM Process Flow

DESIGN & ANALYSIS

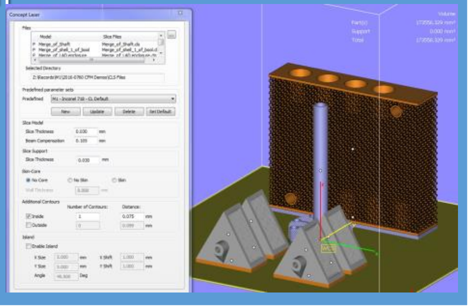
- Performance Requirements

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



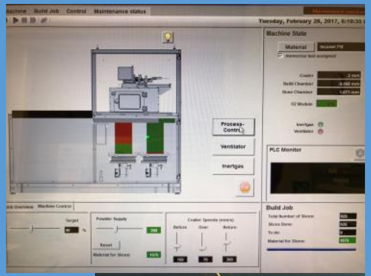
BUILD PREPARATION

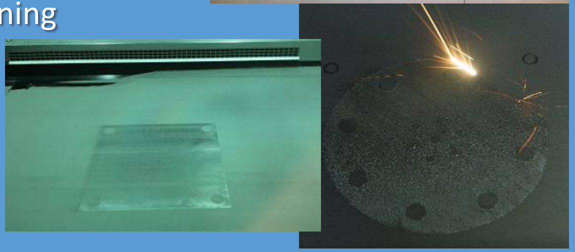
- Repair .stl
- Build placement & orientation
- Thermal stress/distortion prediction
- Support generation
- Slicing
- Scan strategy



BUILD OPERATIONS

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





POST-PROCESS

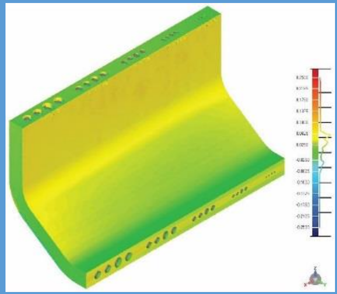
- Powder Removal
- Stress Relieve
- Support Removal
- Plate Separation
- HIP
- Heat Treatments
- Machine/Surface mod
- Mechanical Testing

NONDESTRUCTIVE EVALUATION

- Structured light scanning

- X-ray CT

-Compare inspection models to CAD



IMPLEMENTATION

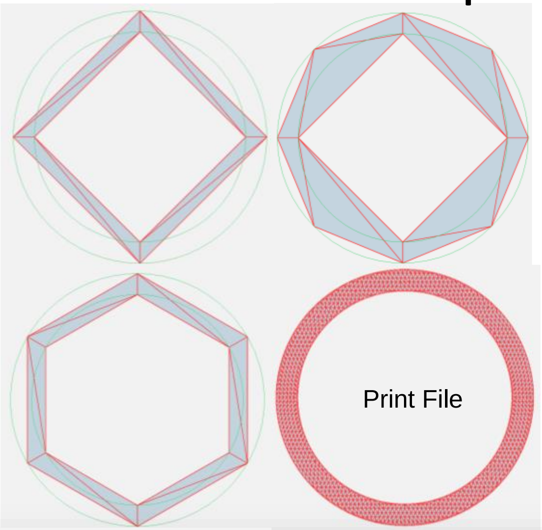
- Test & post-ops inspection

- NDE / Destructive evaluation

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



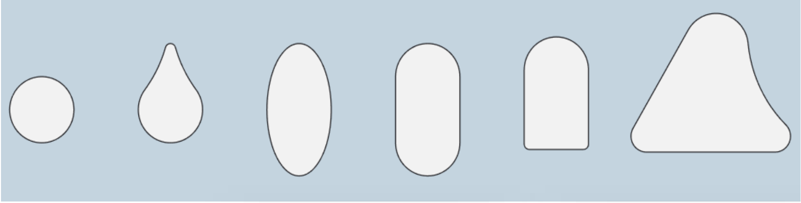
Example of injector elements with facets

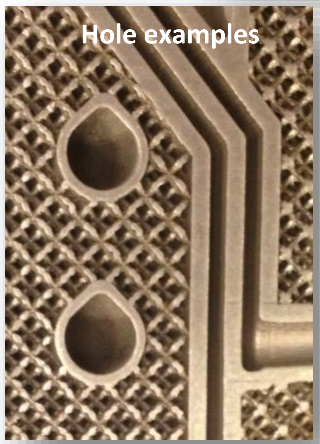
Ref: Will Brandsmeier, Kevin Baker, Dwight Goodman

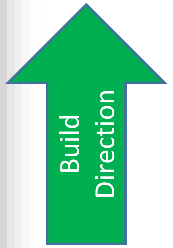
Considerations in Design in Printing

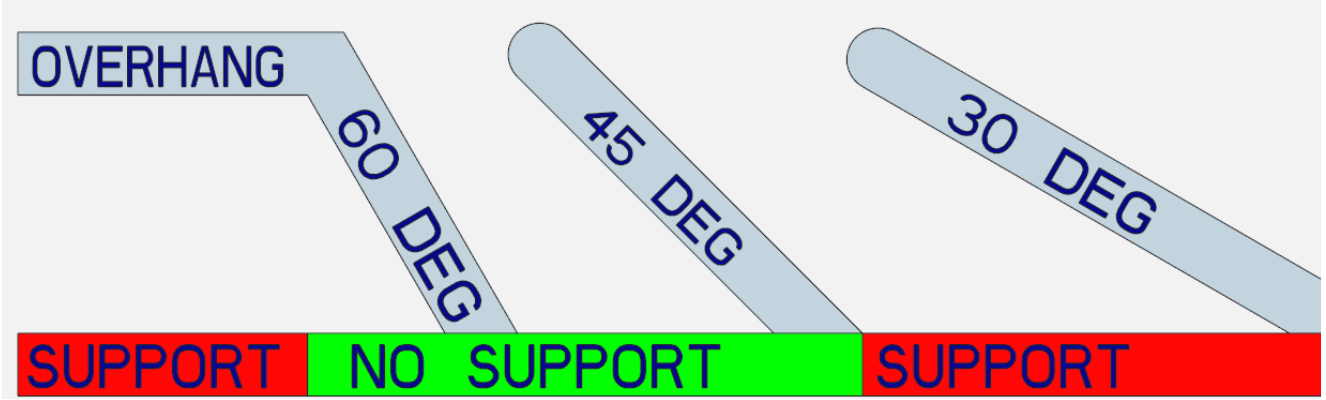
- Angled feature designs are limited (measured from horizontal)
  - Features <45º normally require support
  - Features >45º normally do not require support
  - Consider features in all dimensions
- Holes cannot be printed as true holes if larger diameter
  - Largest unsupported hole ~ .250”
  - Smallest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

Hole design examples





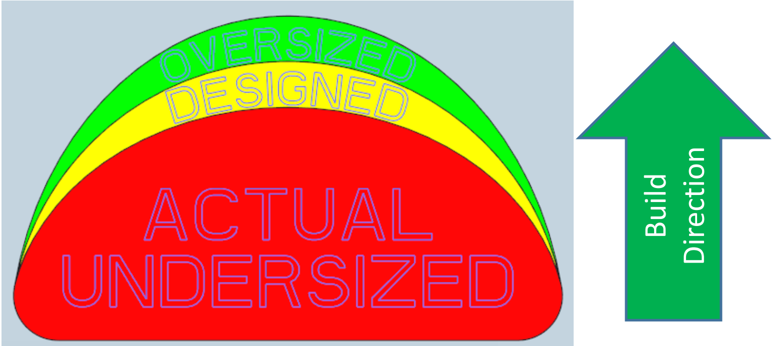


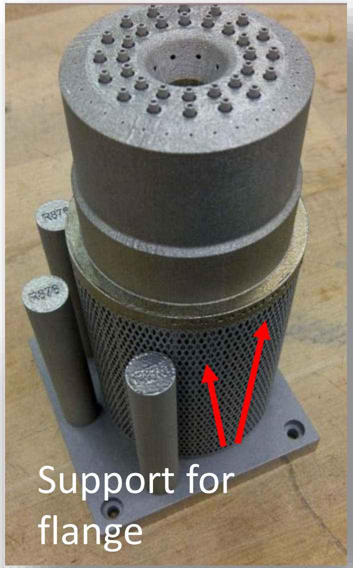


Angled wall design example

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

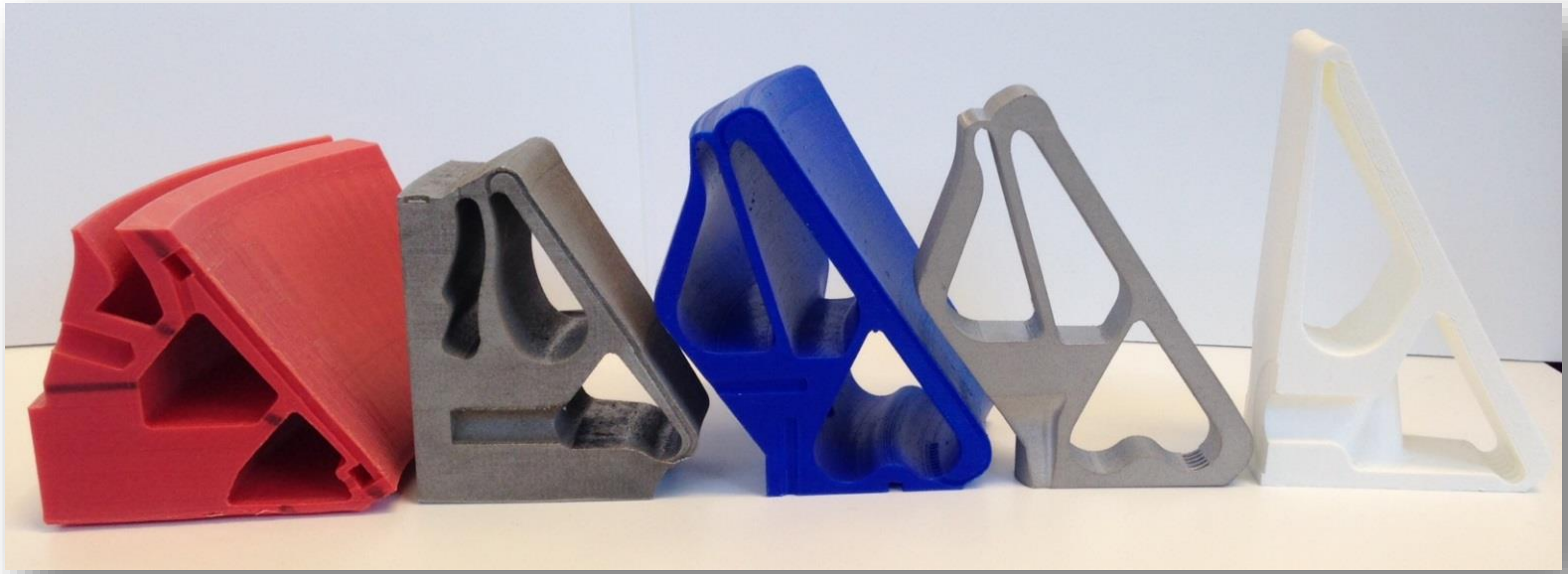




Ref: Will Brandsmeier, Kevin Baker, Dwight Goodman / NASA MSFC ER34

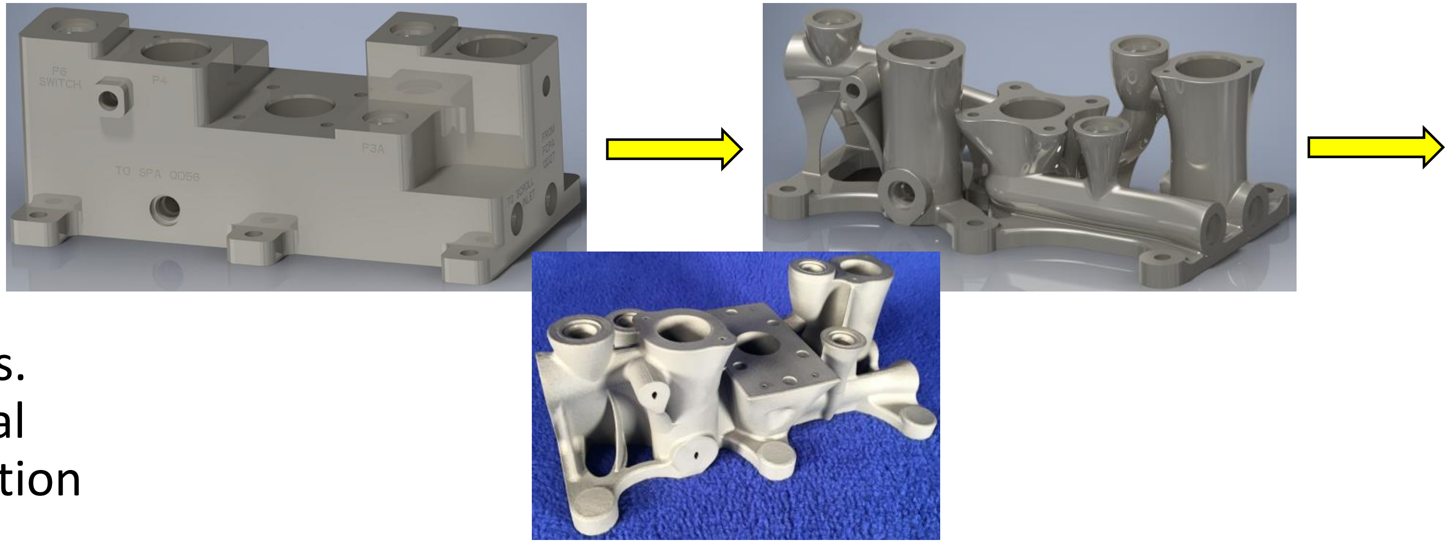
Considerations in Design and Printing

- 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



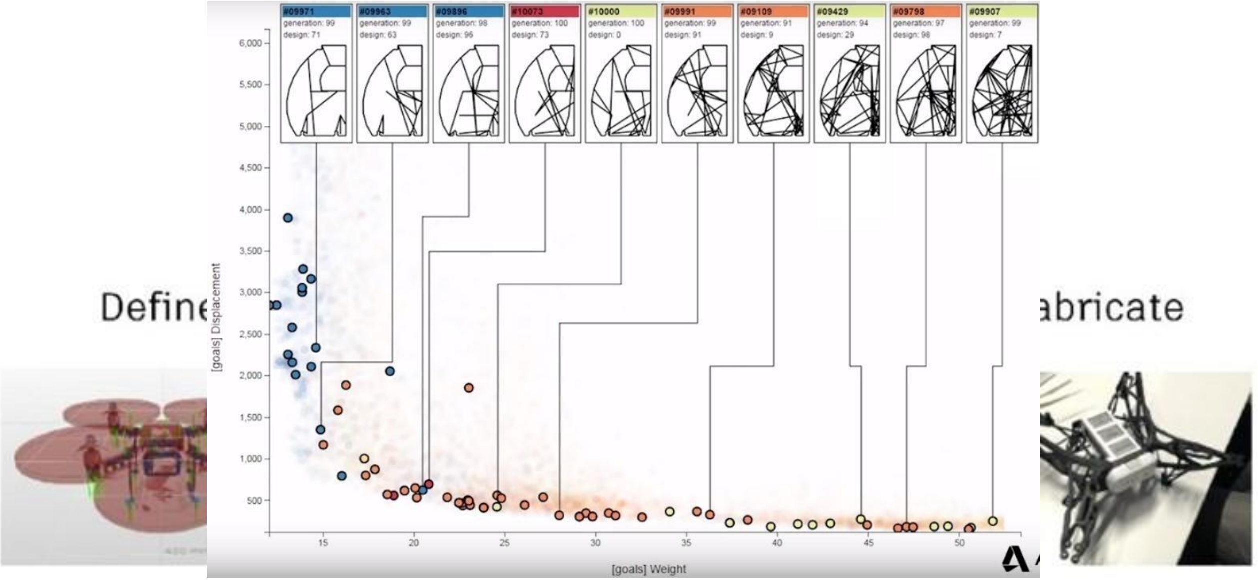
Advanced Design for AM

- 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 Optimized ISS ECLSS APP Manifold, Ti6A4V. 34% mass and 75% cost savings. Courtesy Zach Jones.

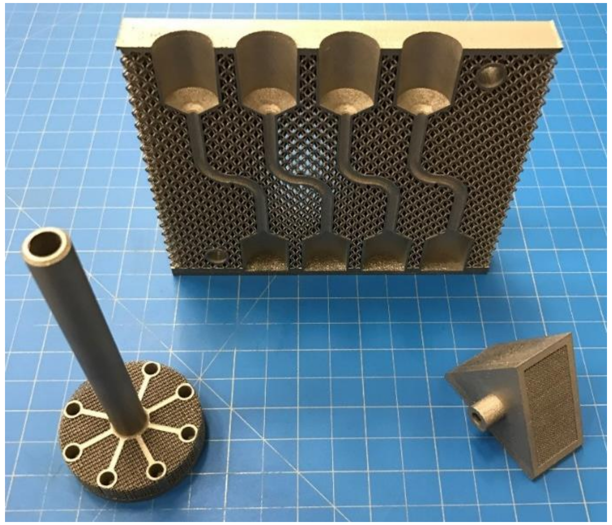
- Generative Design
  - Define interface geometries, enclosure, constraints, loads, material and FS.
  - Software generates numerous point designs and displays an an Ashby chart.
  - Select and prioritize optimized designs: mass, strength, stiffness.
  - Apply when mass and structure dominate.



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.

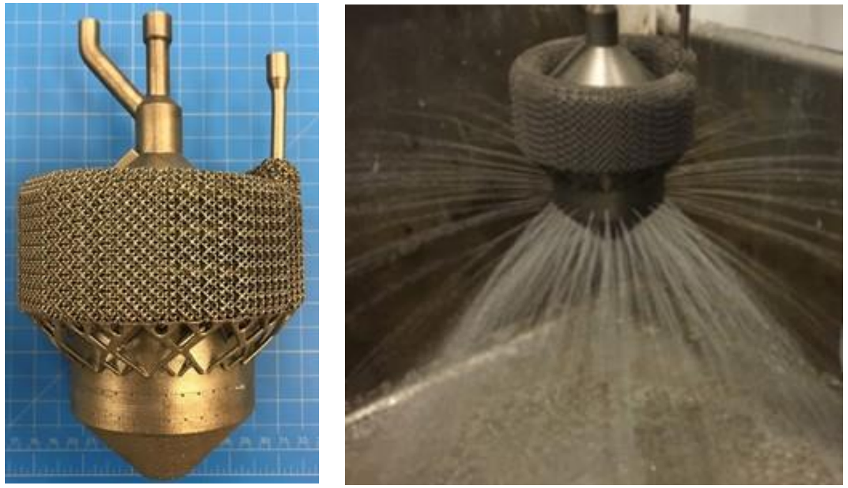


CFM Magnetically Coupled Rotor, Heat Exchanger, LAD demos

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

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

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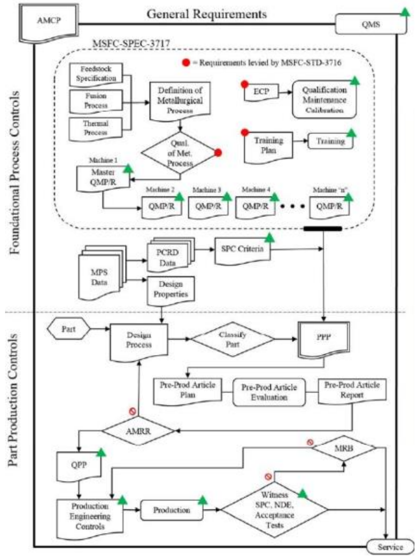
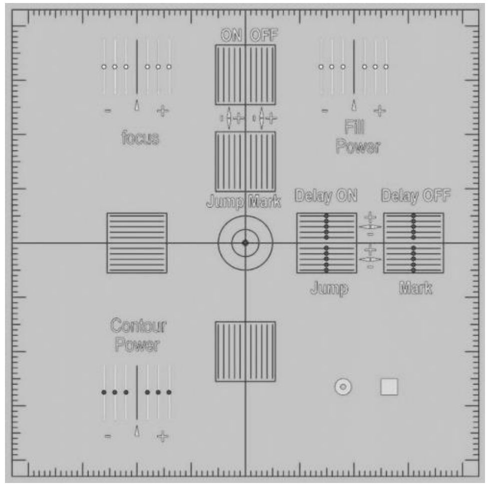


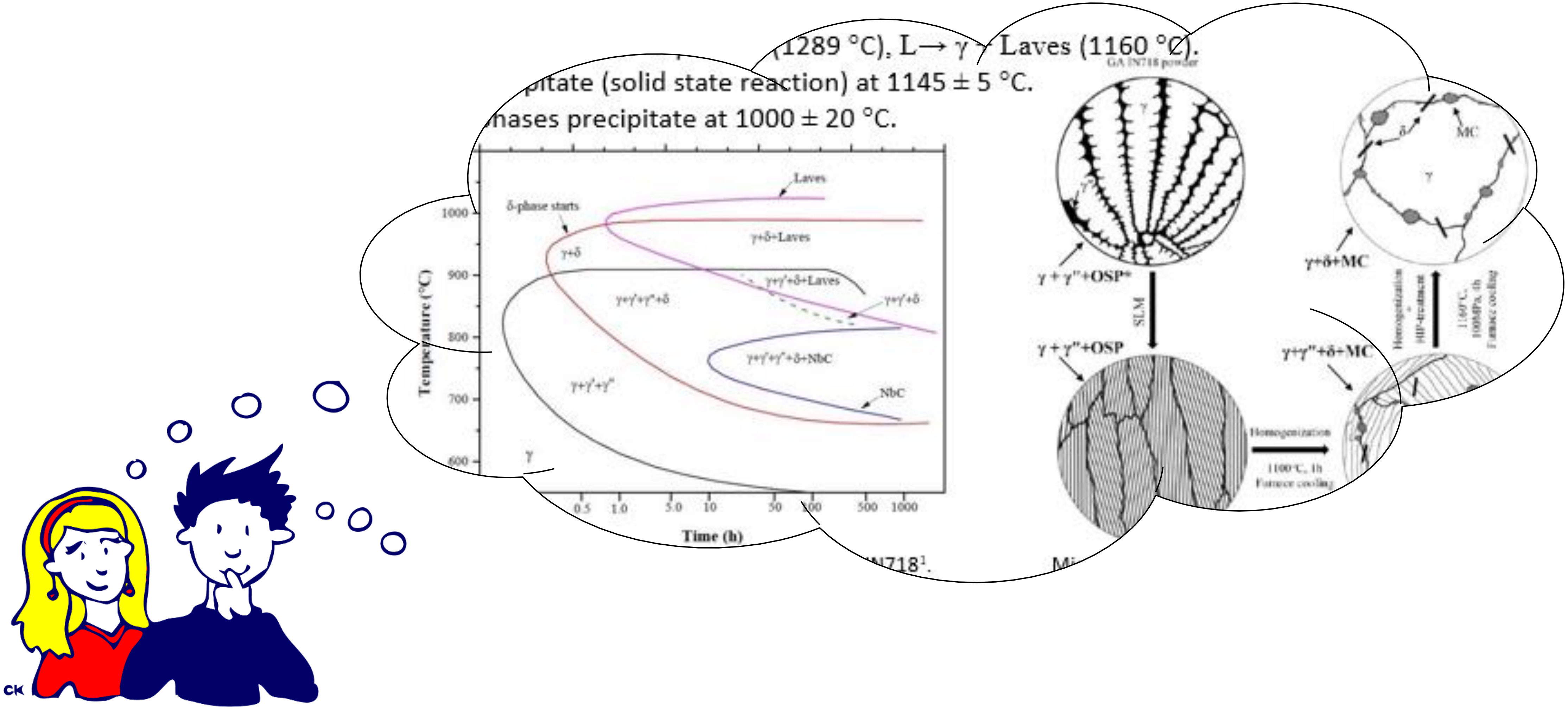
MSFC-STD-3716 & -3717: From powder to acceptance



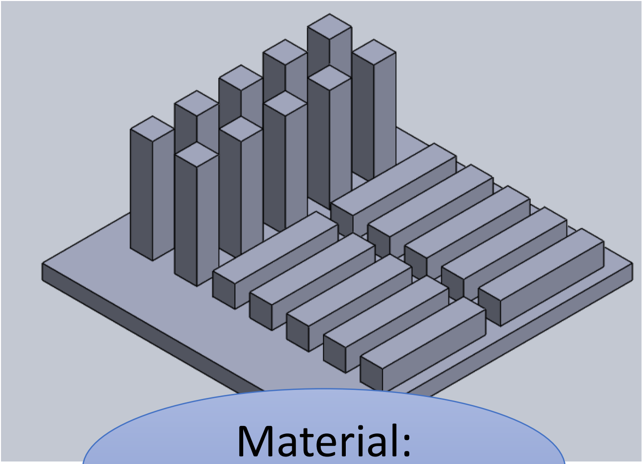
Machine repeatability

Printing Exercise #4

What is my material……really?

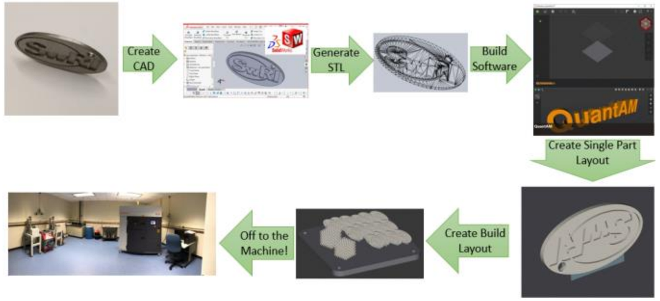


Printing Exercise #4

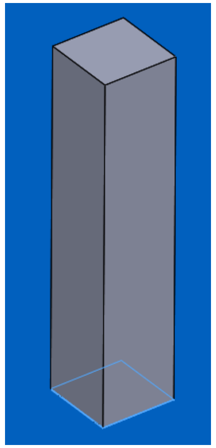


Material:
Inconel 738LC

Prepare for Printing

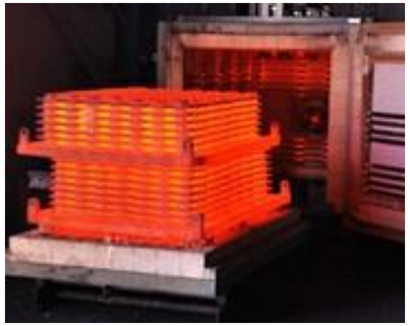


Print and Remove Part



Post Machining

Post Process



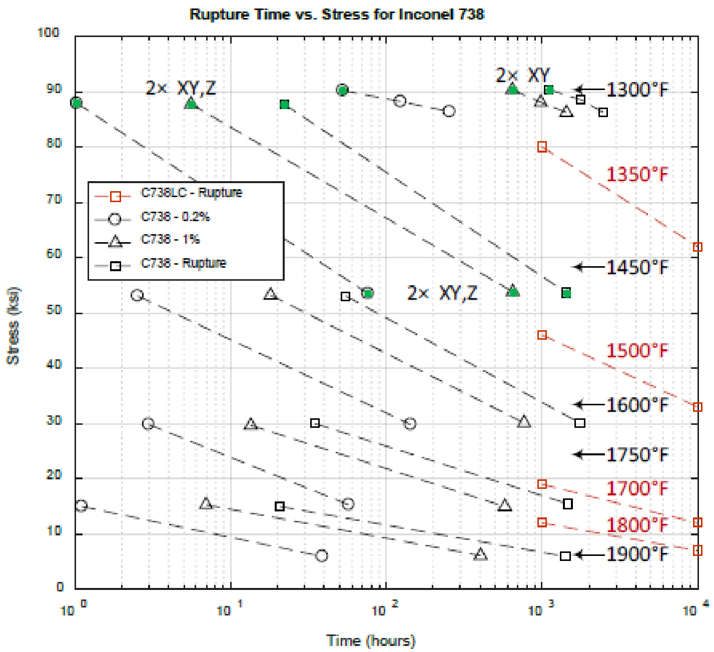
HIP/Heat Treat

Material Test

What Could You Learn?

Printing Exercise #4

Historical Cast In738 Data



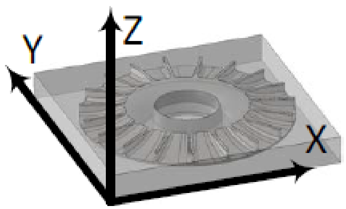
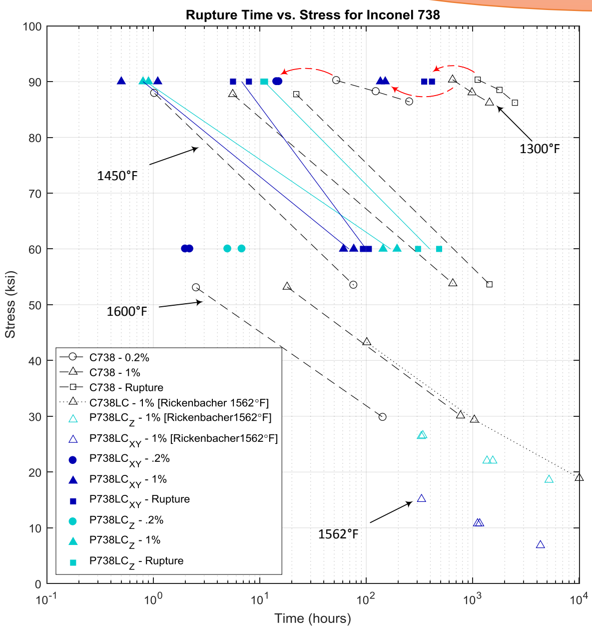
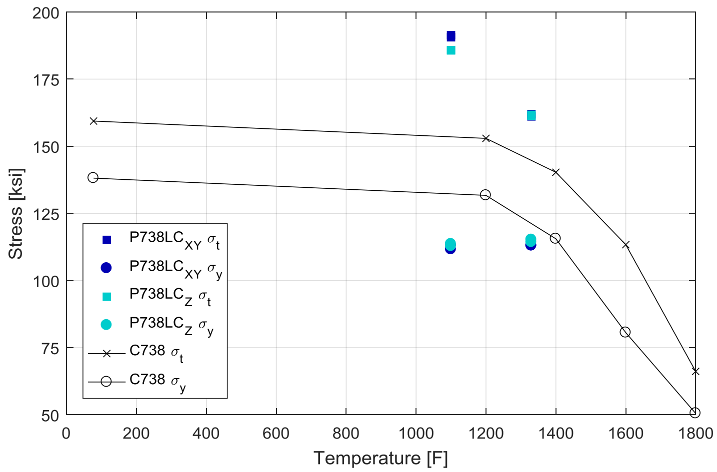


Figure 2: Cast Inconel 738 Creep Sample Data and Associated Test Points (Denoted by Green Accent), Heat Treat - 2050F, 2 hrs, AC +1550F, 24 hrs, AC (data taken from [8])

Printed In738LC Data





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

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.

Oversized sieved powder.

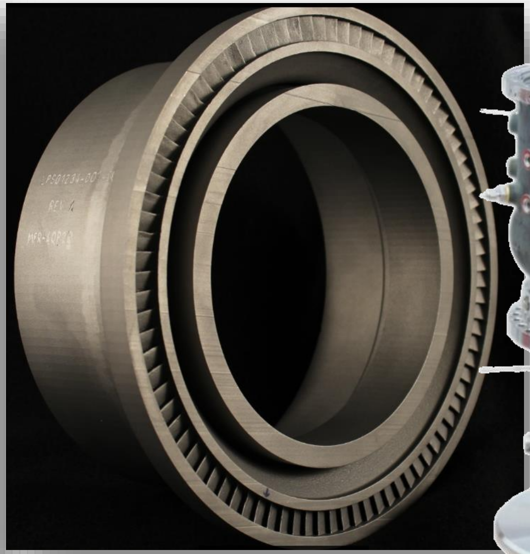
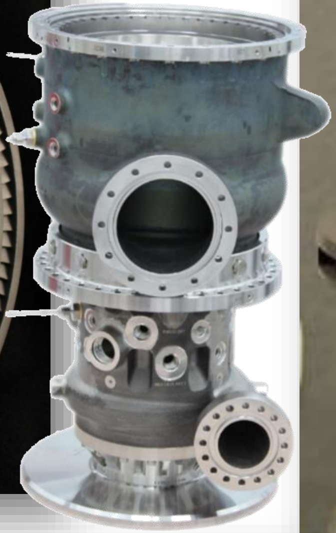
- Disadvantages:
  - L/E-PBF limited to weldable alloys (unless additives included).
  - Build envelope size limits.
  - Design constraints: overhang surfaces, minimum hole size.
  - Surface roughness.
  - As built microstructure will require post processing.

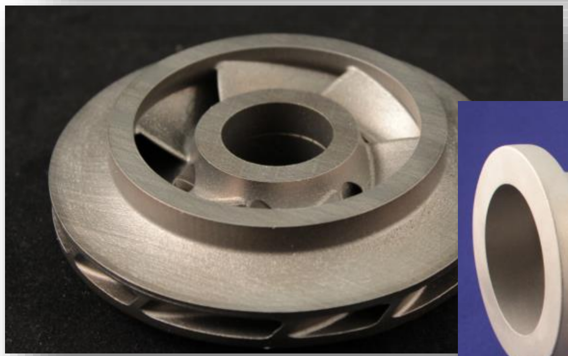
- Property Variability
  - Properties dependent on starting powders, parameters, and post-processing.
  - Anisotropic properties in the build direction (Z).
  - Size: small-scale vs. full-scale builds.
  - Build volume spatial location.

Power from a wet-vacuum.

Turbomachinery



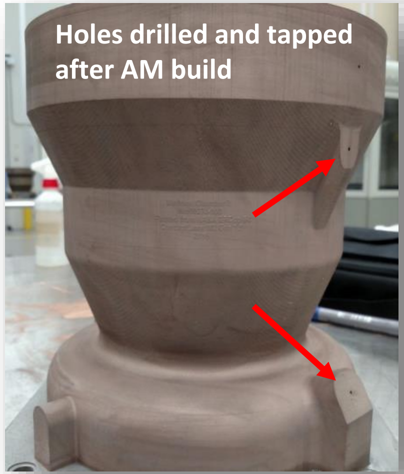


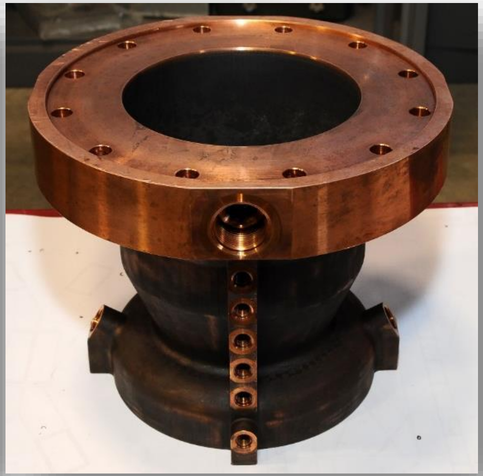

Ref: Derek O'Neal,
Marty Calvert / NASA MSFC

Design and Post-Processing Considerations

- **Geometric Dimensioning and Tolerancing (GD&T) must be considered in design for 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
  - Undersize holes for reaming and tapping

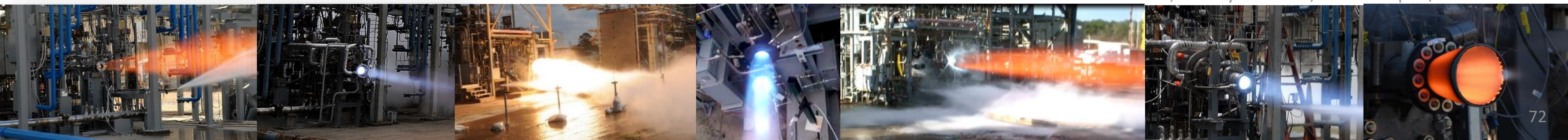




Combustion Chambers

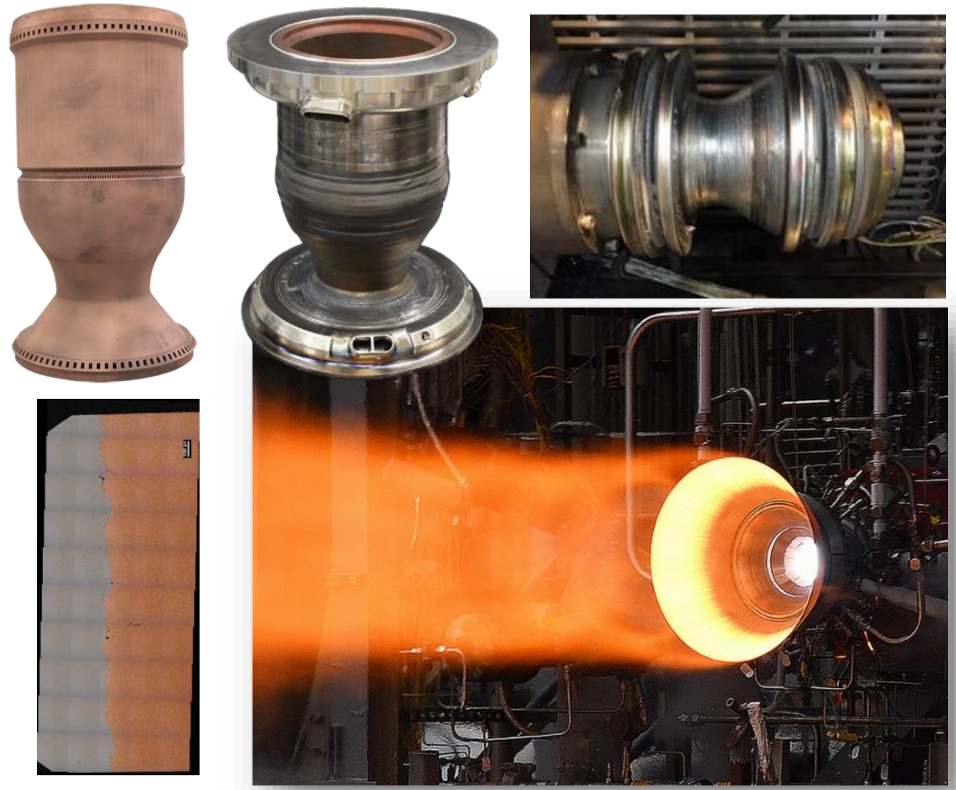
- Additive manufacturing is enabling materials that were historically difficult to process or expensive
  - GRCop-84, GRCop42, C-18150.

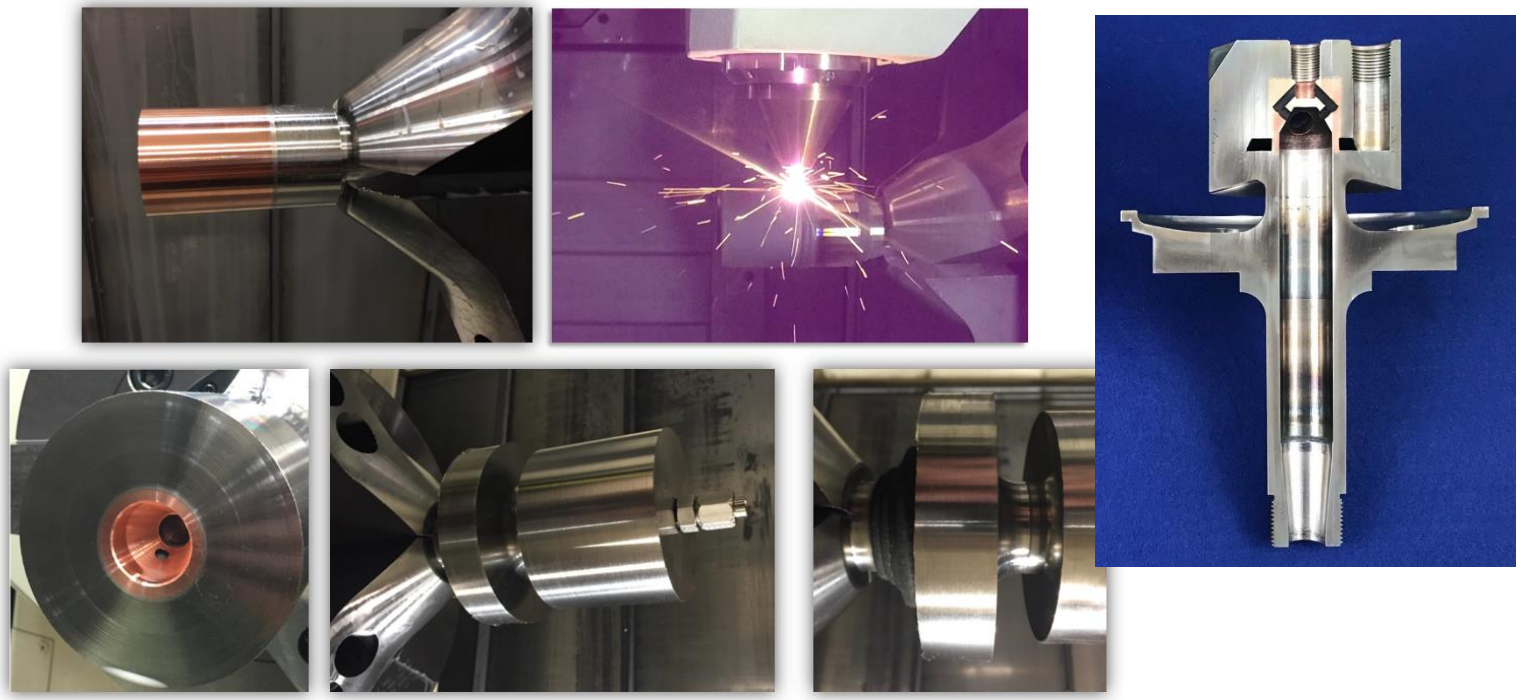
Ref: Chris Protz, Sandy Greene, Ken Cooper/ NASA MSFC



Bimetallic Components

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



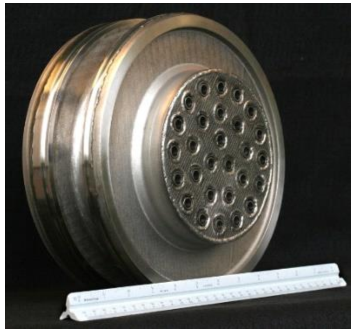


Ref: Chris Protz, Robin Osborne / NASA MSFC

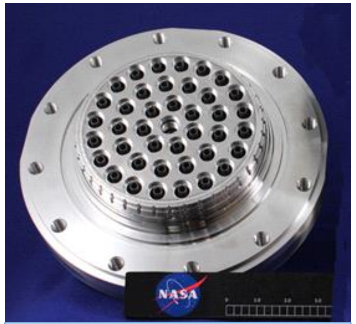
Injectors

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

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

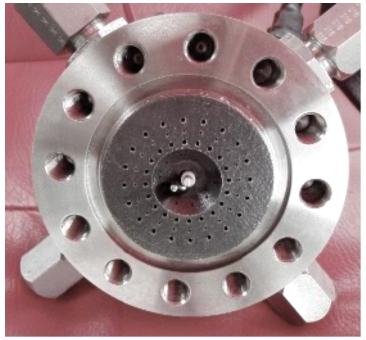


20K LPS Subscale Injector. Tested August 2013



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

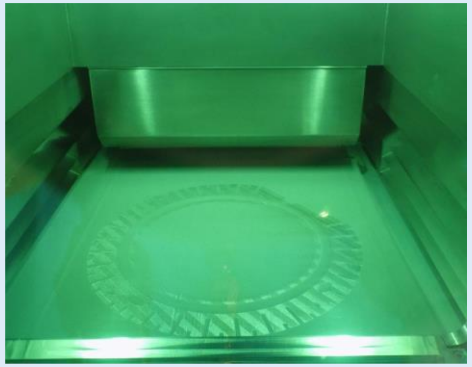
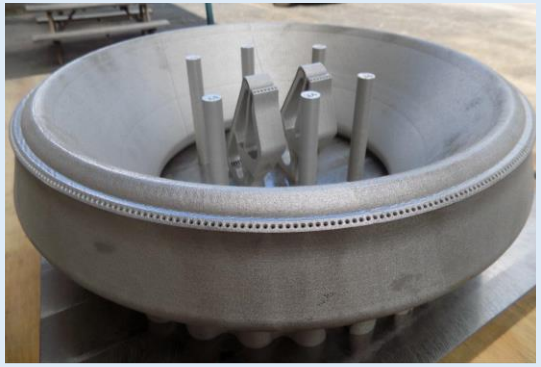
- MSFC has developed a total of 10 unique AM injectors between 2012-2018
  - Materials: Inconel 625, Inconel 718, Monel K-500
  - Element Types: swirl coax, shear coax, FOF
  - Number of Elements: ranging from 6 to 62
  - Diameters: ranging from 1.125” to 7.5”
  - Hot fire tests performed on 7 of these 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 part count, joining 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

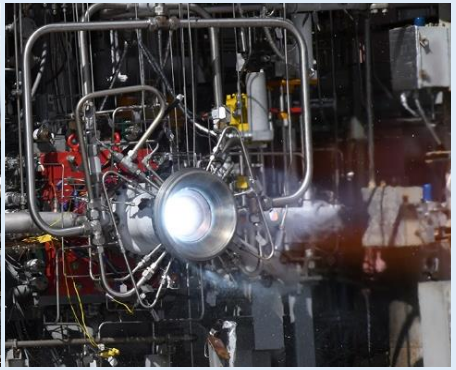
Ref: Brad Bullard, Jim Hulka, Sandy Greene, Greg Barnett, Jessica Wood

Nozzles

Laser-Powder Bed Fusion

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

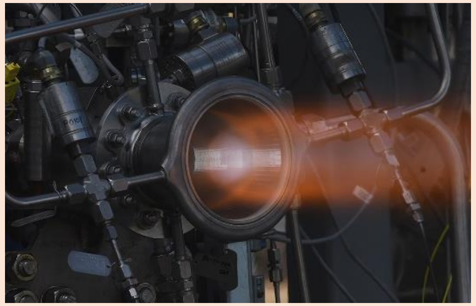





Directed Energy Deposition

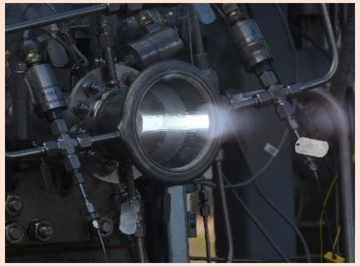
- Scale is not limited
- High deposition rates
- Loss of resolution (compared to L-PBF)
- (3) DED techniques being evolved
- Potential for casting and forging replacements

Laser Wire Deposition

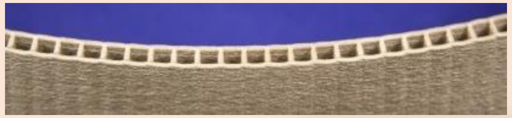
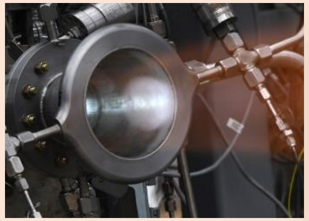
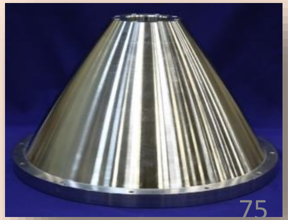
Arc-Wire Deposition



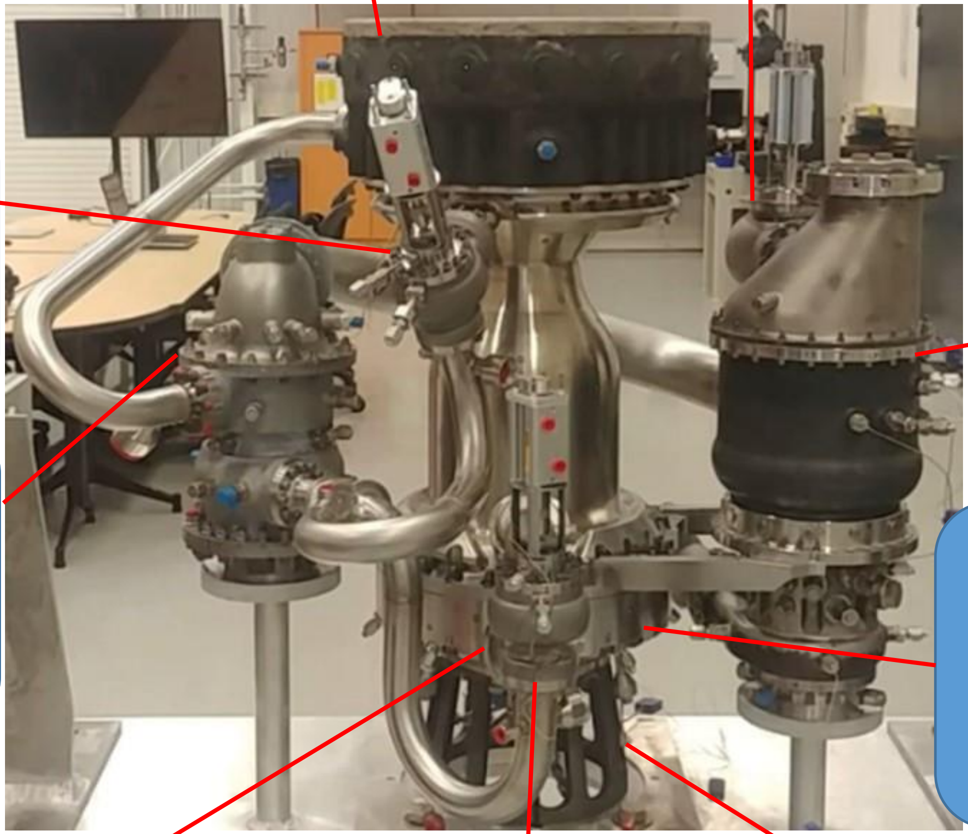



Blown Powder Deposition



System Integration Example



Main Fuel Valve
Part reduction: 5 to 1
Successfully tested

Fuel Turbopump
Schedule reduction by 45%
Part reduction: 40 to 22
Tested to 90,000 RPM

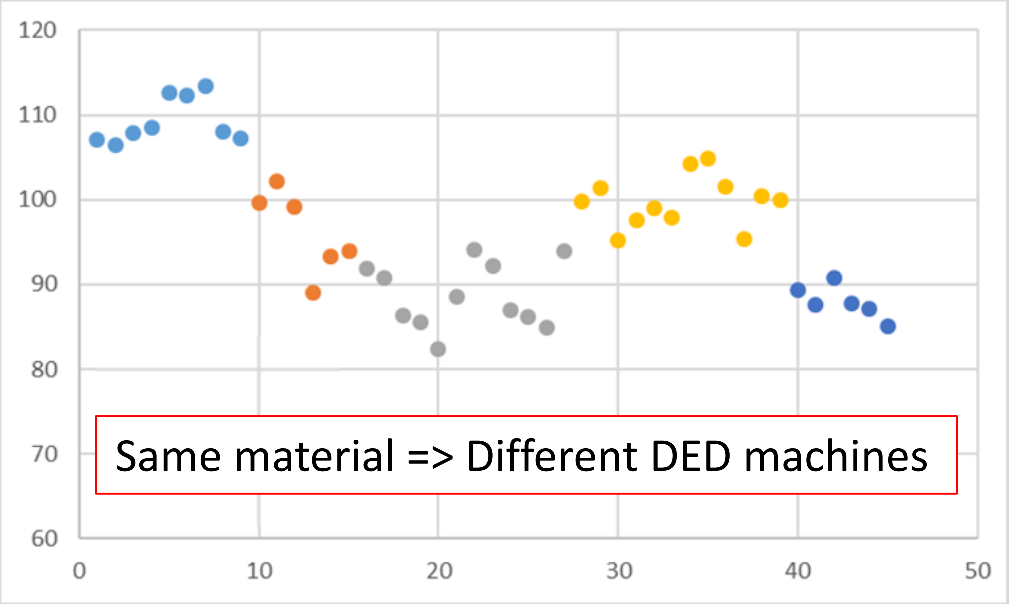
Main Oxidizer Valve
Part reduction: 6 to 1
Successfully tested
(Hidden)

Oxidizer Turbopump
Part reduction: 80 to 41
Tested to 40,000 RPM.

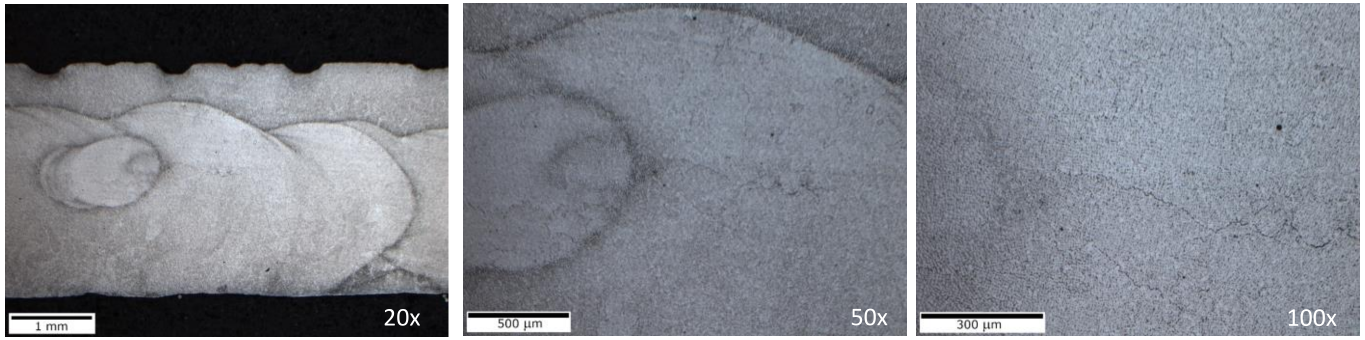
Injector
Cost Reduction: 30%
Part reduction: 252 to 6
Eliminated braze joints
Tested to 100%

Directed Energy Deposition

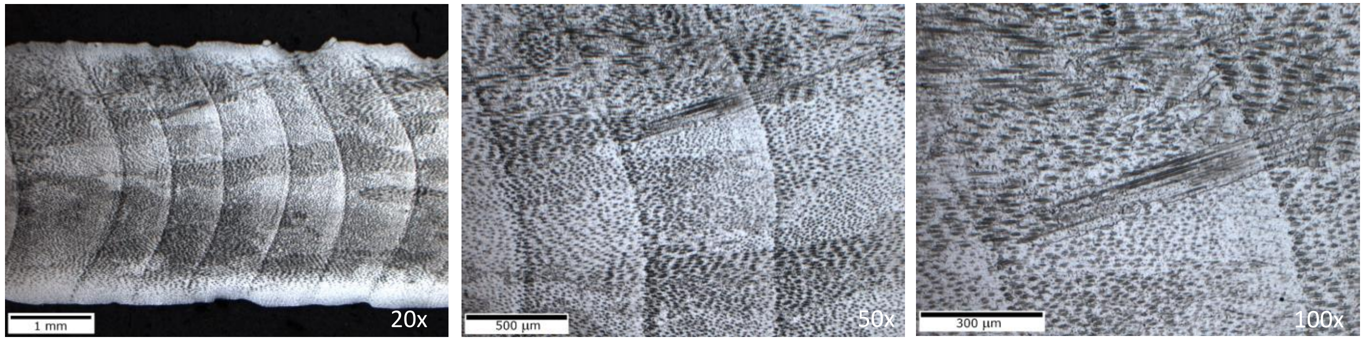
Material properties are dependent on a number of processing parameters (material, build rates, environment, orientation…) => highly variable

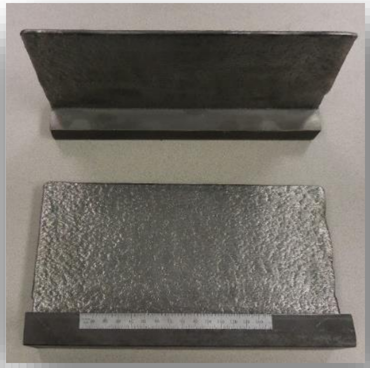


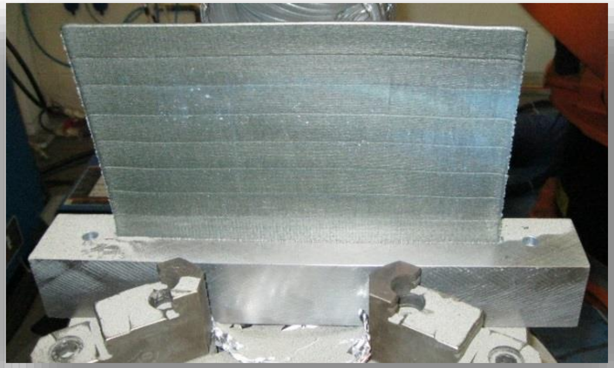
Inco 625 As-Built - Hoop



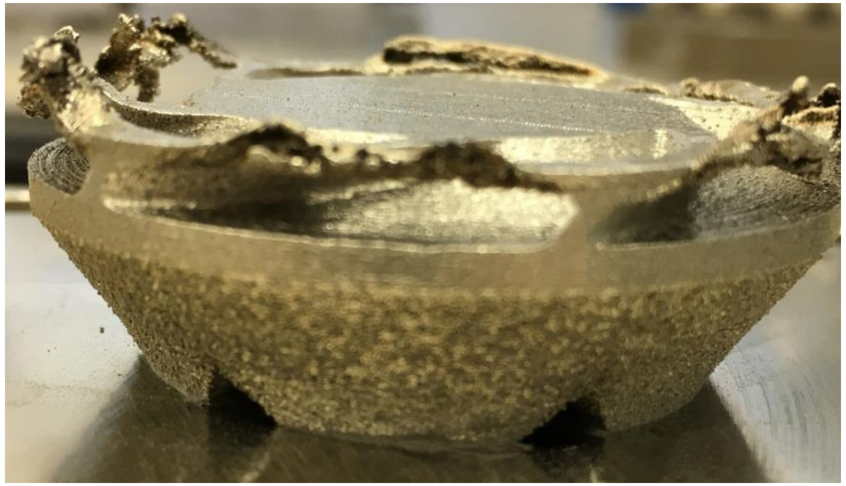
Inco 625 As-Built - Axial

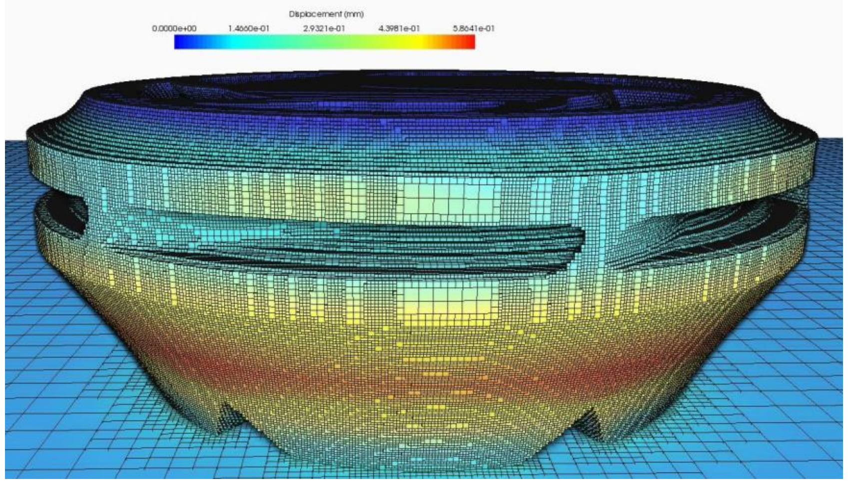


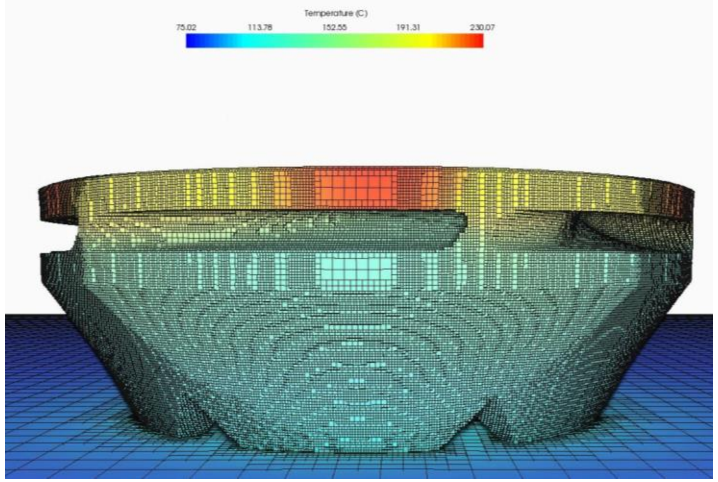




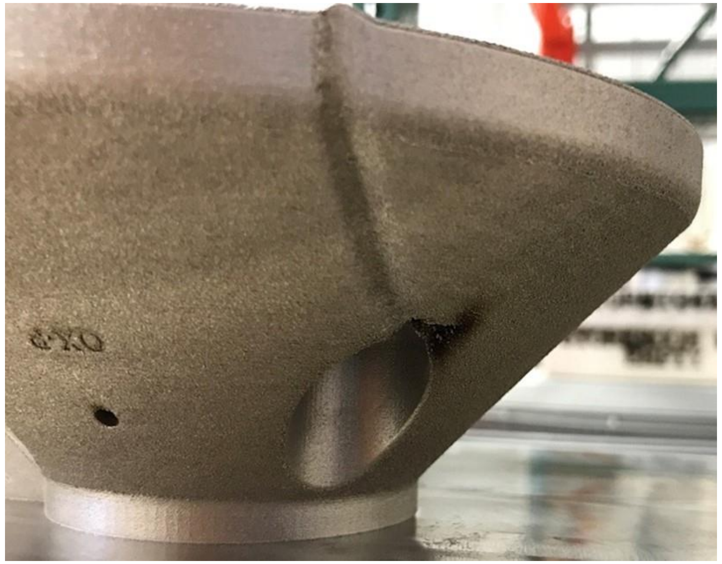
Build Simulation: Residual Stress & Distortion Failure Prediction

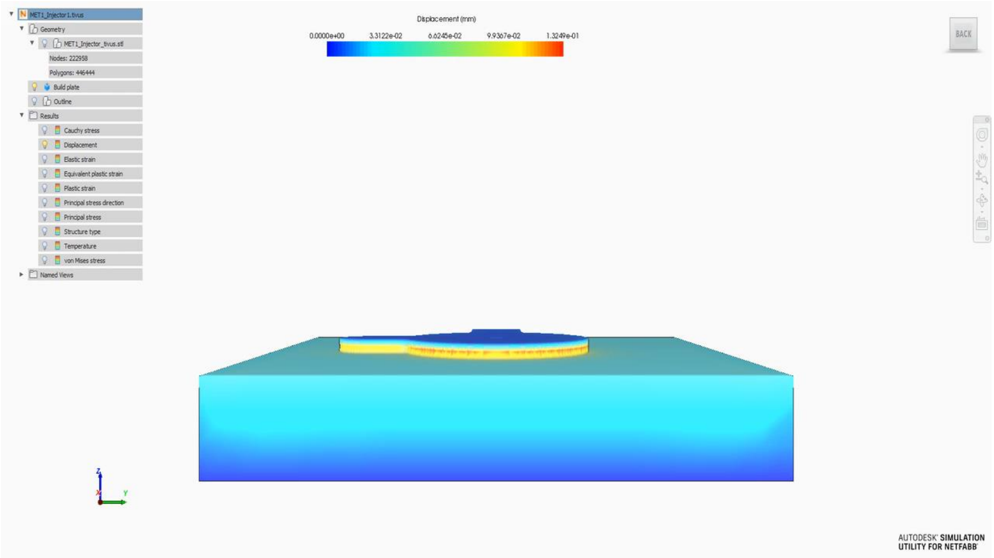






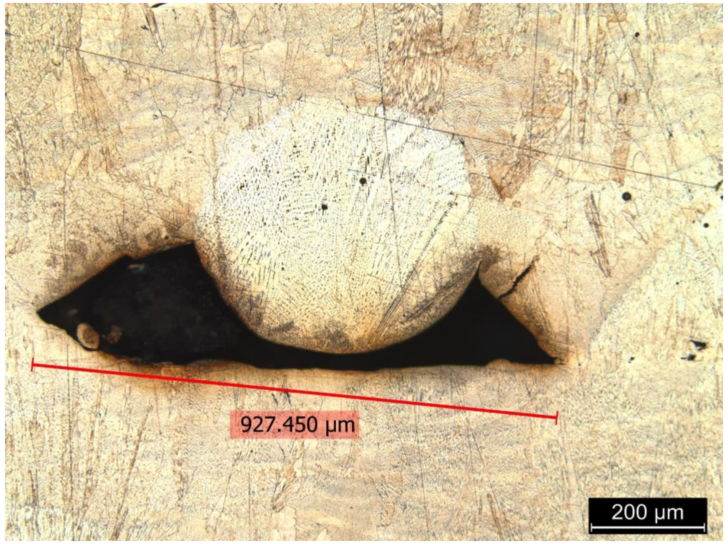
AMPd Engine LOX Impeller (Shrouded) V1 on EOS M290. Build time - $0.3k (3 hrs), Powder - $ 0.01k (0.25 kg), Saw - $0.2k, Plate resurface - $0.2k, Total - $0.71k





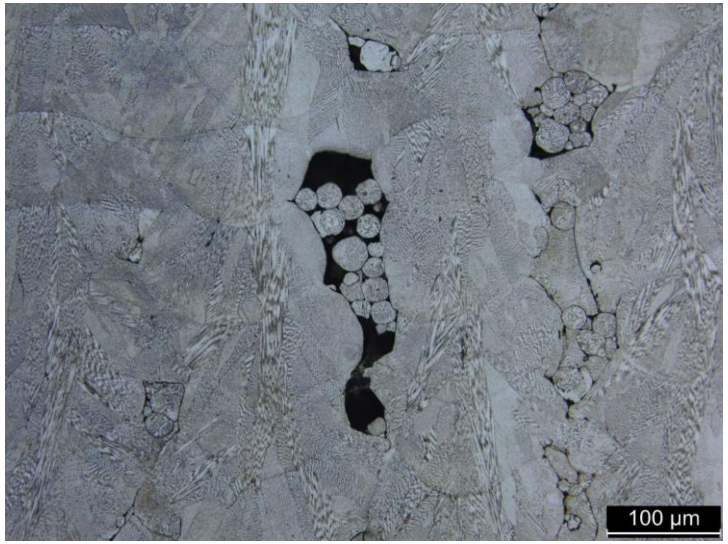
MET1 Injector V1 on EOS M290. Build time - $5.5k (55 hrs), Powder - $ 0.32k (5.82 kg), Saw - $0.2k, Plate resurface - $0.2k, Unsuccessful total - $6.22k. Successful total $6.22k. Total Cost $12.44k. 15 minute long simulation.

Build Failure Examples

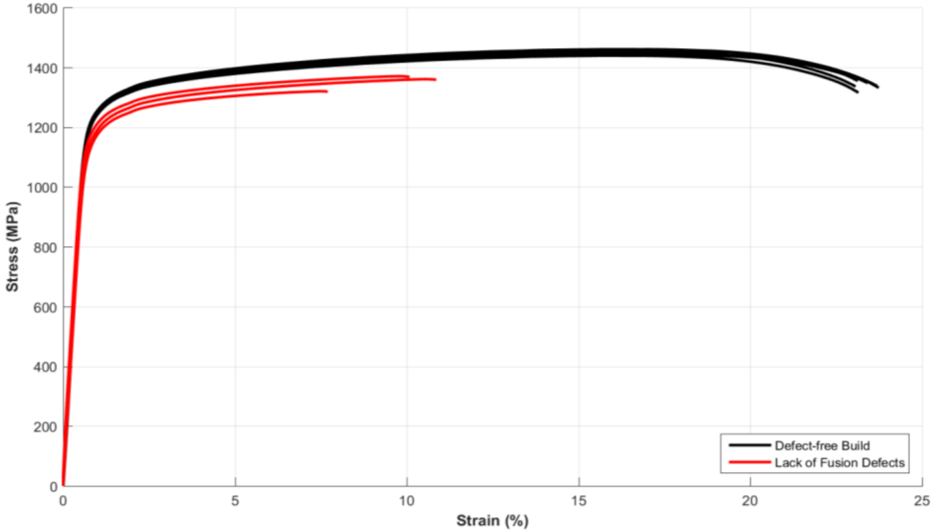


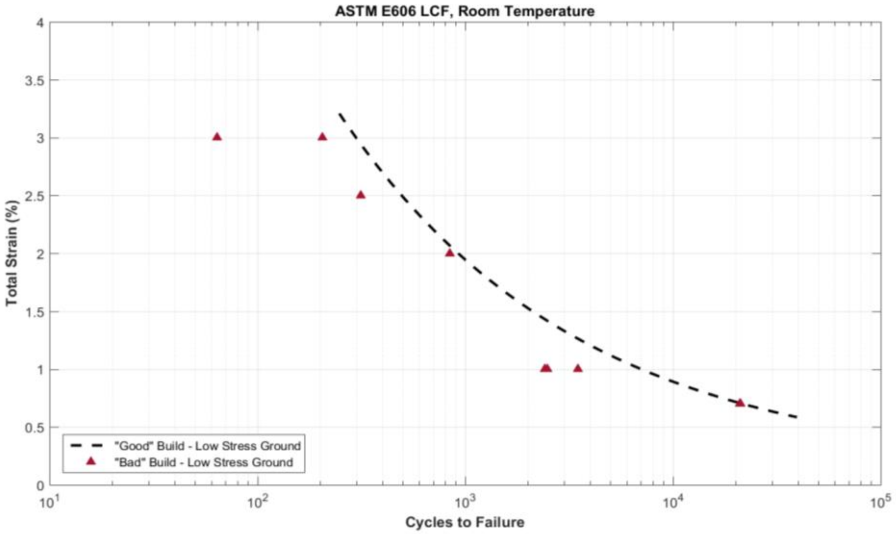
Horizontal Lack of Fusion (LOF) defect from ejecta.

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