Additive Manufacturing for Propulsion Systems

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JANNAF Liquid Propulsion Subcommittee (LPS)
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Ground rules and basic terminology

- This section is focused on metal additive manufacturing
- Examples are all aerospace-based, but process will apply broadly
- Additive manufacturing – may refer to as build, print, AM, grow, fabricate…
- Terminology:
  - AM = Additive Manufacturing
  - DED = Directed Energy Deposition
  - DfAM = Design for Additive Manufacturing
  - PBF = Powder Bed Fusion
  - LP-DED = Laser Powder DED
  - L-PBF = Laser Powder Bed Fusion
  - EB-PBF = Electron beam powder bed fusion
  - LW-DED = Laser Wire DED
  - AW-DED = Arc Wire DED
  - EB-DED = Electron Beam DED
  - AFSD = Additive friction stir deposition
  - UAM = Ultrasonic additive manufacturing

Overview of Presentation

- Introduction / Use Cases
- Metal AM Process Selection
- Overview of AM Materials & Microstructure
- Metal AM Feedstock
- AM Post-Processing
- Design for AM (DfAM)
- Certification of Metal AM

Additive Manufacturing Typical Process Flow

Process Parameters

AM Design and Pre-Processing
- Part Design
- Analysis
- Model Check
- Build Layout
- Support Generation
- Model Slicing
- Toolpath

Additive Manufacturing Process

Metal Feedstock

Post-Processing
- Powder Removal
- Heat Treatments
- Support Removal
- Build Plate Removal
- Inspections
- Final Machining
- Welding / Brazing
- Polishing
- Cleaning

Part in Service
- Assembly
- Validation / Testing
- Qualified Metallurgy
- Part Production Plan

Qualification

Proper AM process selection requires an integrated evaluation of all process lifecycle steps

Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

Opportunities for Metal Additive Manufacturing

- High complexity applications
- Rapid prototyping for design iterations (design-fail-fix-cycle)
- Low production volume applications
- Time critical applications
- Maintenance, repair, and operations (MRO)
- Part obsolescence
- Part consolidation
- Performance improvements (heat transfer, packaging, reduced mass)
- Novel alloys not feasible with traditional manufacturing
- Reduced scrap (and lower buy-to-fly ratio)
- Sustainability
- Local manufacturing

Advantages and Disadvantages

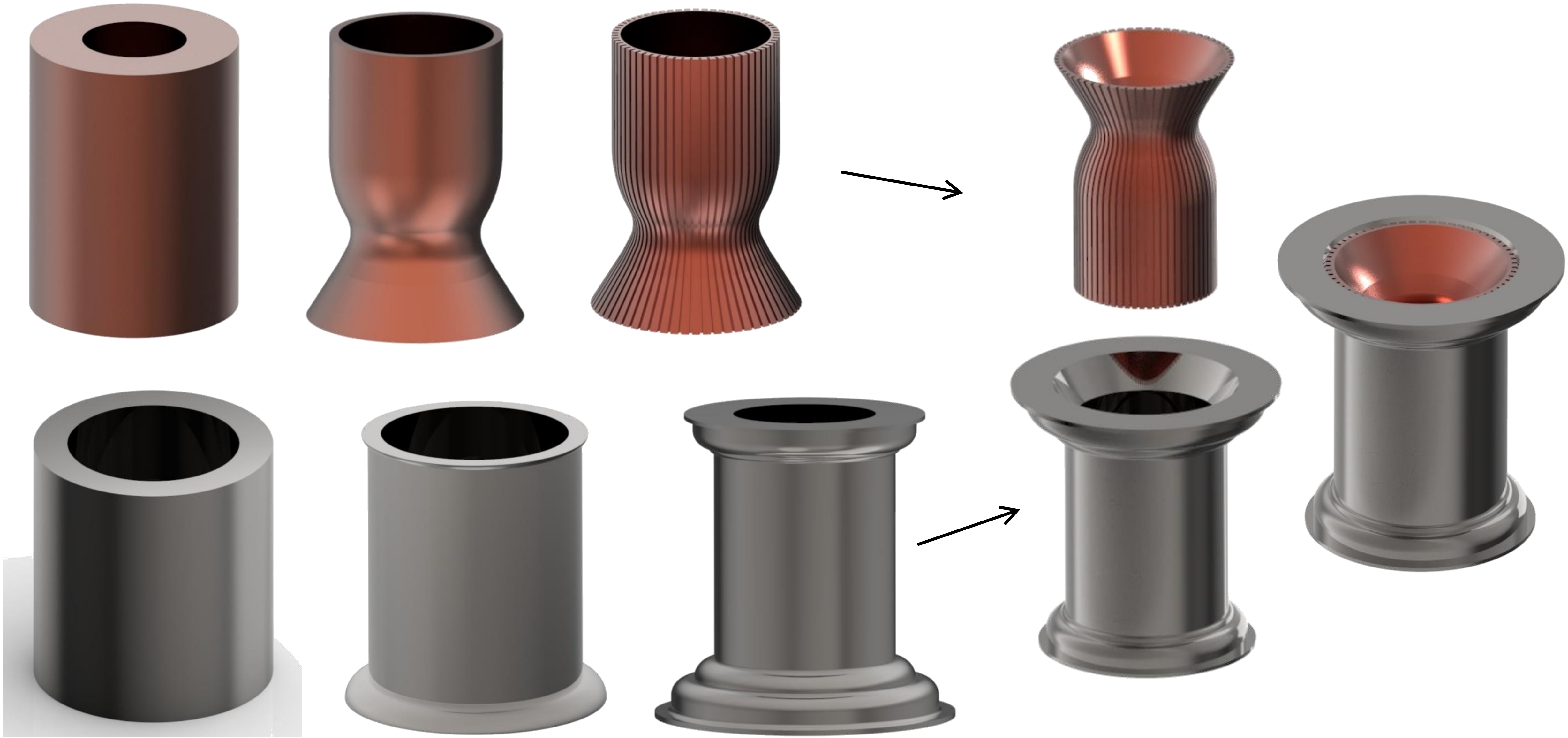
Advantages

1) No or limited tooling is required.
2) Reductions in part count or mass can be achieved through increased design freedom.
3) A broad range of metal alloys can be used.
4) Various sized and featured parts can be manufactured using different methods.
5) Overall processing time and subsequent cost are reduced.
6) Design freedom is increased, as fewer manufacturing constraints are imposed to enhance performance.
7) Production lead time is reduced.
8) New supply chains, such as critical spares, are enabled.

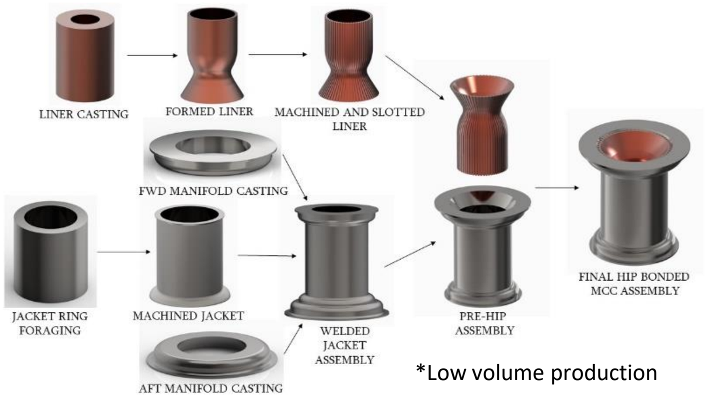
Challenges

1) Production volume and time can be limited.
2) Many metal alloys can be used, but they typically must be weldable and still require a powder or raw material supply chain.
3) Distortion and residual stresses are intrinsic to the melt and solidification process.
4) The entire AM process from design to service application must be understood and considered.
5) Variations occur across different processes.
6) Not all AM machine platforms can build the same part.
7) AM machines represent a significant capital investment and can present a barrier to entry.

Traditional Manufacturing…Forging to final assembly



A rocket combustion chamber case study for AM



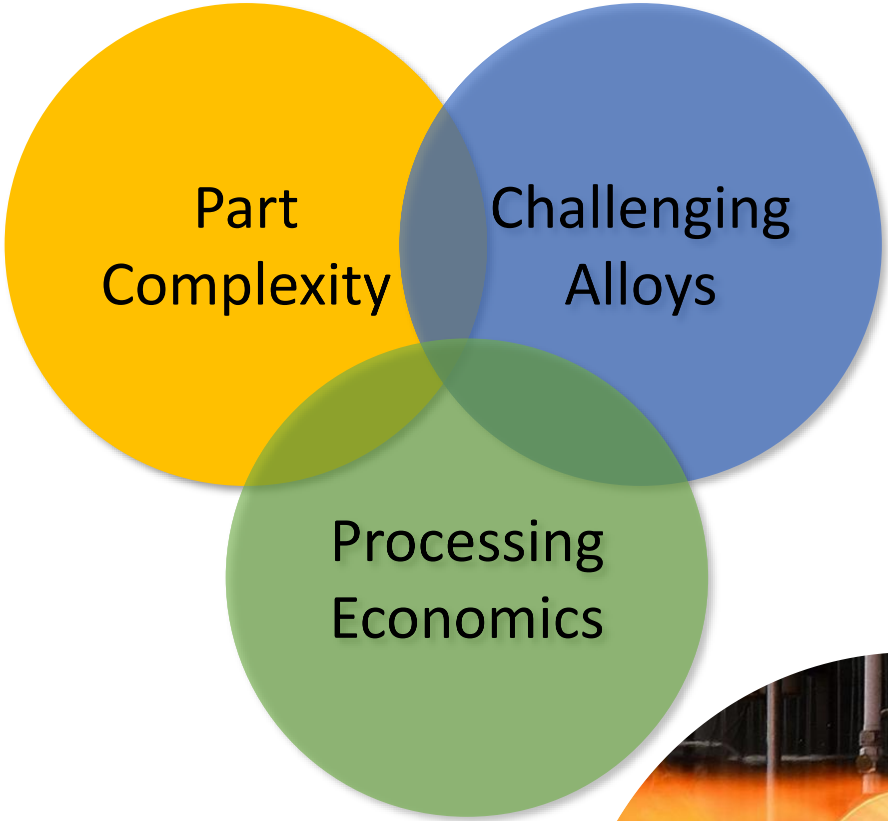
*Low volume production

Category	Traditional Manufacturing	Initial AM Development	Evolving AM Development
Design and Manufacturing Approach	Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly	Four-piece assembly using multiple AM processes; limited by AM machine size. Two-piece L-PBF GRCop-84 liner and EBW-DED Inconel 625 jacket	Three-piece assembly with AM machine size restrictions reduced and industrialized. Multi-alloy processing; one-piece L-PBF GRCop-42 liner and Inconel 625 LP-DED jacket
Schedule (Reduction)	18 months	8 months (56%)	5 months (72%)
Cost (Reduction)	$310,000	$200,000 (35%)	$125,000 (60%)

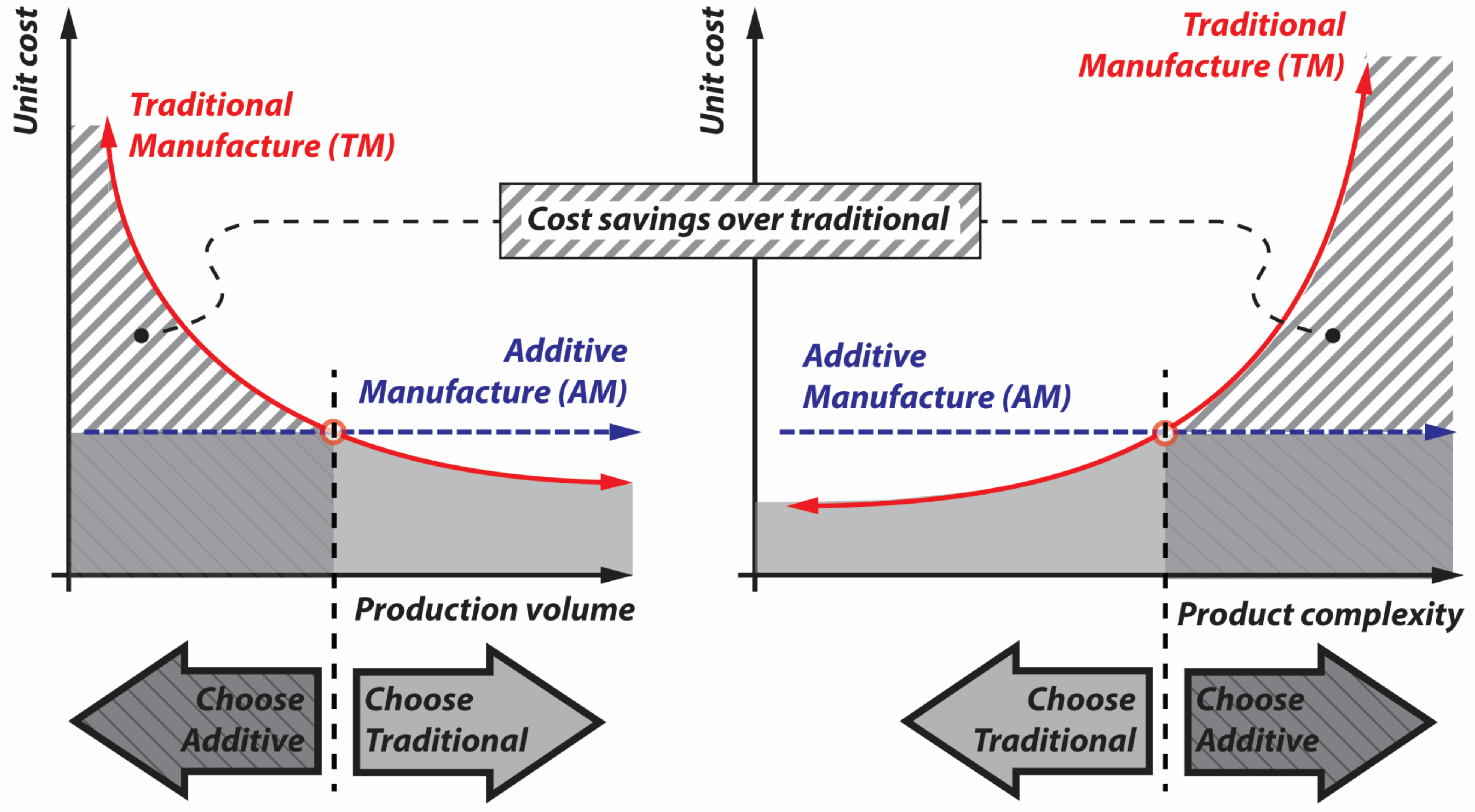
As AM process technologies evolve using multi-materials and processes, additional design and programmatic advantages are being discovered

The Case for Additive Manufacturing in Propulsion

- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities.
- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing.

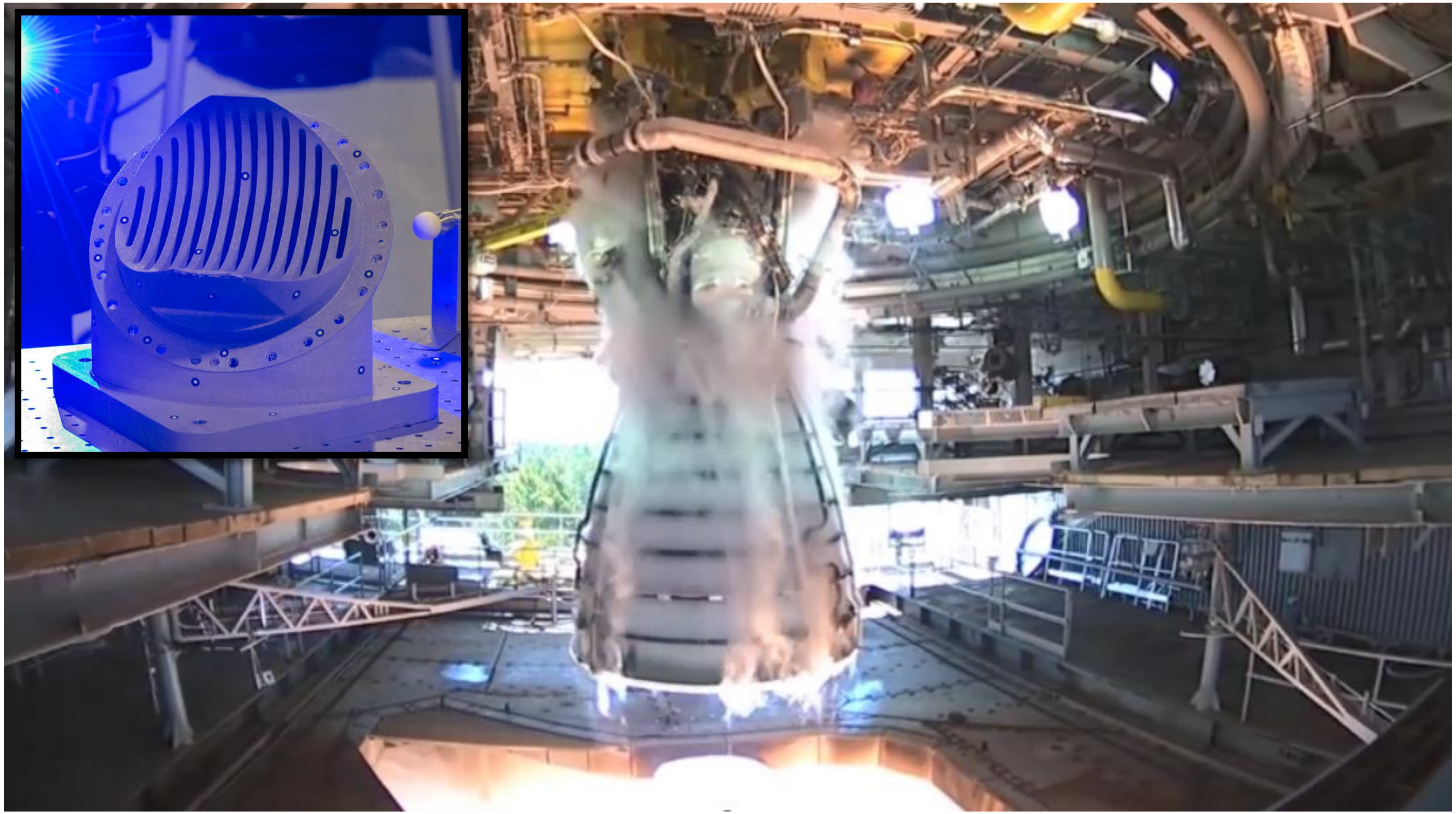


When do we use additive manufacturing?



From: Martin Leary, Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

Additive Manufacturing in use on NASA Space Launch System (SLS)



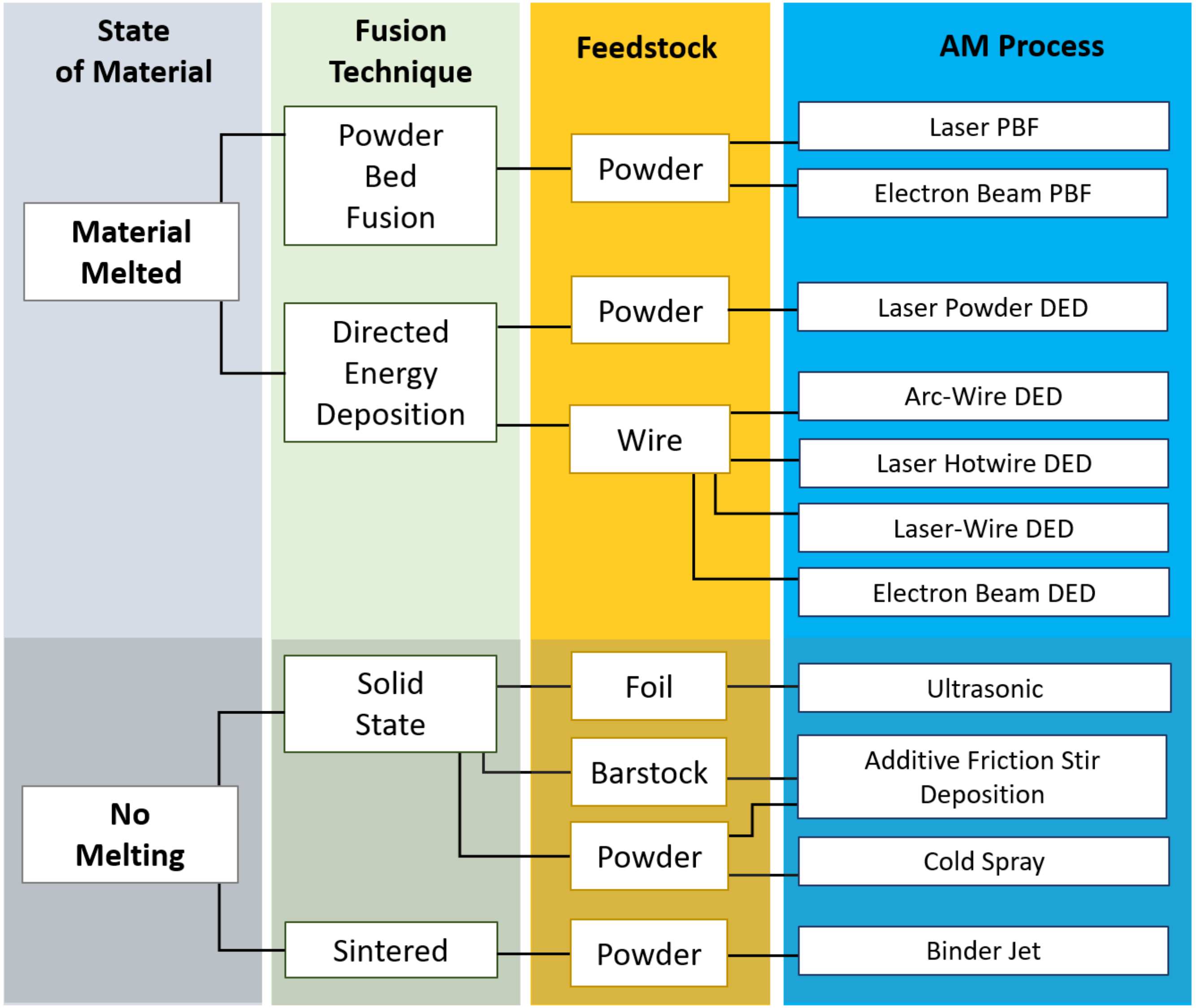
Successful hot-fire testing of full-scale additive manufacturing (AM) Part to be flown on SLS RS-25 RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from <u>127 welds to 4 welds</u>

Ref: Andy Hardin, Steve Wofford/ NASA MSFC

Additive Manufacturing in Flight and Development

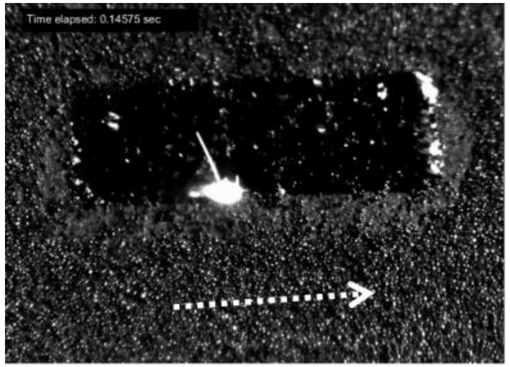
Pictures used by permission of respective owners.

Various Metal AM Processes



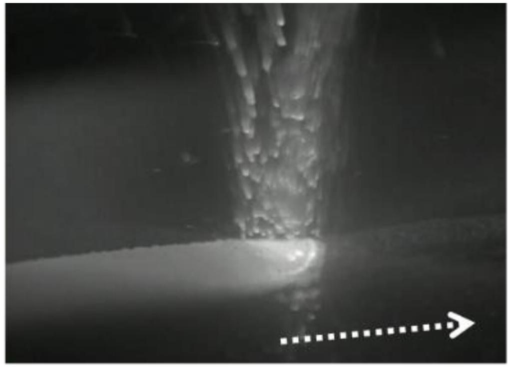
Many AM processes exists and must be traded (along with traditional techniques) to optimize

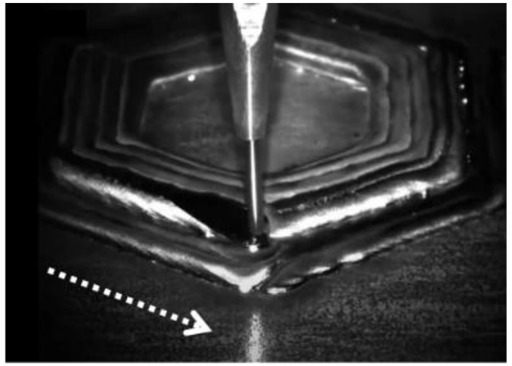
AM Processes for various applications



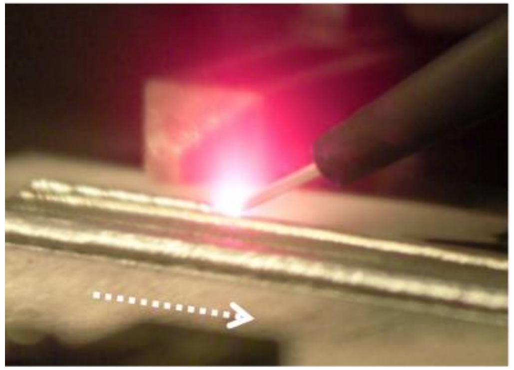
Laser Powder Bed Fusion

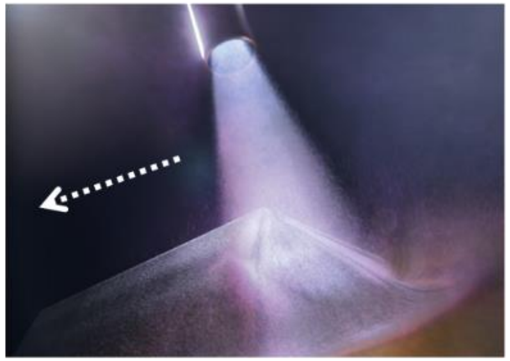

Electron Beam Powder Bed Fusion

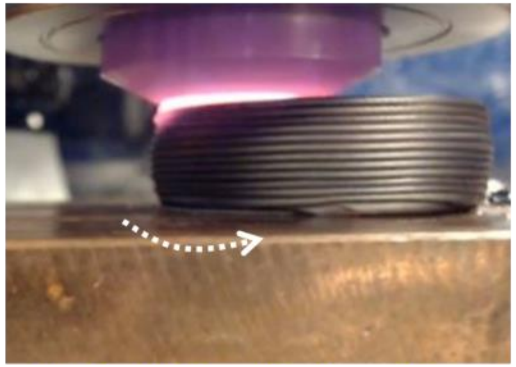

Laser Powder DED


Laser Wire DED


Arc Wire DED


Electron Beam Wire DED


Cold Spray

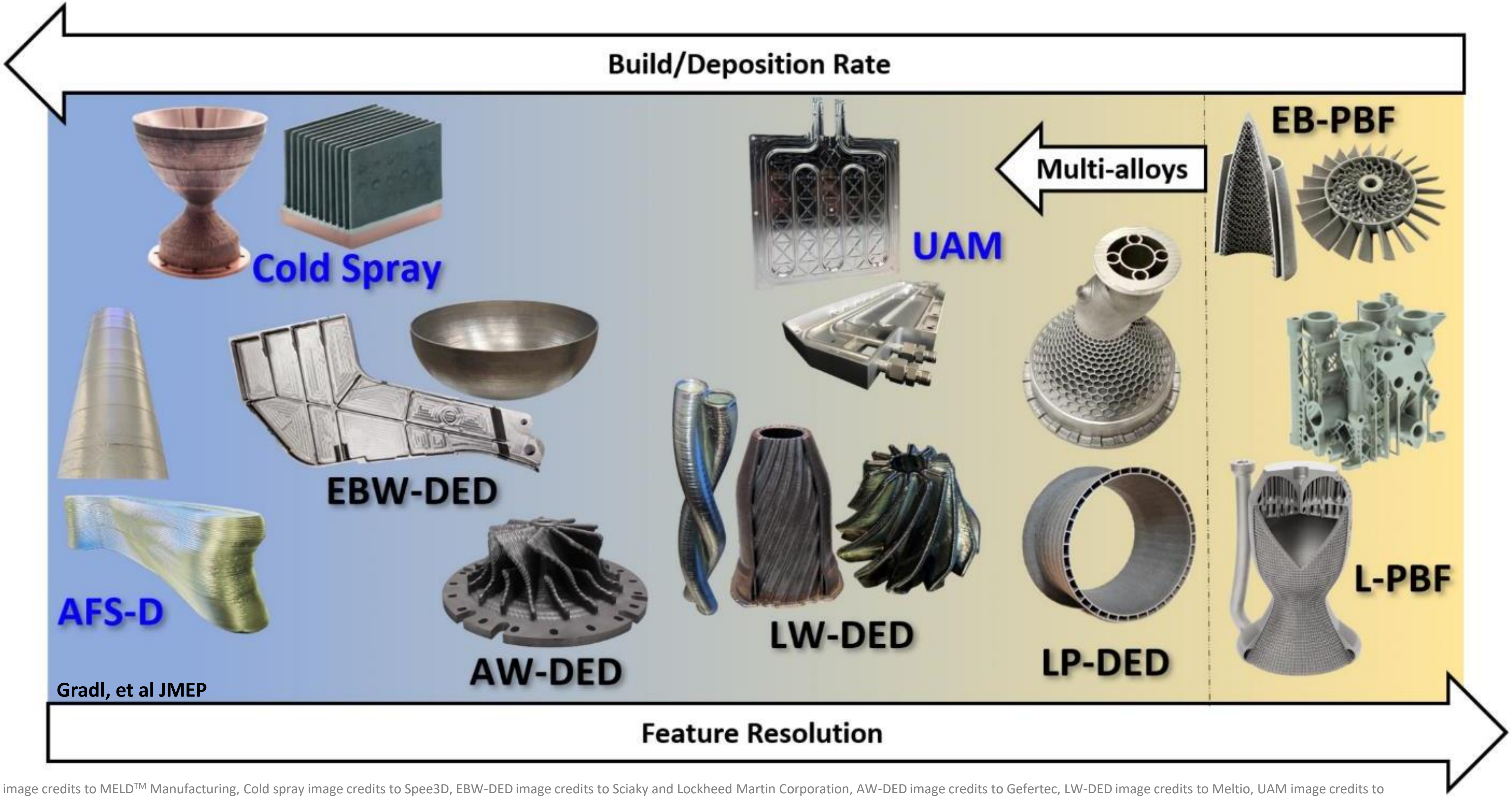

Additive Friction Stir Deposition


Ultrasonic Additive Manufacturing

A) Laser Powder Bed Fusion [https://doi.org/10.1016/j.actamat.2017.09.051], B) Electron Beam Powder Bed Fusion *[Credit: Courtesy of Freemelt AB, Sweden],* C) Laser Powder DED *[Credit: Formalloy],* D) Laser Wire DED *[Credit: Ramlab and Cavitar],* E) Arc Wire DED *[Credit: Institut Maupertuis and Cavitar],* F) Electron Beam DED *[NASA],* G) Cold spray *[Credit: LLNL],* H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM *[Credit: Fabrisonic].*

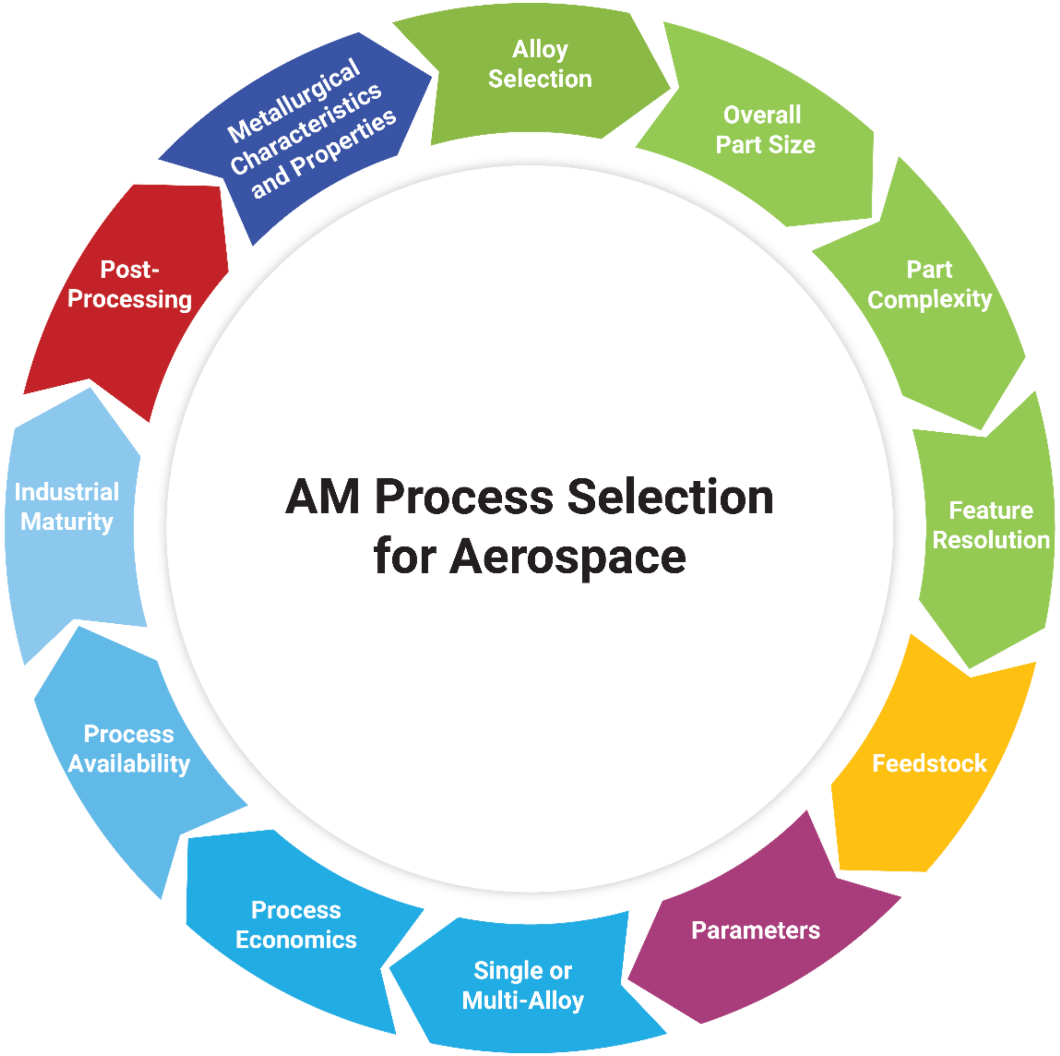
Reference: Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

Criteria and Comparison Various Metal AM Processes



CREDITS: AFS-D image credits to MELD™ Manufacturing, Cold spray image credits to Spee3D, EBW-DED image credits to Sciaky and Lockheed Martin Corporation, AW-DED image credits to Gefertec, LW-DED image credits to Meltio, UAM image credits to Fabrisonic and NASA JPL, LP-DED image credits to DEPOZ project led by IRT Saint-Exupery and Formalloy, L-PBF image credits to Renishaw plc and CellCore GmbH/Sol Solutions Group AG, EB-PBF image credits to Wayland and GE Additive/Arcam.

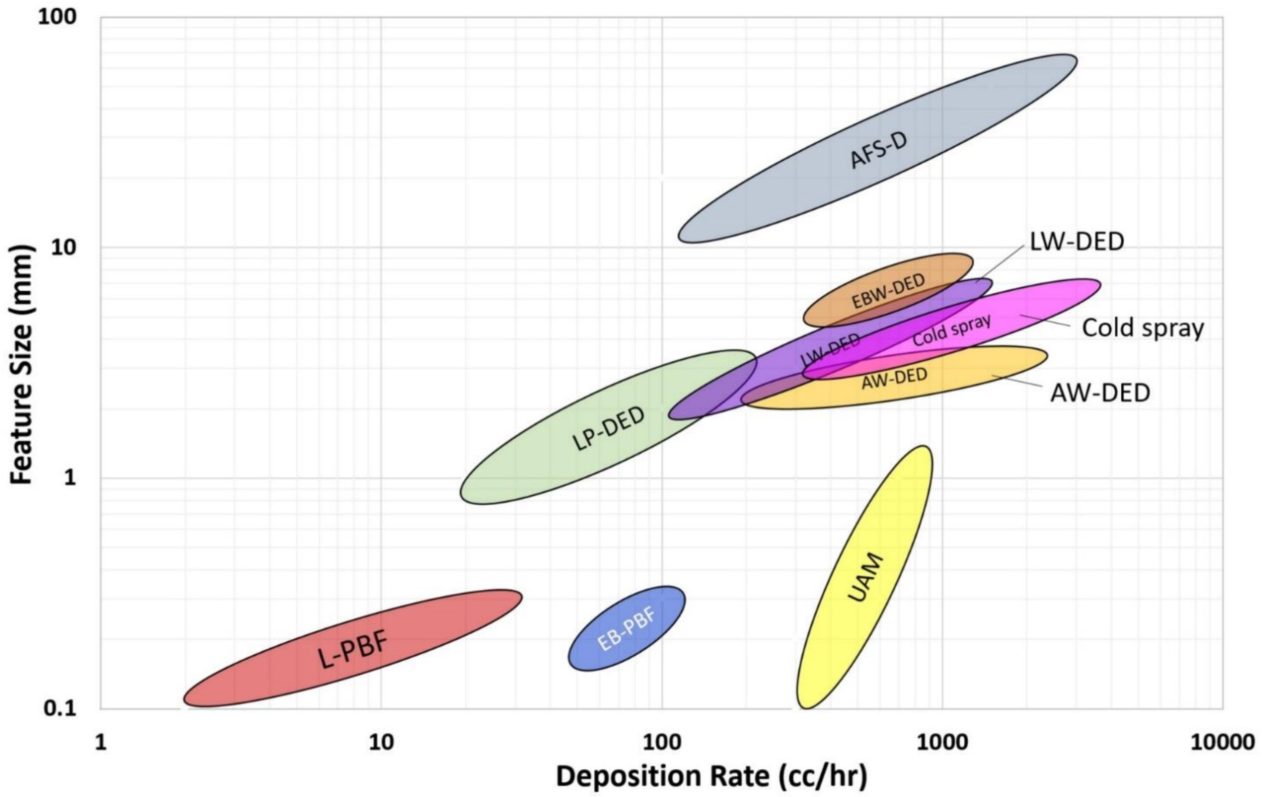
Methodical AM Process Selection

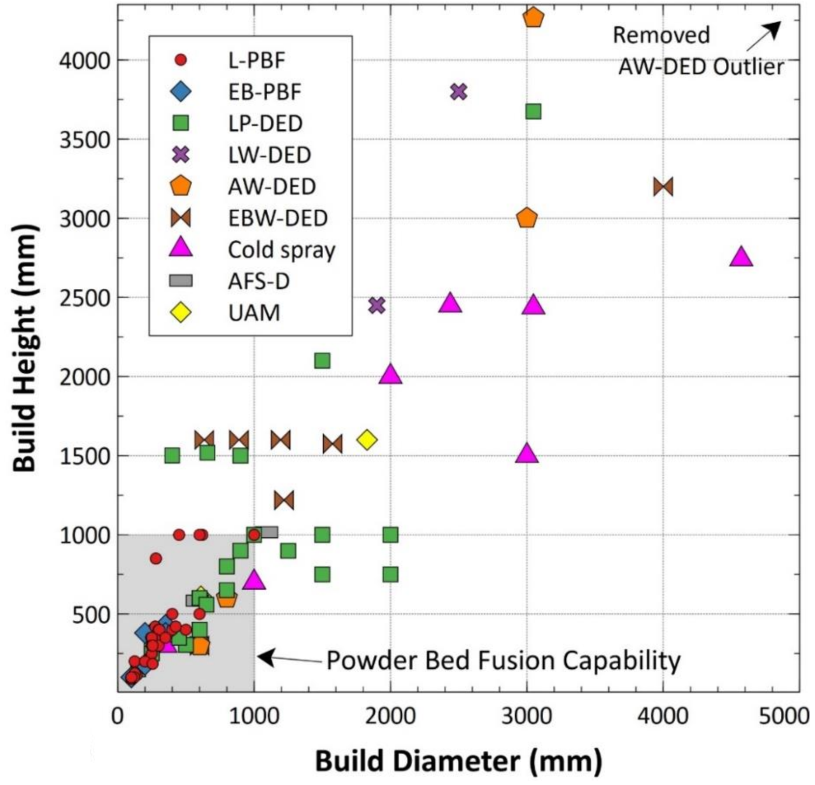


- What is the **alloy** required for the application?
- What is the **overall part size**?
- What is the **feature resolution** and internal **complexities**?
- Is it a **single alloy or multiple**?
- What are **programmatic requirements** such as cost, schedule, risk tolerance?
- What are the end-use environments and **properties required**?
- What is the **qualification/certification** path for the application/process?

Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

Various criteria for selecting AM techniques





Complexity of Features | Scale of Hardware | Material Physics | Cost | Material Efficiency

Speed of Process | Material Properties | Internal Geometry | Availability | Post Processing

References:

- Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0
- Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, 2022. Metal Additive Manufacturing for Propulsion Applications, 1st ed, Metal Additive Manufacturing for Propulsion Applications. American Institute of Aeronautics and Astronautics, Inc., Reston, VA. https://doi.org/10.2514/4.106279

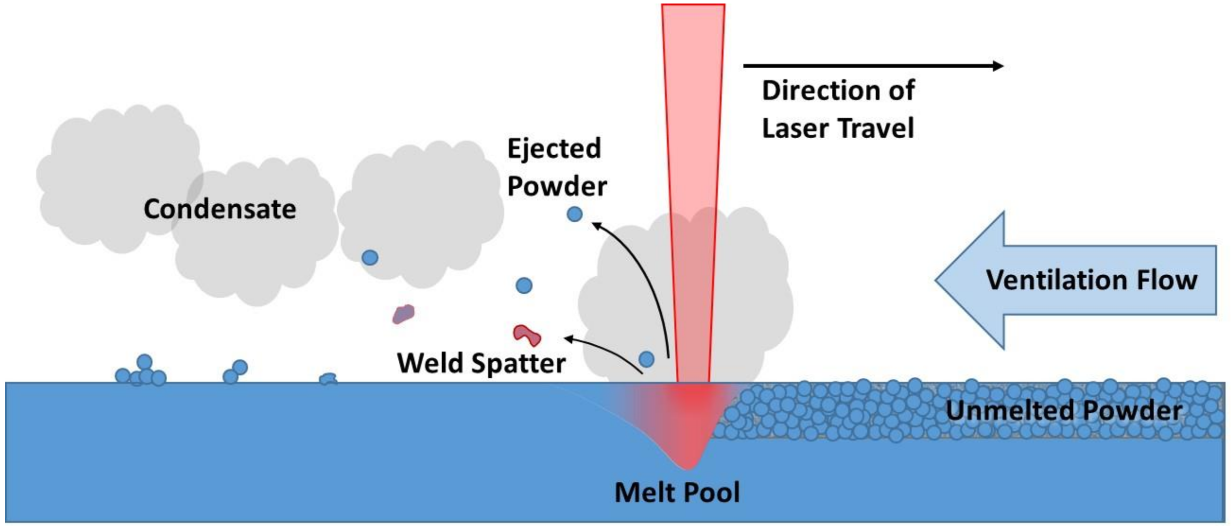
Complexity of Features vs Process

- Complexity of Internal and External Features
  - High Complexity
    - L-PBF
    - E-PBF
    - Binder Jet
  - Medium Complexity
    - Laser Powder DED
    - Ultrasonic AM
    - Laser Wire DED
  - Low Complexity
    - Arc Wire DED
    - Cold Spray
    - Electron Beam DED
    - Friction Stir AM
    - Laser Hot Wire DED

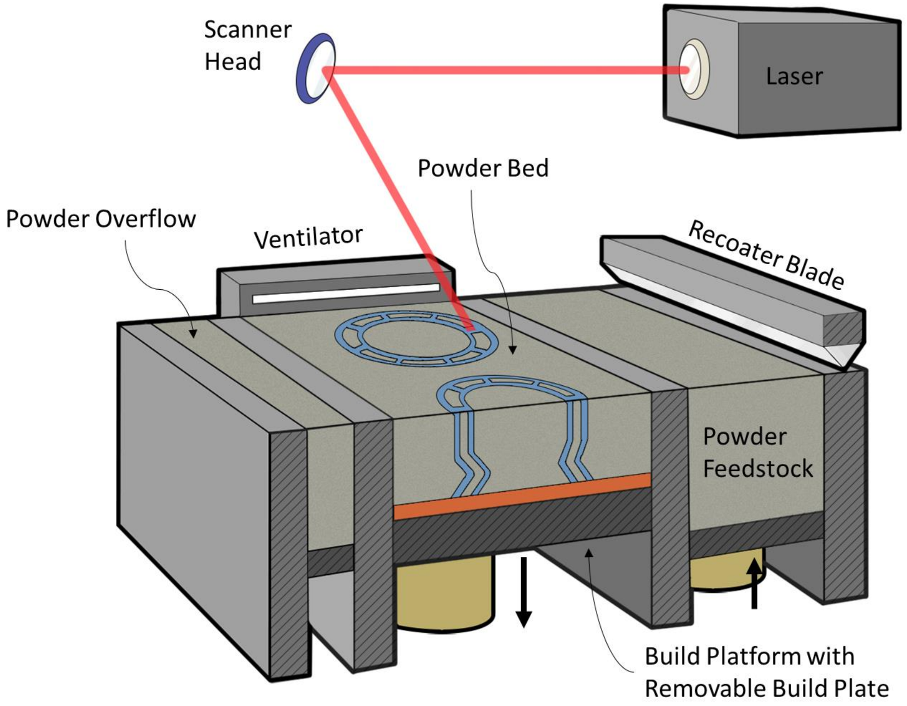
Maturity of Metal AM for NASA Applications

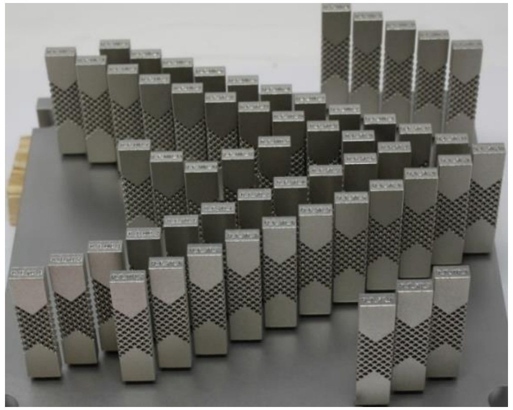
Laser Powder Bed Fusion (L-PBF)

- **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 and external geometric features, the most common and mature AM platform type in service.
  - Disadvantages: Scale limited to machine build envelope, relatively low deposition rate, generally limited to weldable metals and alloys.



L-PBF AM process diagram





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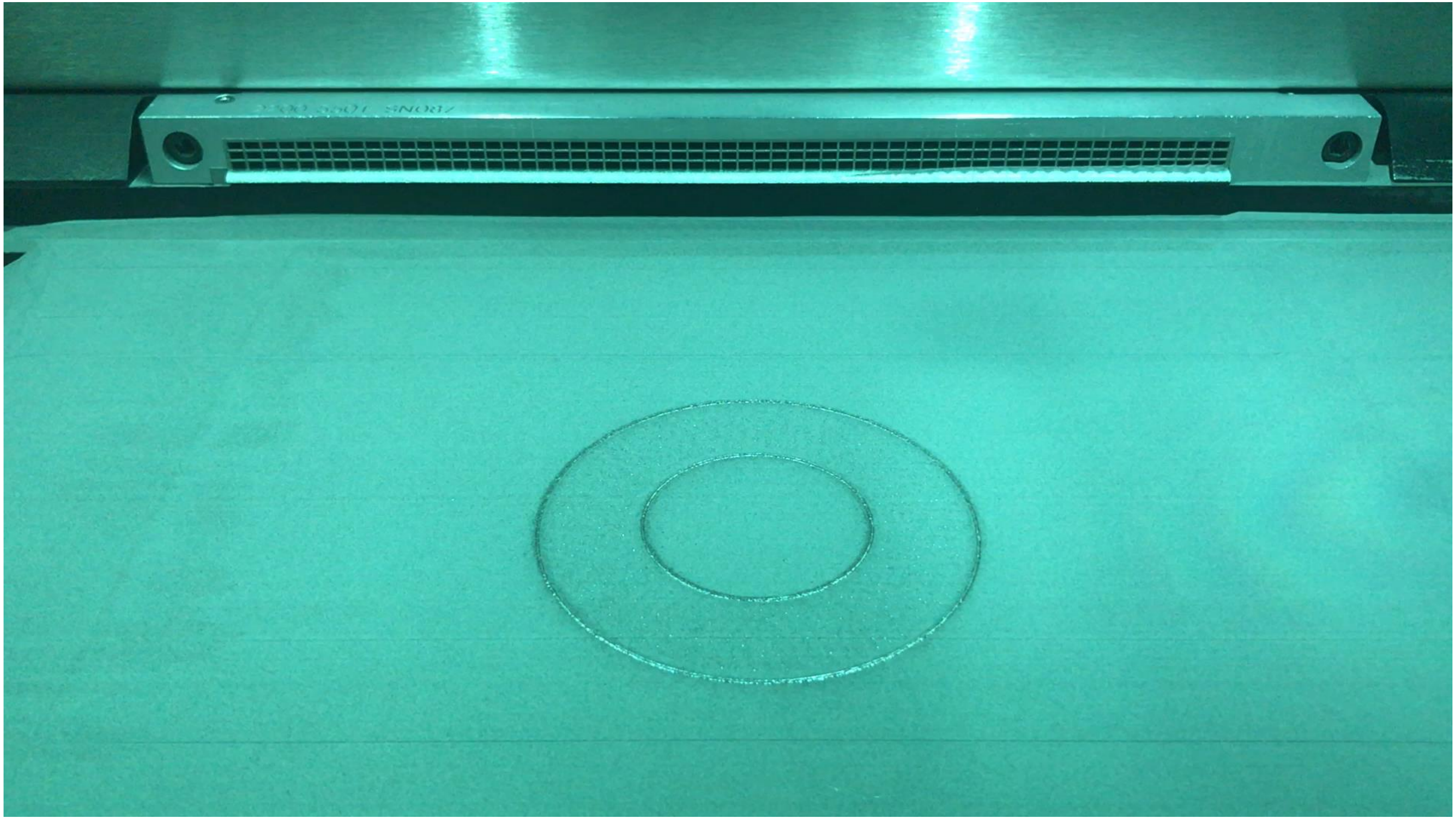
Laser Powder Bed Fusion (L-PBF)

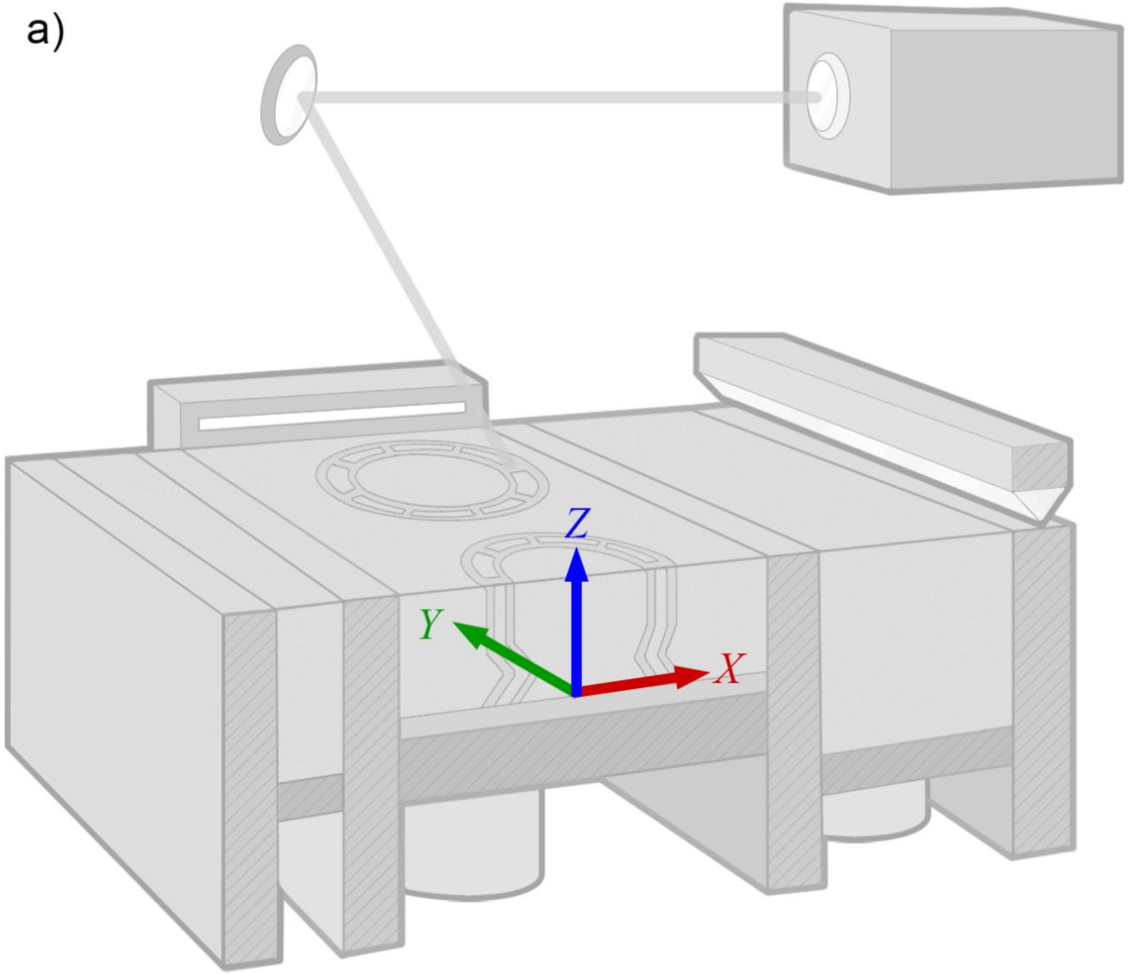


PBF Coordinate System

Machine Coordinate System

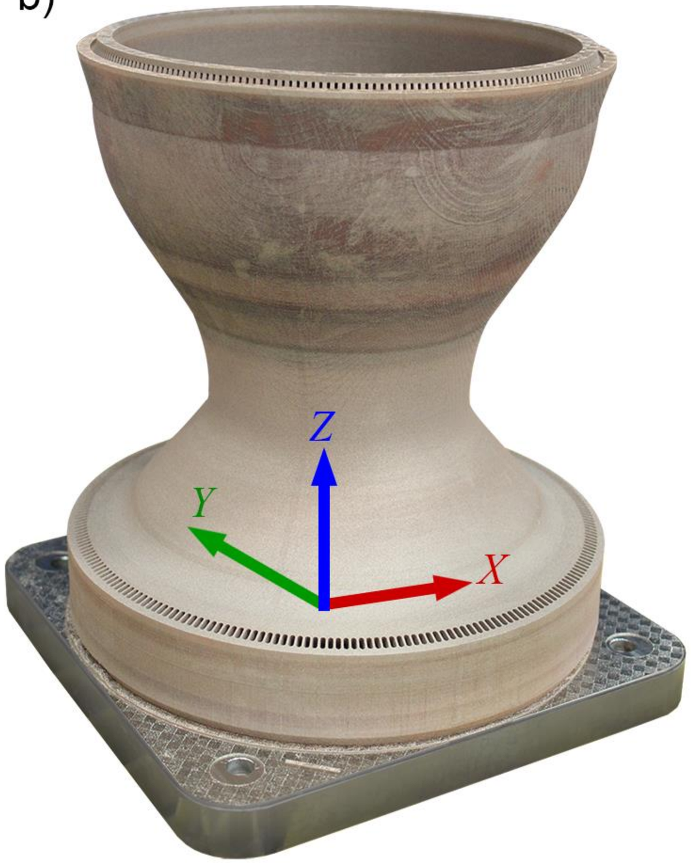
Z is always direction of build

a)



Coordinate system translates directly to part

b)



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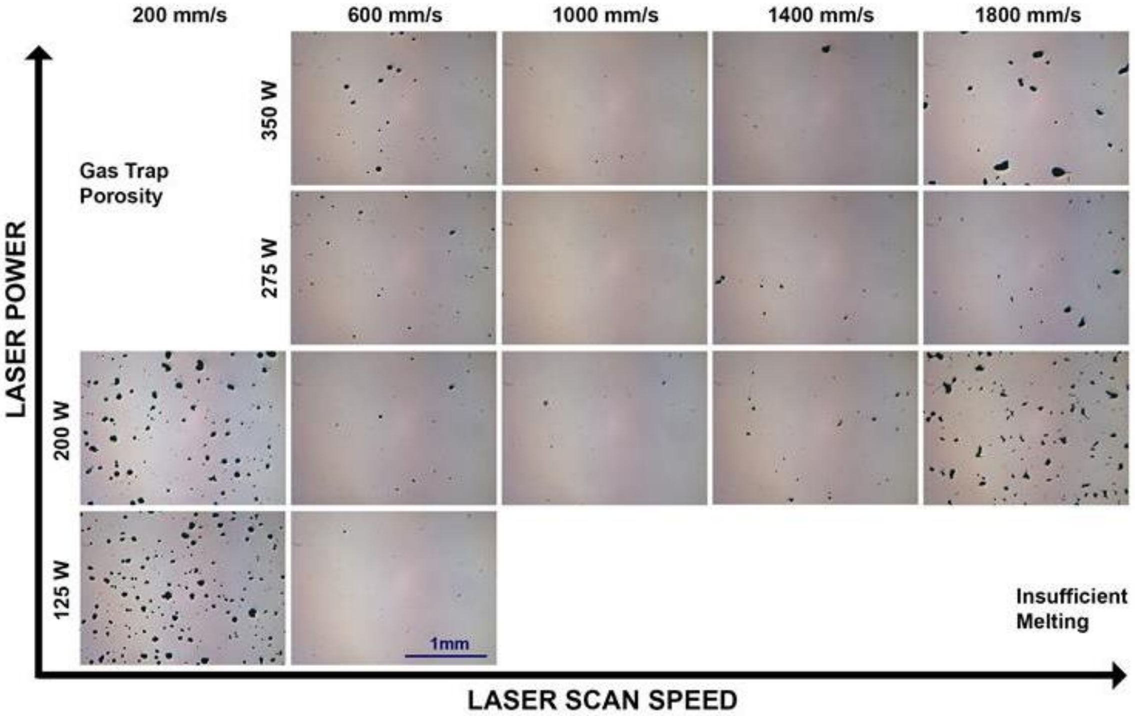
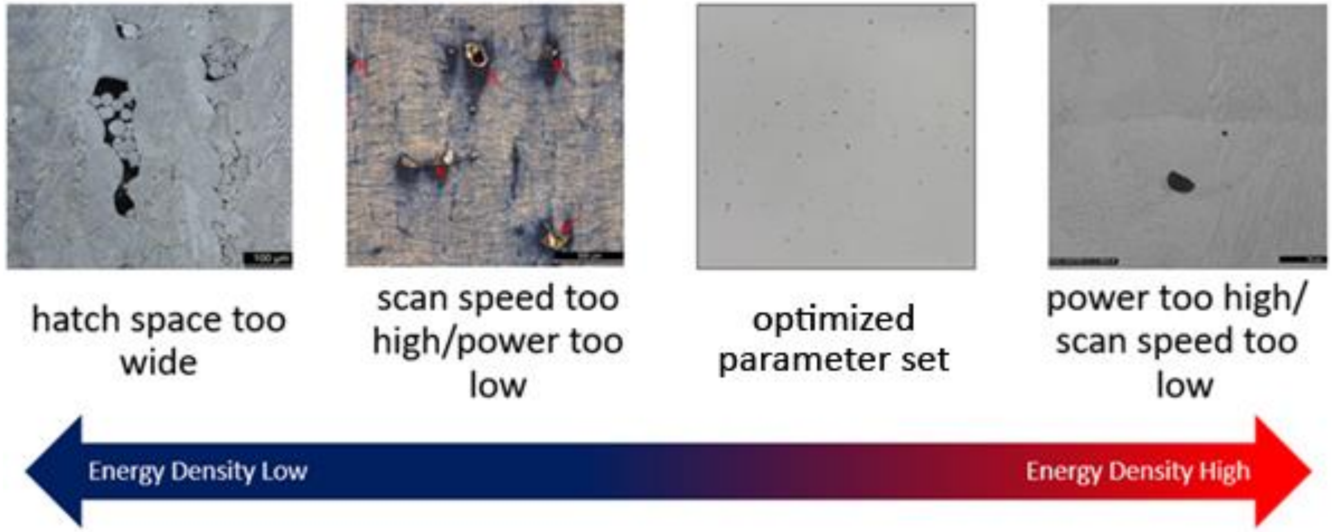
Parameter Development

- **Laser Related**
  - Laser Power
  - Spot Size
  - Scan Speed
- **Volume Related**
  - Hatch Spacing
  - Powder Thickness
- **Other**
  - Ventilation Flow Rate
  - Scan Strategy

$$E_v = \frac{P}{VDt}$$

E_v = Volumetric Energy Density (J/mm^3)
P = Power (W)
V = Velocity (mm/s)
D = Hatch Distance (mm)
t = Layer Thickness (mm)





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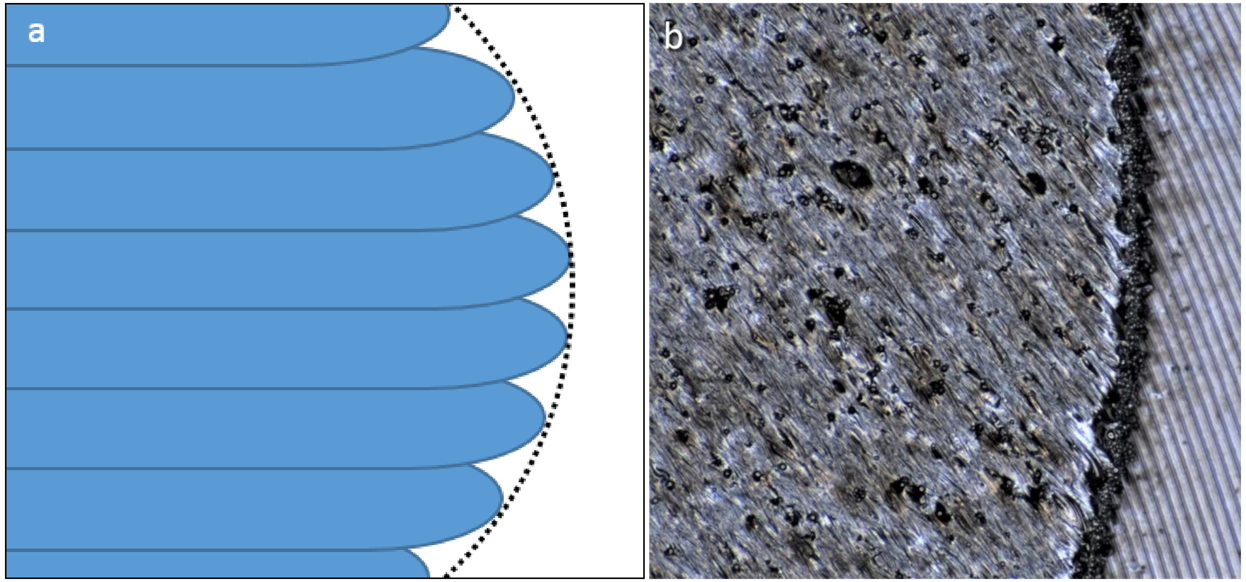
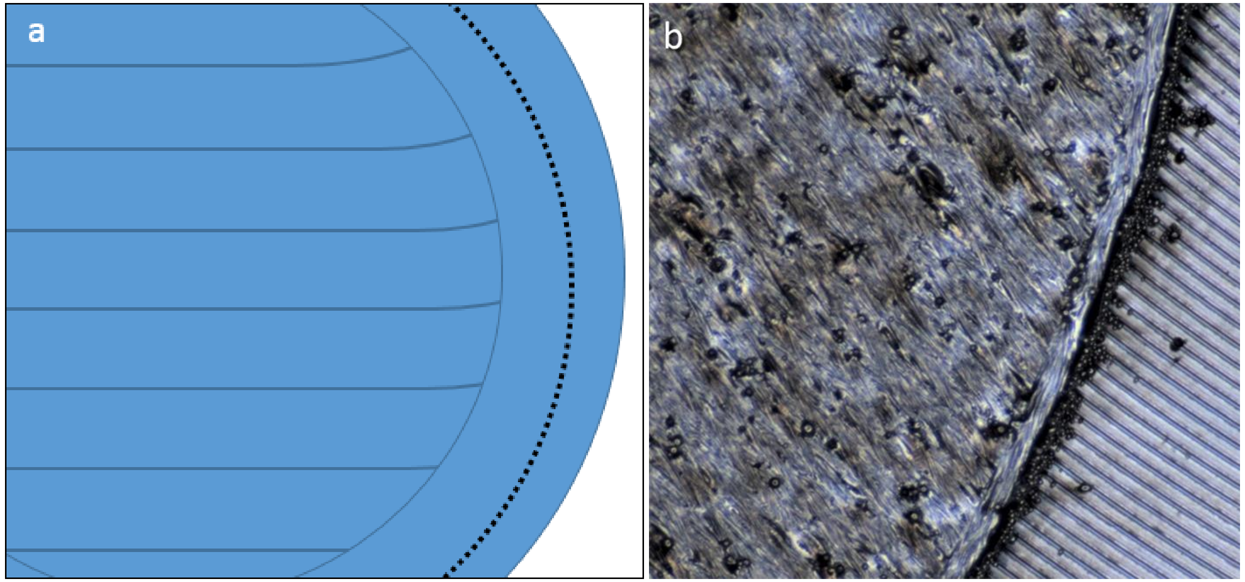
L-PBF Contours



Deposition layers without contours.



Deposition layers with contours.

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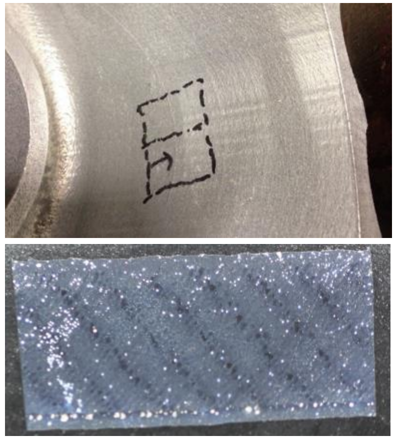
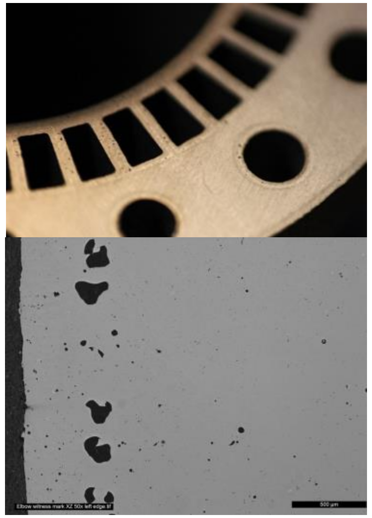
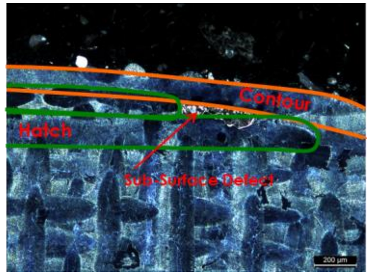
L-PBF Failure Modes

Build Artifacts

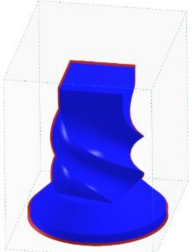

Witness marks on the surface and interior


Edge and internal Porosity


Restart line observed post-build

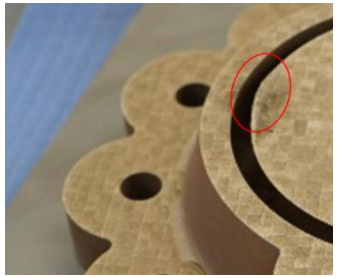


Edge Porosity from excessive beam offset.


Cooling shrinkage

Catastrophic Build Failures

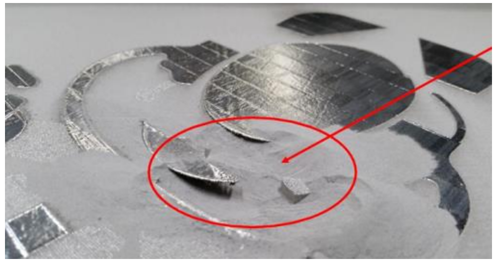

Short feed where insufficient/non-uniform powder distribution occurs. Over time the powder layer will be excessively thick when corrected and the laser melt pool will not be sufficiently deep to bond the thick layer to substrate underneath. The re-coater blade is eventually damaged by curling.

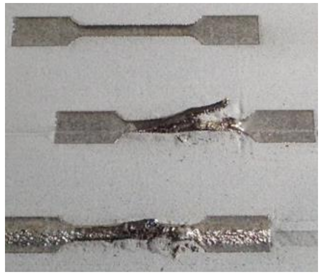

Material curl on knife edge

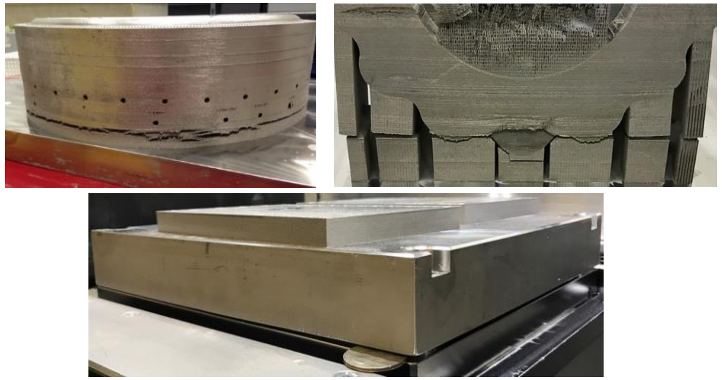

Damaged re-coater blade


Stray vectors


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.



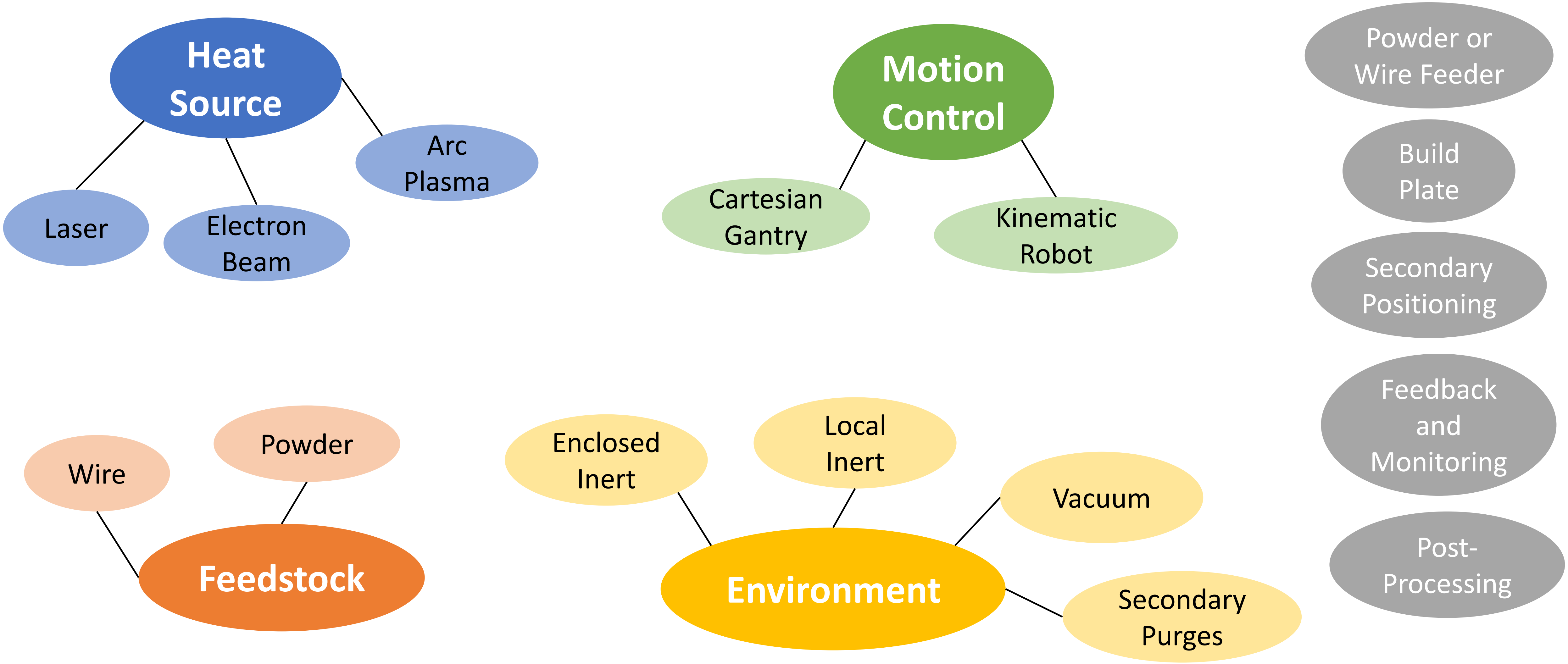



Deformation and Cracking from Residual Stresses during build

Why DED?

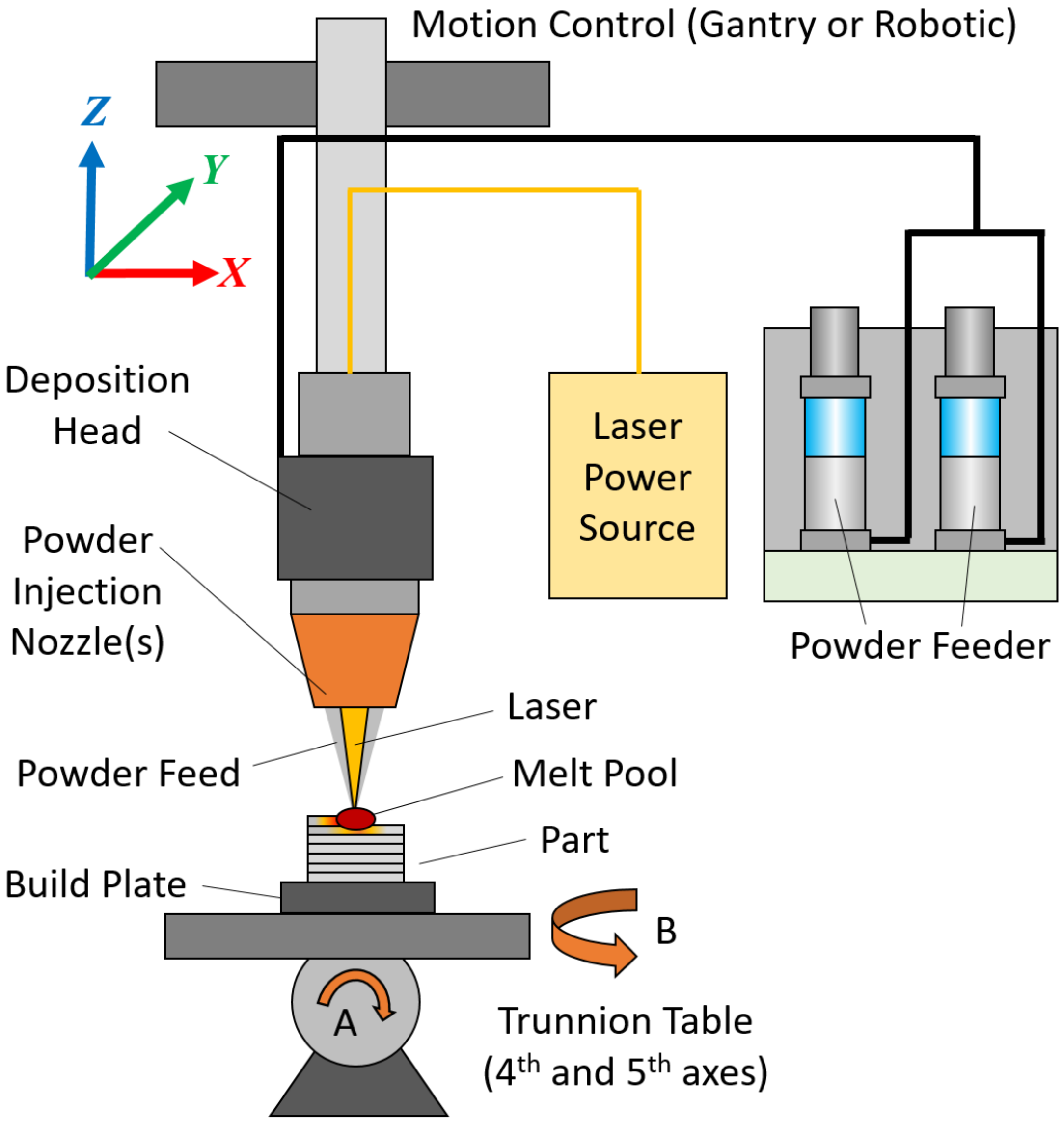
- Each Metal AM process provides advantages and disadvantages
  - Often complementary to each other
- DED offers advantages for various applications
  - Large Scale
  - Multi-axis
  - Use wire or powder feedstock
  - Ability to use multiple materials in same build
  - Ability to add material in a secondary operation
  - High deposition rates
  - Integration of secondary processes (machining)
  - Process feedback and closed loop control
- Disadvantages
  - Residual stresses (more heat input)
  - Lower resolution (less detailed complexity)
  - Higher surface texture (depending on process)

Aspects of AM DED Systems



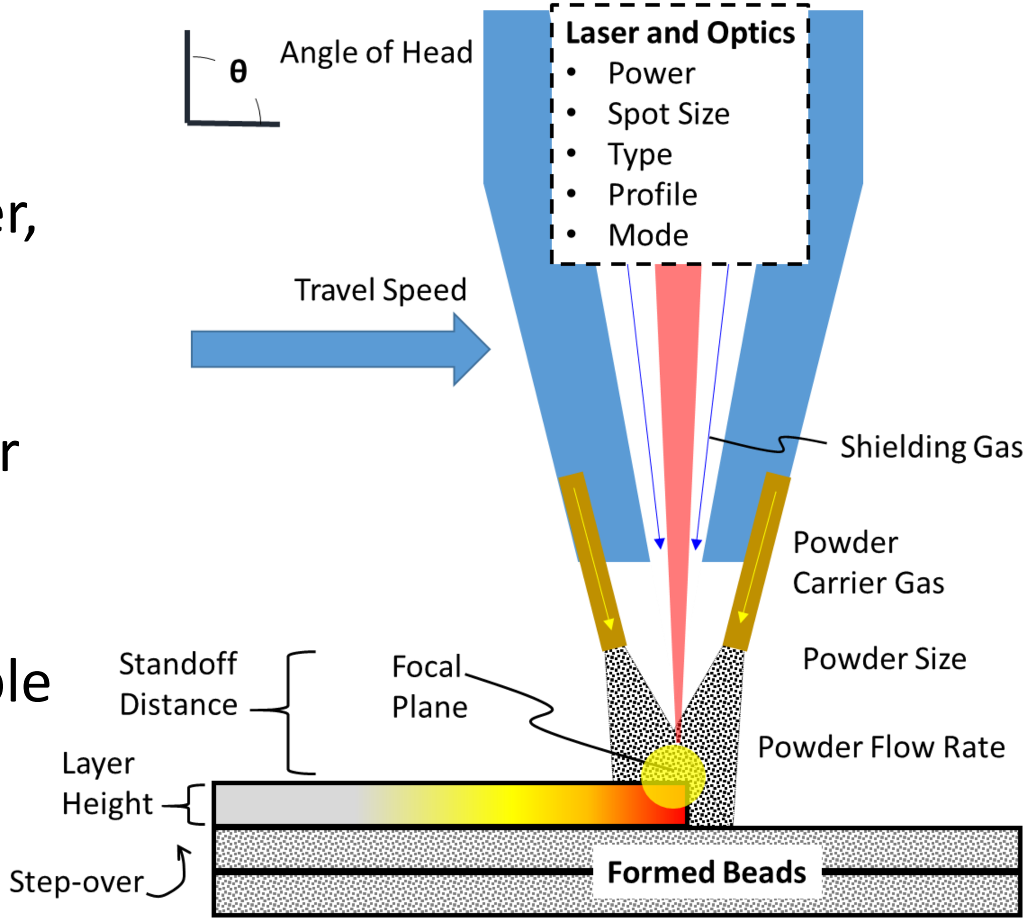
LP-DED Process Overview

- LP-DED system includes laser power source, powder feeder, and deposition head
- Attached to gantry or robotic motion control system
- Deposition head incorporates powder feed nozzle and optical path to focus laser beam and powder.
- A melt pool is created with the laser and powder blown into the melt pool depositing a bead.

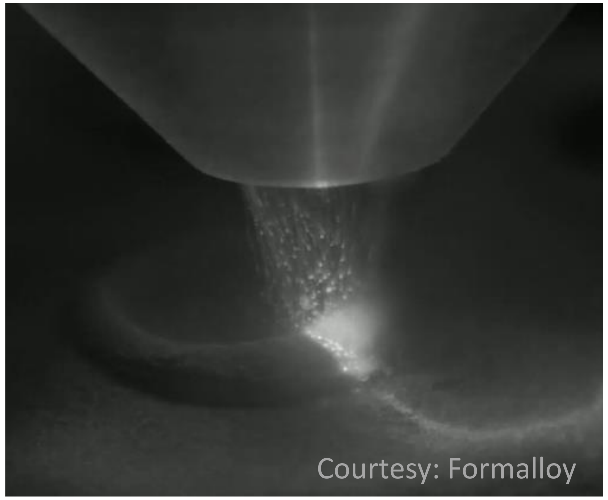


LP-DED Process Overview

- Powder and laser beam path (sometimes optics) integrated into deposition head
- Basic parameters include power, powder feedrate, travel speed, layer height
- Additional geometry control for layer height, step over (hatching), standoff distance, angle of head and trunnion table
- Can vary spot size

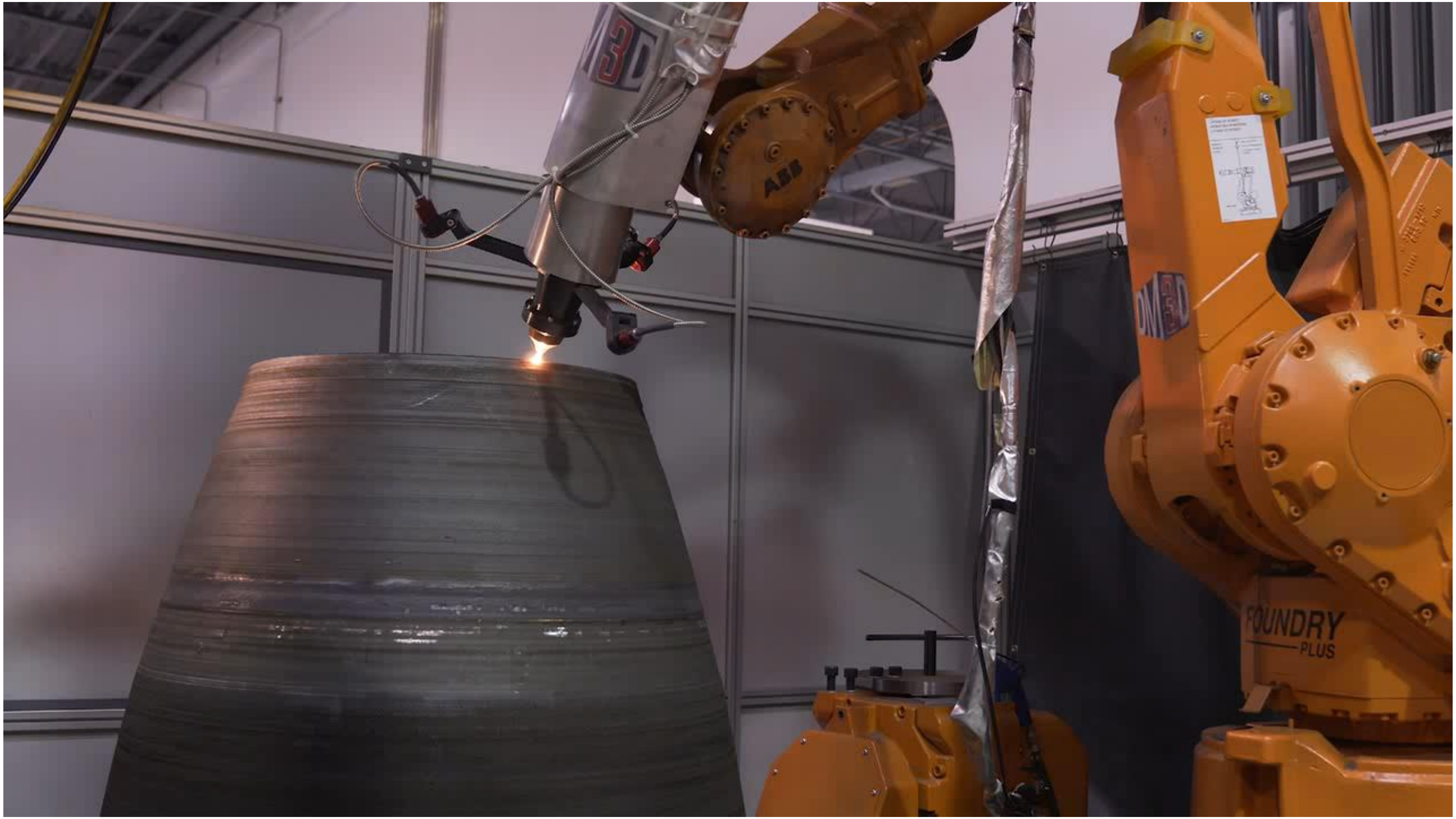


AIAA: Metal Additive Manufacturing for Propulsion Systems, Gradl et al (unreleased)

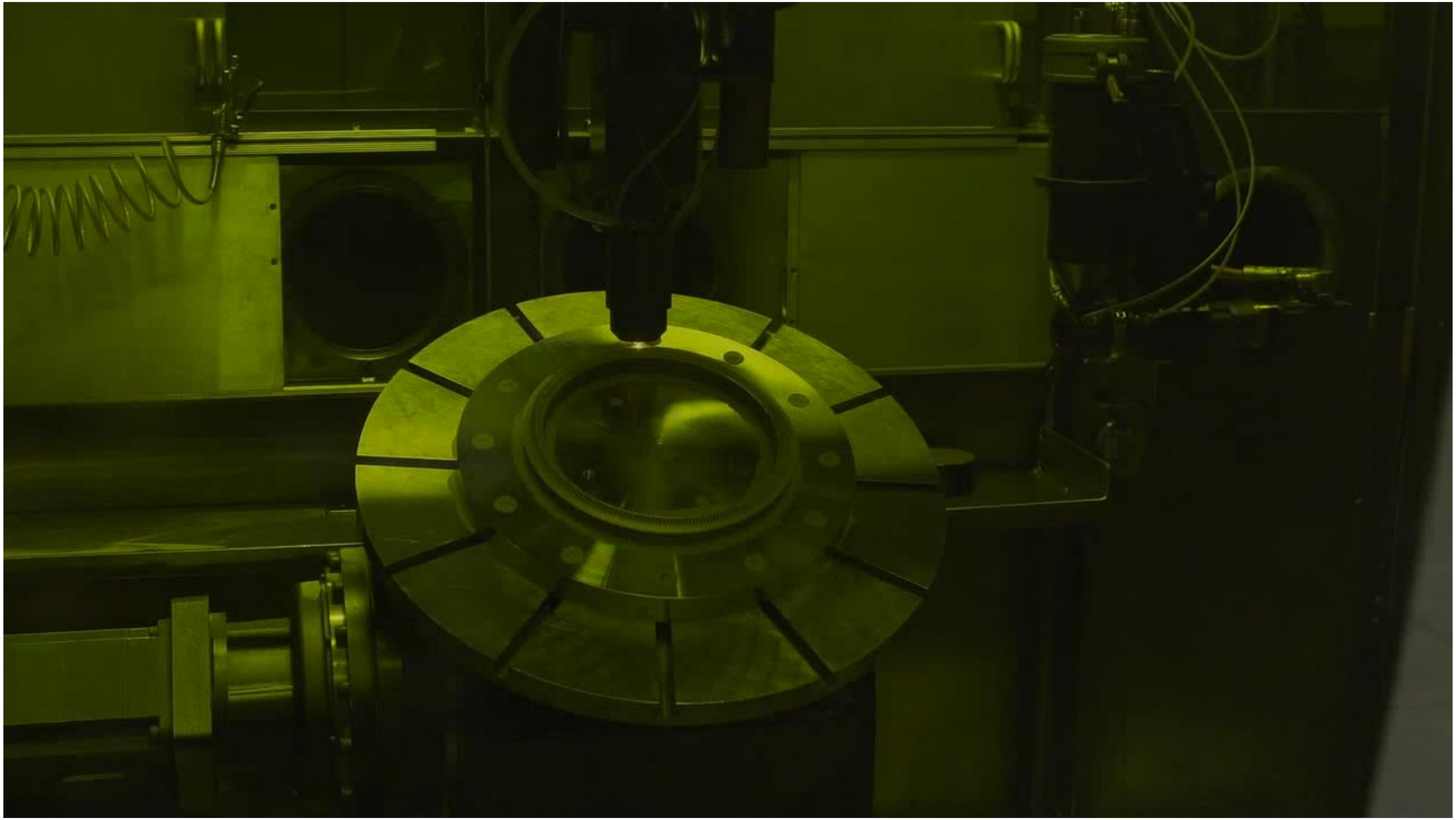


- Gradl, P. R., & Protz, C. S. (2020). Technology advancements for channel wall nozzle manufacturing in liquid rocket engines. *Acta Astronautica*. https://doi.org/10.1016/j.actaastro.2020.04.067
- AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl, Mireles, Protz, Garcia

Laser Powder Directed Energy Deposition (DED)

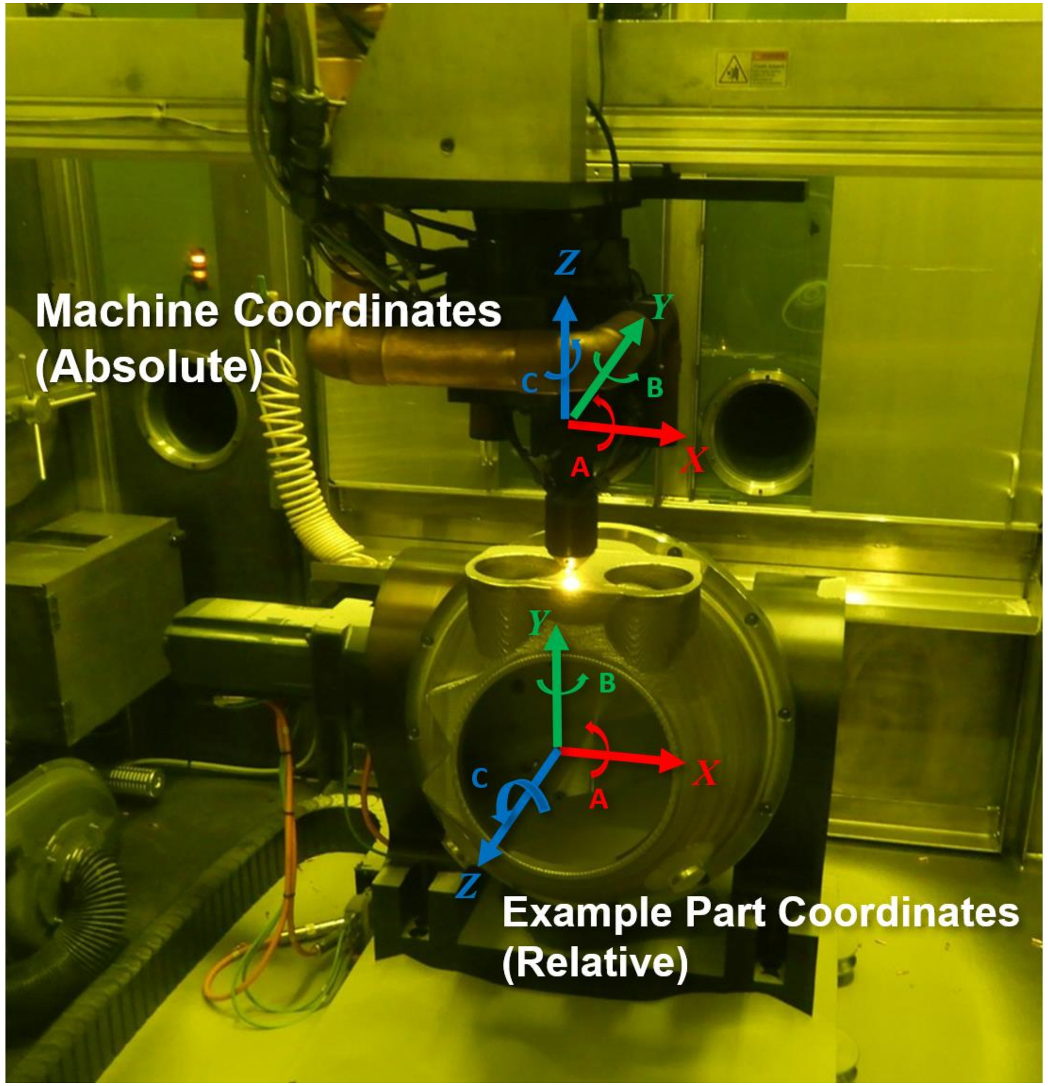


Example of LP-DED with small features



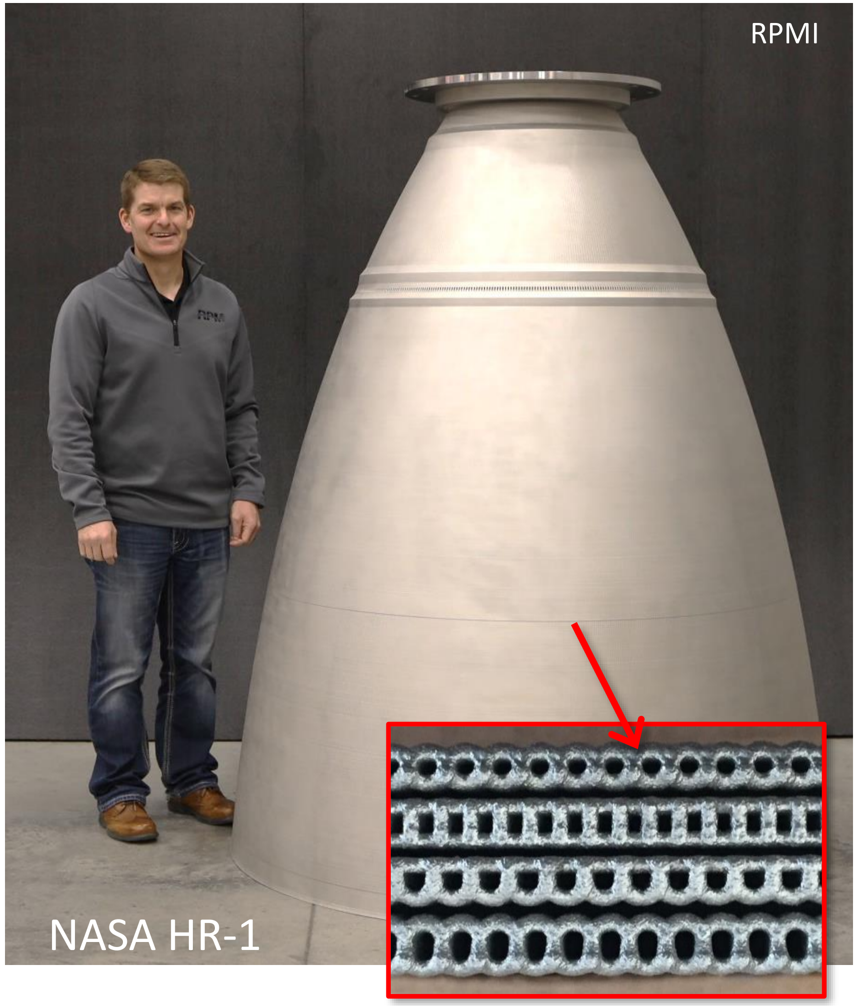
DED Machine Coordinates

- Coordinates defined by ASTM 52921 based on ISO 841
- 3D Cartesian coordinates (X, Y, Z) but includes swiveling and gimbaling
  - Trunion table – **rotate and tilt**
- Z is the build direction
- Similar to traditional CNC machining
- Absolute coordinate system is based on machine coordinates
- Relative coordinate system based on part



Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

Large Scale LP-DED Nozzle Development



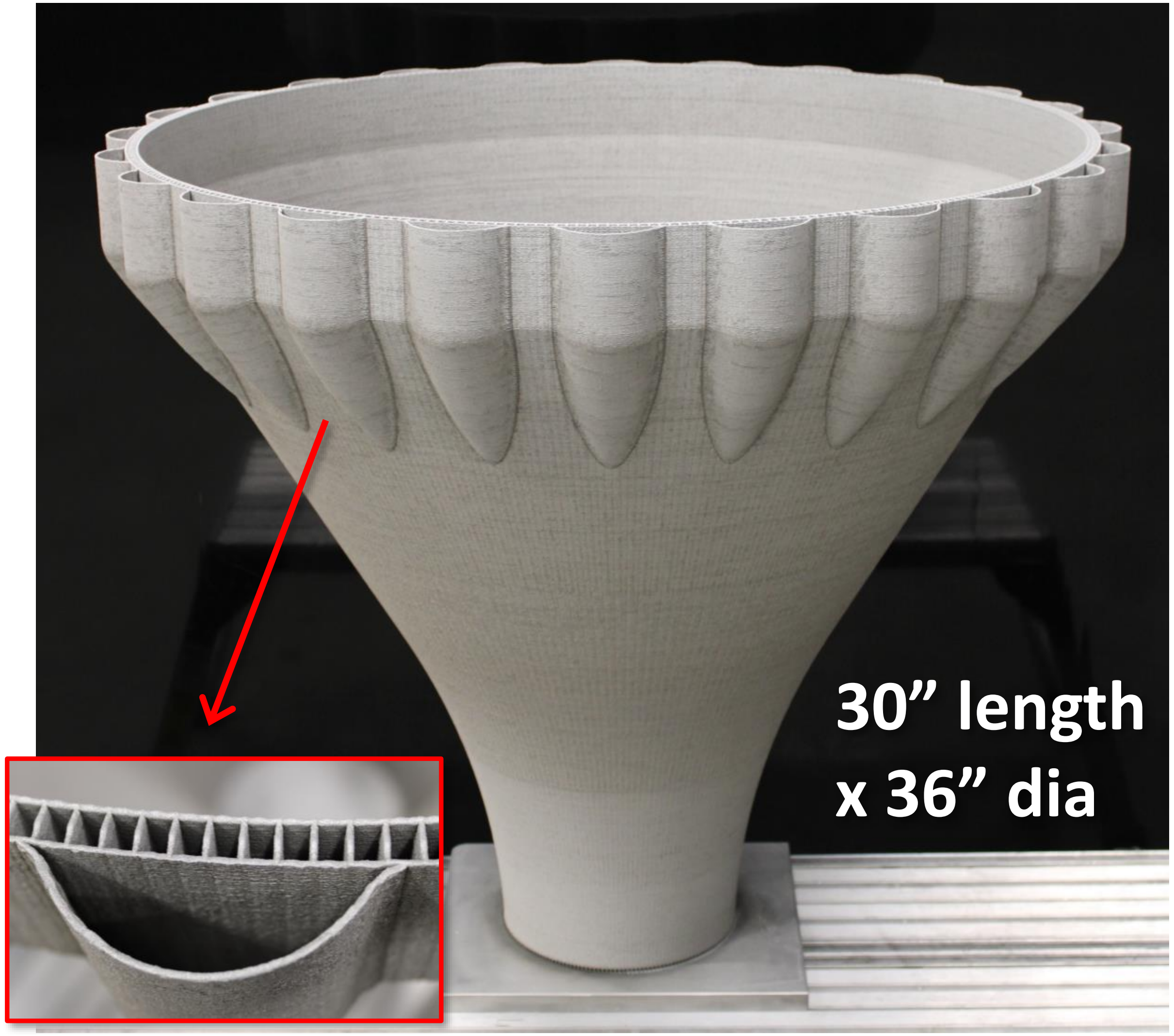
60” (1.52 m) diameter and 70” (1.78 m) height with integral channels
90 day deposition

95” (2.41 m) dia and 111” (2.82 m) height
Near Net Shape Forging Replacement

Reference: P.R. Gradl, T.W. Teasley, C.S. Protz, C. Katsarelis, P. Chen, Process Development and Hot-fire Testing of Additively Manufactured NASA HR-1 for Liquid Rocket Engine Applications, in: AIAA Propuls. Energy 2021, 2021: pp. 1–23. https://doi.org/10.2514/6.2021-3236.

Aluminum Development with LP-DED

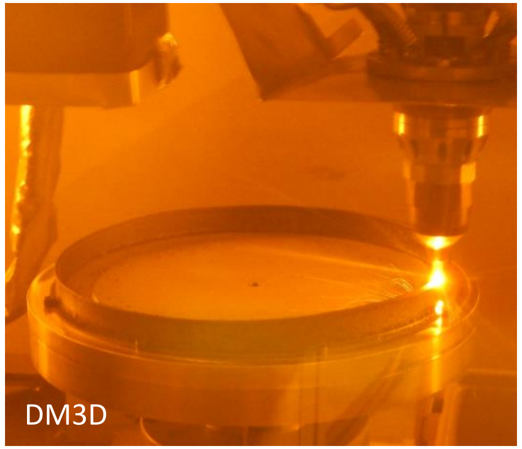
6061-RAM2 with 1.5 mm single-bead wall thickness



Component Applications using LP-DED

½ Scale RS25 Nozzle Liner

Multi-material combination with L-PBF and DED (RAMPT Project)



Spot size (Power) and Deposition Rates

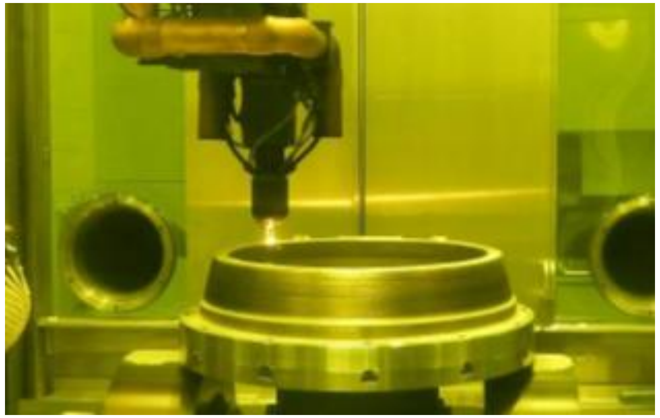
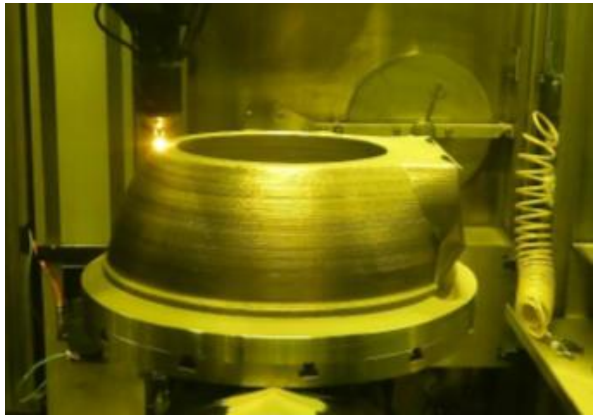
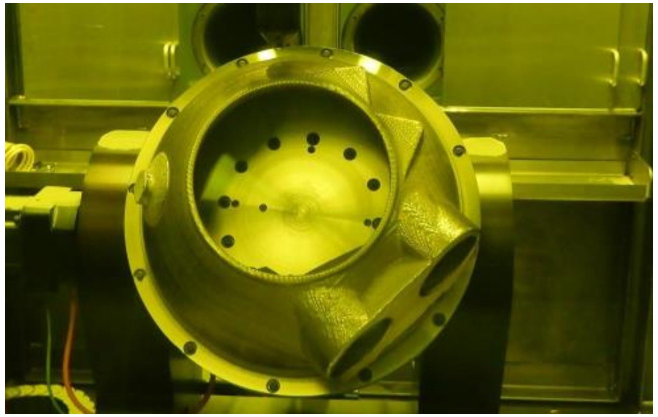
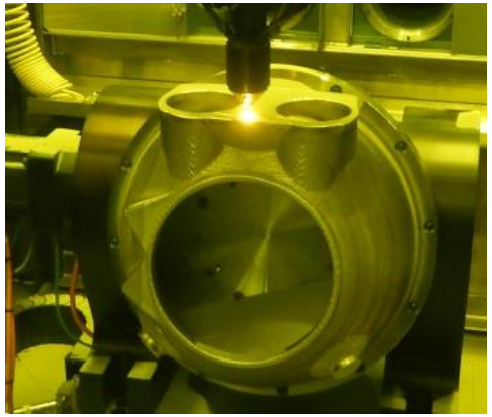
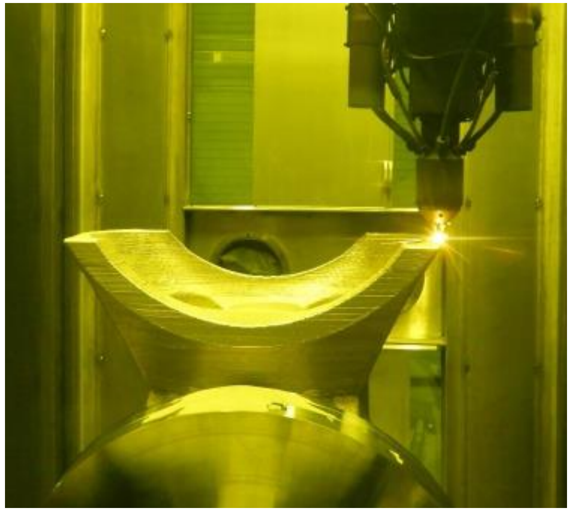
Laser Power: 1070 W	Laser Power: 2000 W	Laser Power: 2620 W
Dep. Rate: 1 in.^{3}/h (23 cm^3/h)	Dep. Rate: 3 in.^{3}/h (49 cm^3/h)	Dep. Rate: 5 in.^{3}/h (82 cm^3/h)
Deposition Time: 24 hours	Deposition Time: 11 hours	Deposition Time: 6 hours

Credit: RPMI

FEATURE RESOLUTION ← → DEPOSITION SPEED

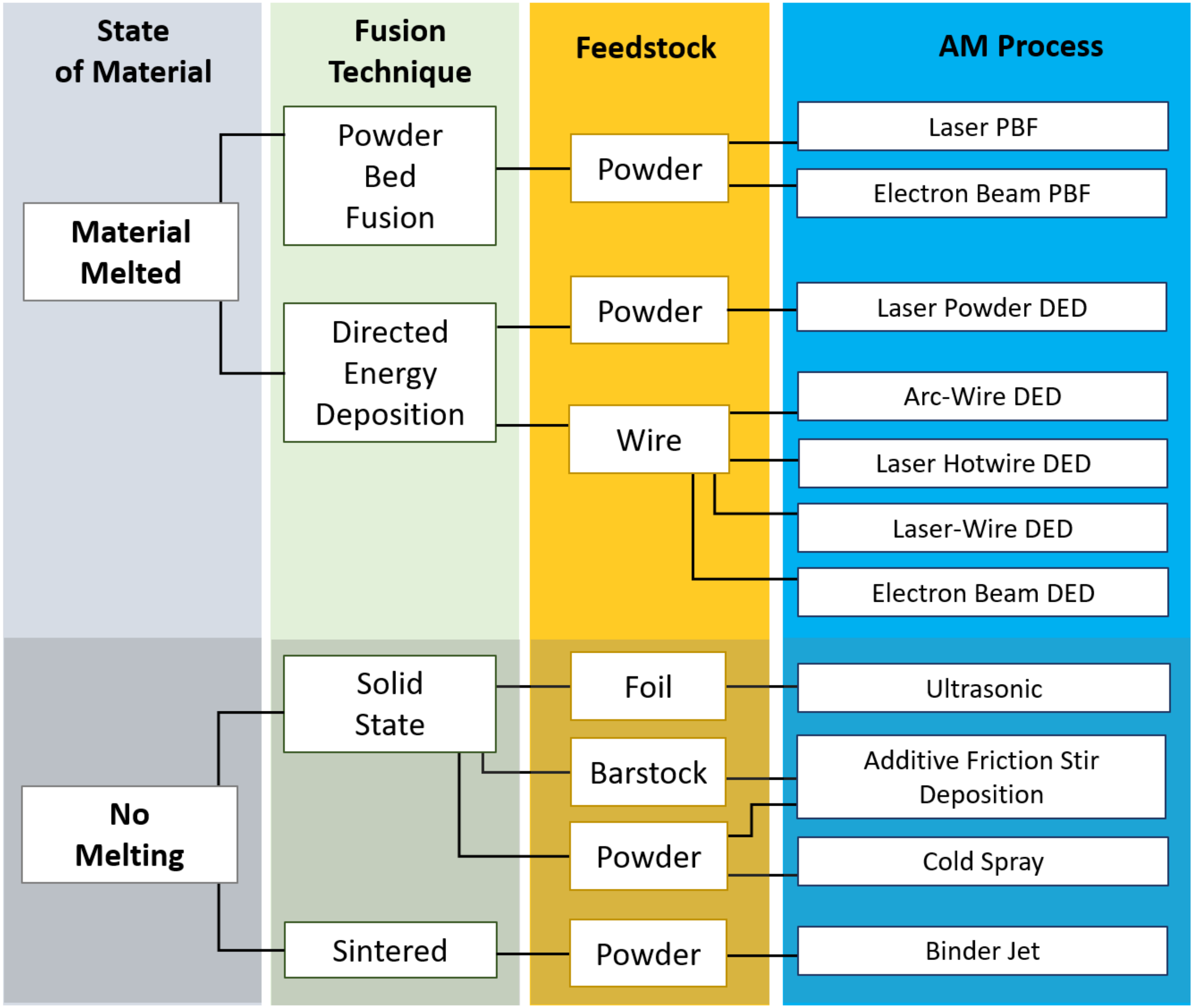
Freedom in DED design and deposition strategies

Ability to use multiple axes for complex features fabricated locally

RS25 Powerhead demonstrator using LP-DED under NASA SLS Artemis Program (Courtesy: RPMI)

Various Metal AM Processes

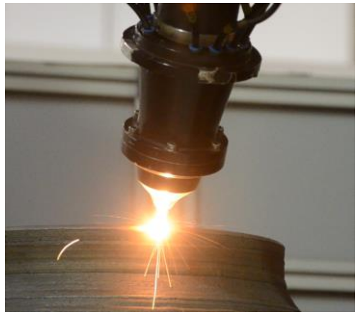


Comparison of L-PBF and DED

Different methods for different components!

Laser Powder Bed Fusion (L-PBF)

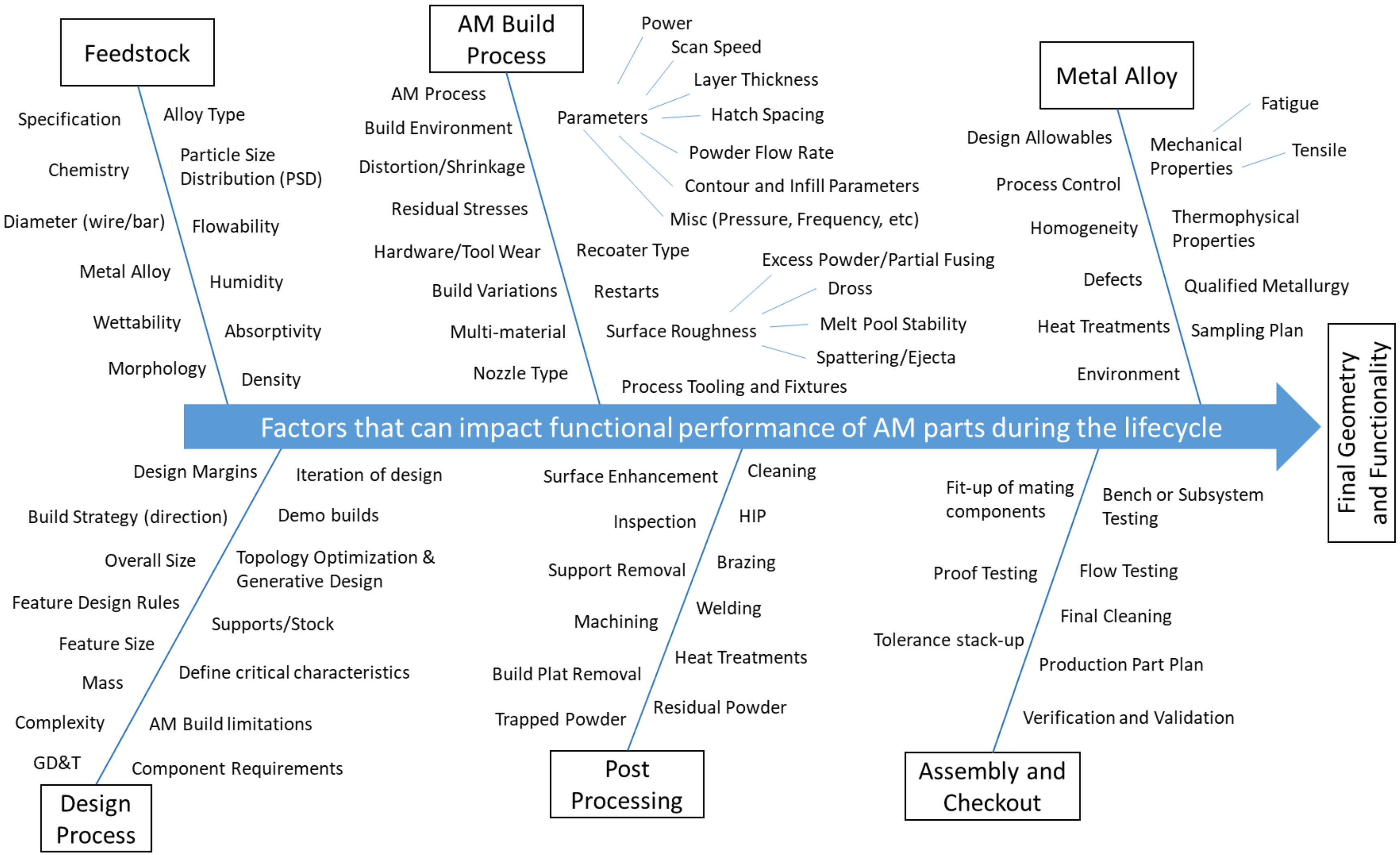
Directed Energy Deposition (DED)



	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 (400mm) 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

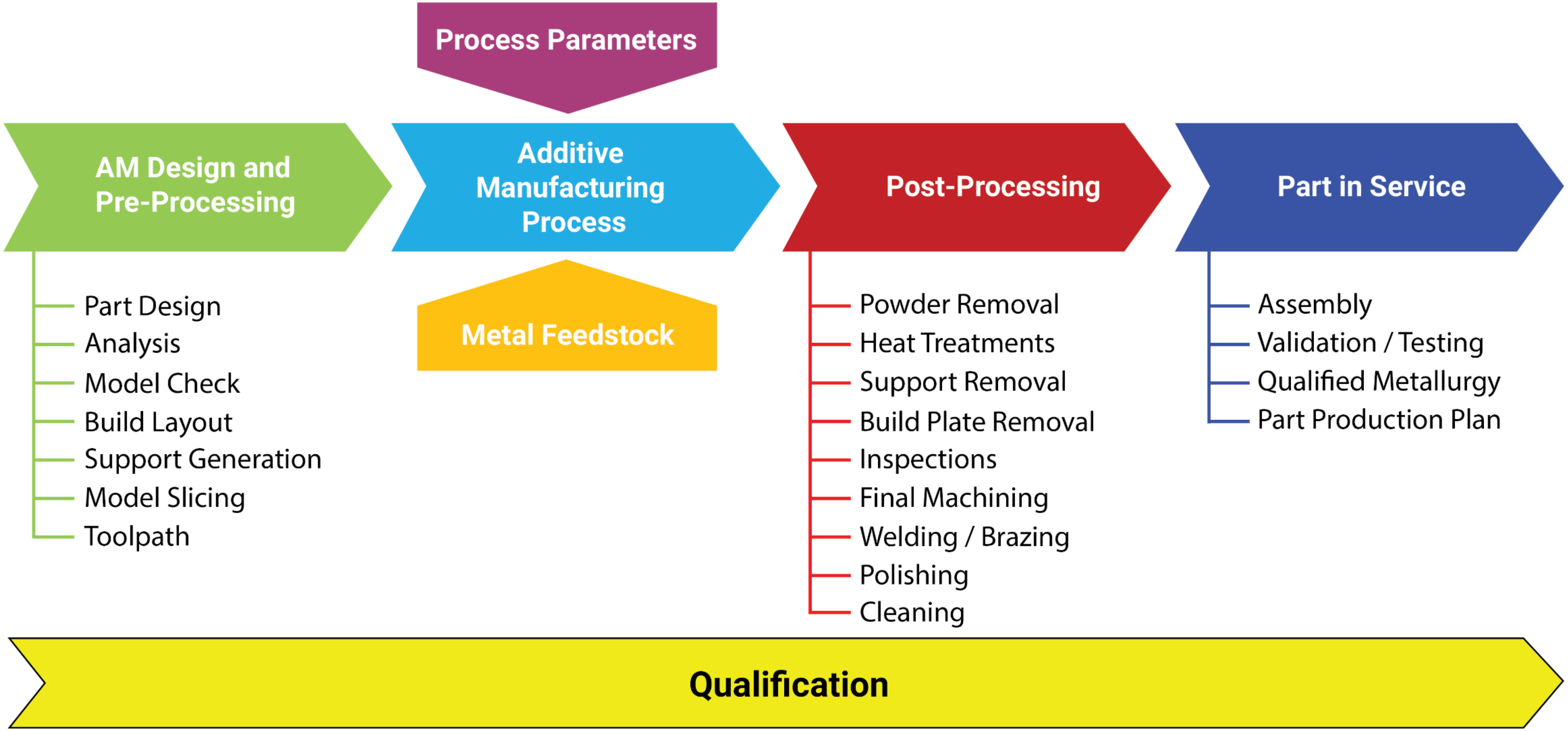
Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

The Challenges with AM Processes



There are a lot of inputs and steps in the AM lifecycle that must go right to meet the expected geometry

Additive Manufacturing Typical Process Flow



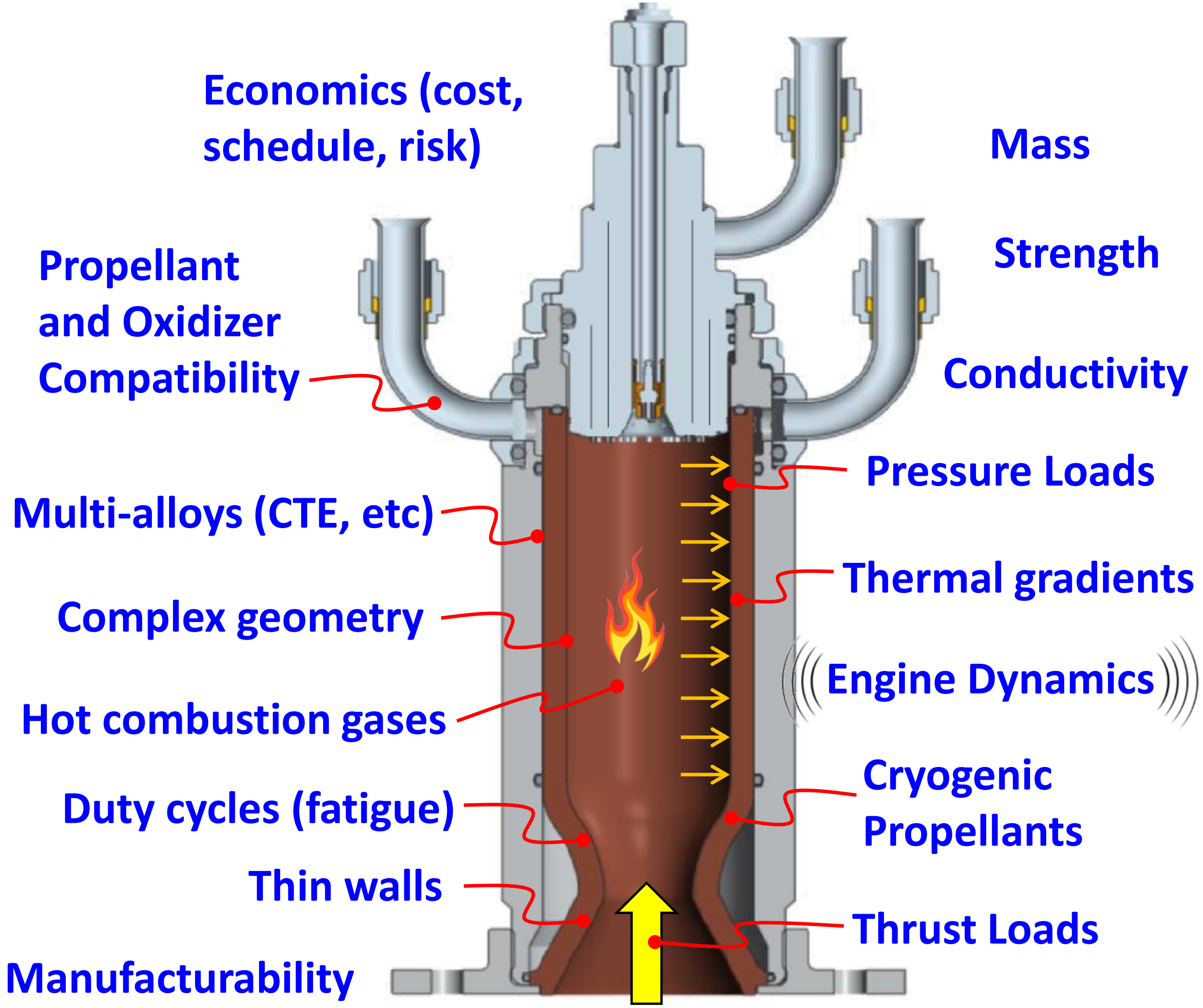
Proper AM process selection requires an integrated evaluation of all process lifecycle steps

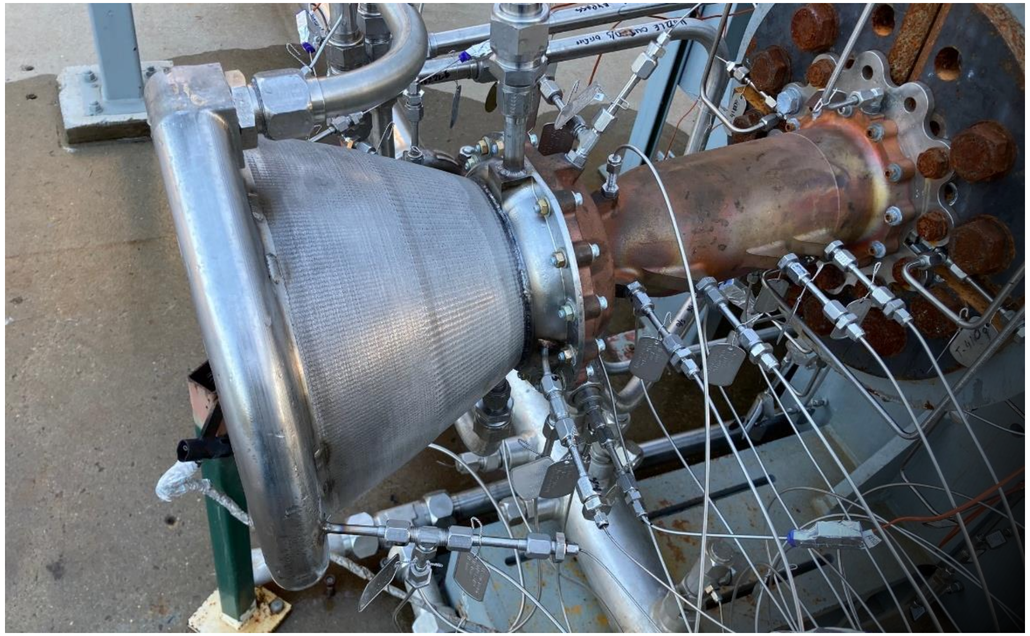
Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

Material Selection

- Extreme environments, combined loads, mass limitations, and processing economics drive selection.
- Understanding the manufacturing technique and all steps required.
- Perform a trade study for each component *(hint: additive manufacturing will not be the best process or most economical for all components.)*
- One of the most frequent reasons for failure in DfAM is lack of attention to metallurgical characteristics from the process.

Example: Combustion Chamber Material Considerations





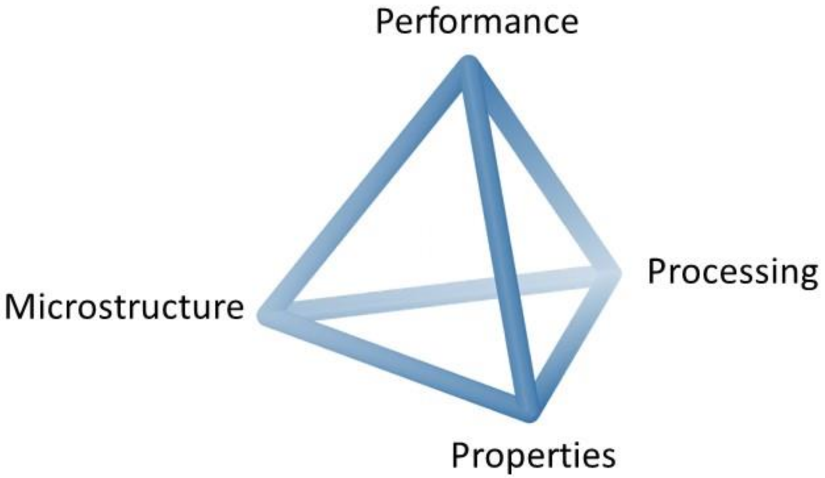
Material Selection – General Requirements

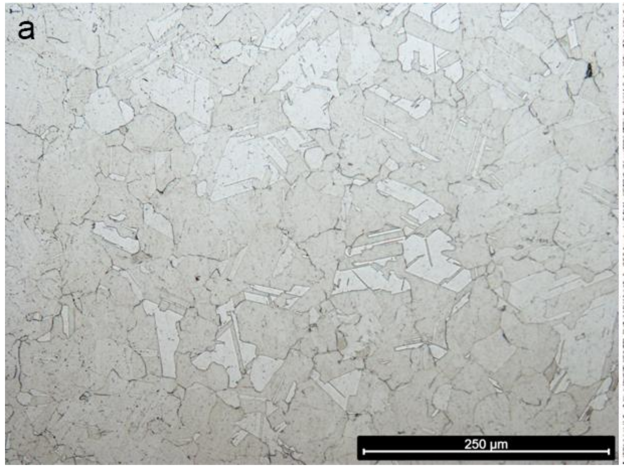
1) Operate under static and dynamic loads in both tension and compression.
2) Compatible with fuels and oxidizers (hydrogen, oxygen, hydrocarbons).
3) Integrate multiple subsystems (possibly different metal alloys).
4) Optimized for strength-to-weight ratio (design- and metal-based).
5) Operate in extreme environments (cryogenic and high temperatures, high pressure, combustion, oxidizing or reducing condition).
6) Withstand high thermal gradients and high heat transfer in a high-heat-flux environment.
7) Exhibit high fracture toughness at temperature for potential impacts by domestic object debris (DOD) or foreign object debris (FOD).
8) Exhibit corrosion resistance when in contact with other alloys and operating fluids or contaminants.
9) High wear resistance for contact or running surfaces between components.

Material Science Fundamentals

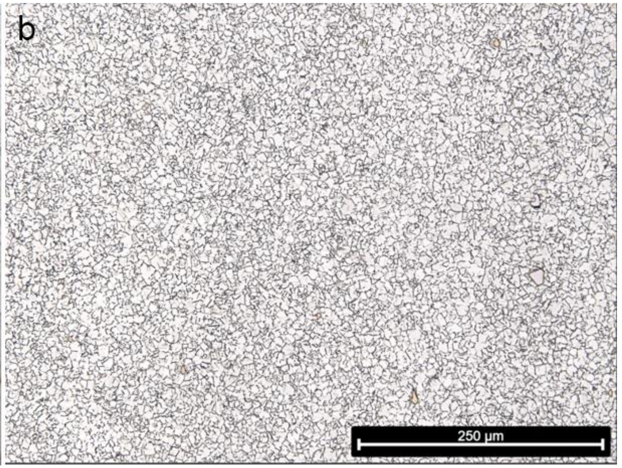
Process → Microstructure → Properties → Performance

- Each manufacturing process forms or modifies a material that establishes a microstructure.
- The properties are dependent on the microstructure and ultimately the end performance.
- AM is no different and each process can result in different microstructures.
- AM is different than wrought, forged material, cast material…
- **Based on AM process, orientation, process parameters, geometry.**





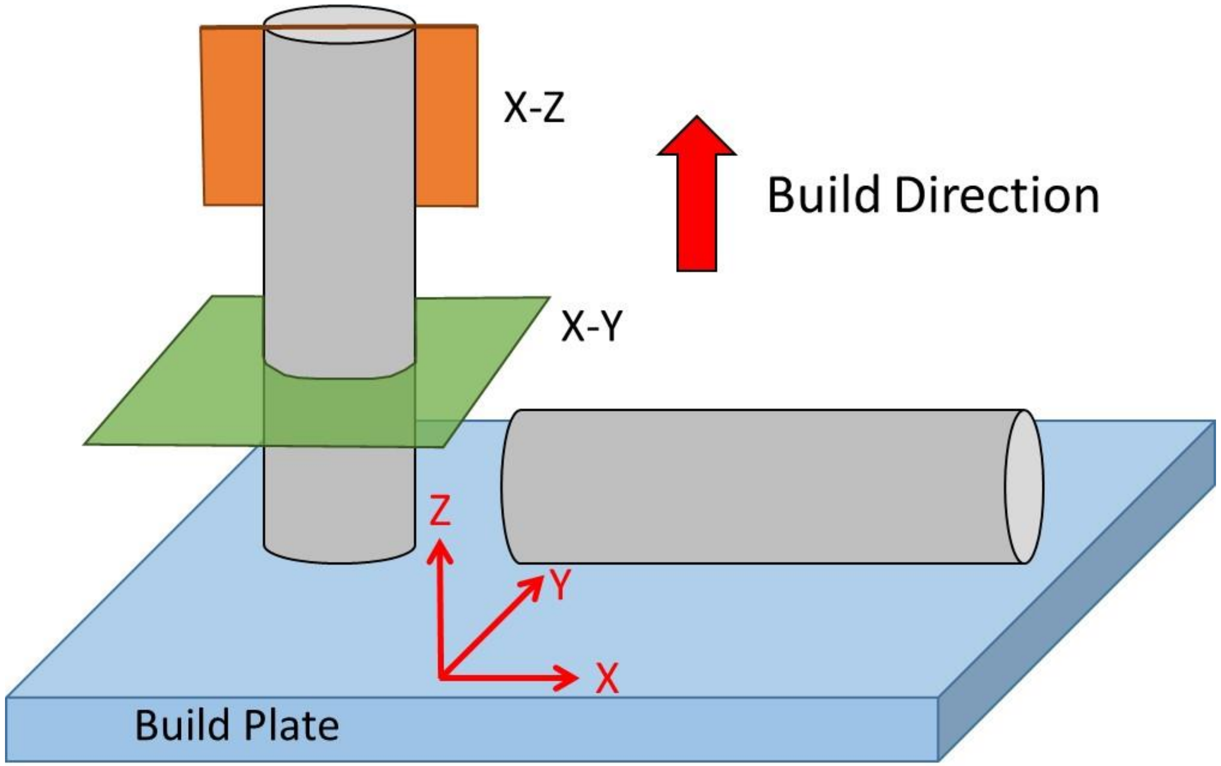
Inconel 718 built using L-PBF (200x)



Inconel 718 bar stock (200x)

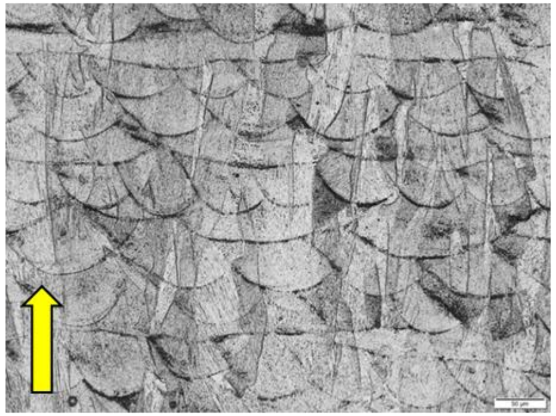
Coordinate System Reference

- Build direction (Z) dominates microstructure orientation.
- Anisotropy exists in AM materials, primarily between interlaminar (Z) and intralaminar (XY) directions.
- Variation due to heating and cooling direction and rates.

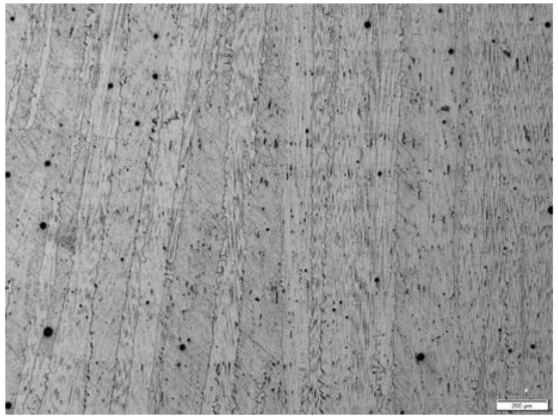


Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

Microstructure of Various AM Processes
Alloy 625 – As-Built

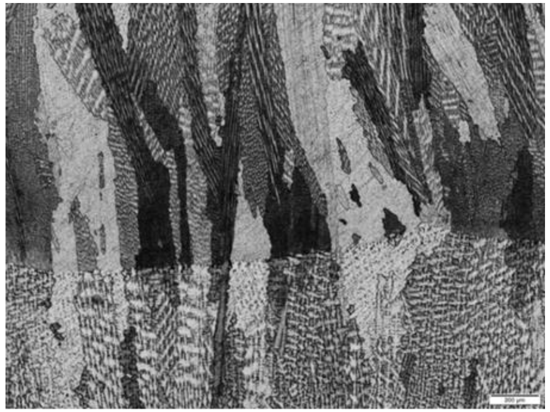


Laser Powder Bed Fusion

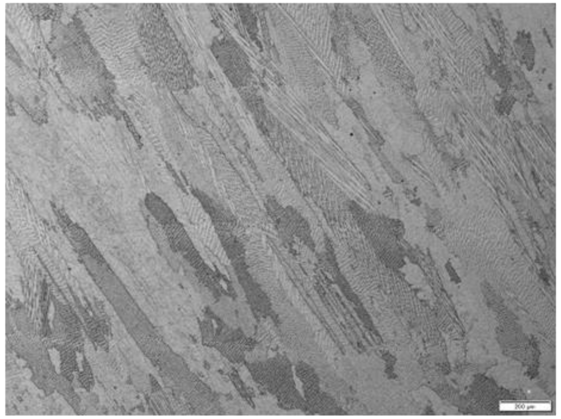


Electron Beam Powder Bed Fusion

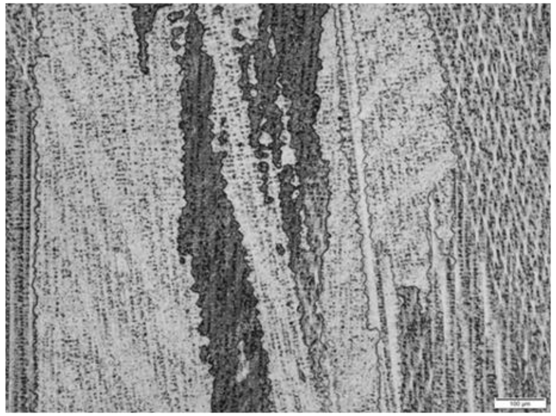
Laser Powder DED (1070 W)



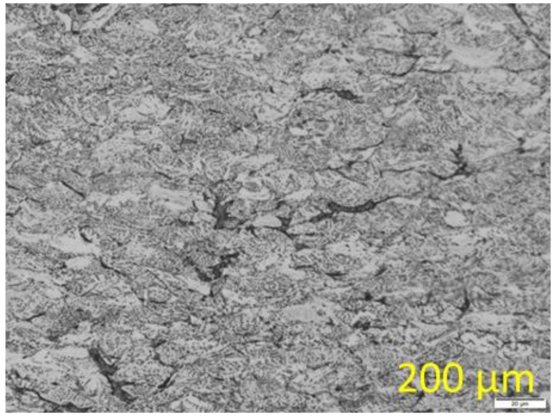
Electron Beam Wire DED



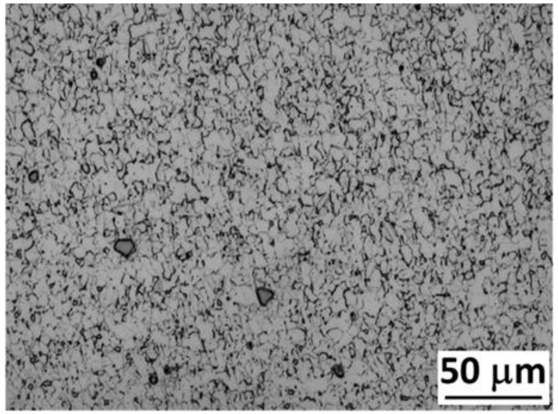
Laser Wire DED



Arc Wire DED



Cold Spray



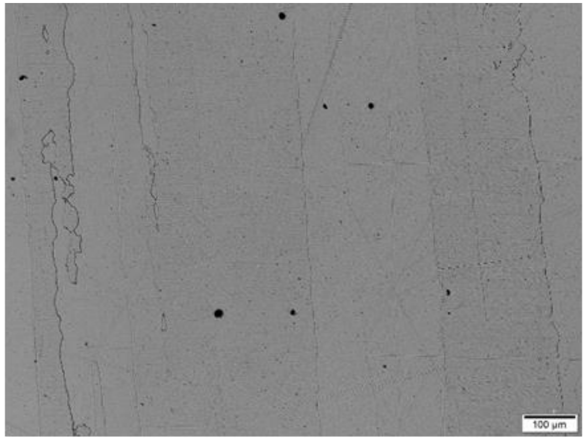
Additive Friction Stir Deposition

Each AM process results in different grain structures, which ultimately influence properties

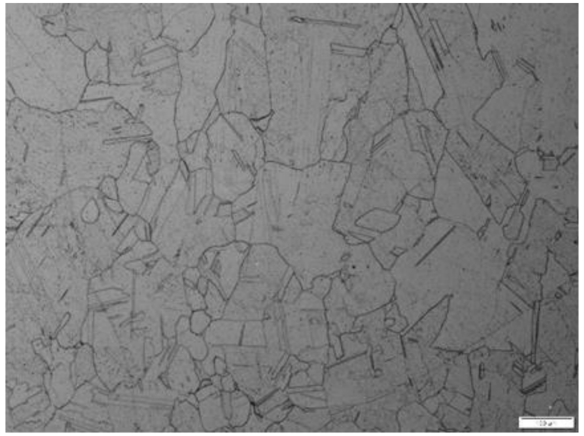
- Gamon, A., Arrieta, E., Gradl, P.R., Katsarelis, C., Murr, L.E., Wicker, R.B., Medina, F., 2021. Microstructure and hardness comparison of as-built Inconel 625 alloy following various additive manufacturing processes. Results in Materials 12. https://doi.org/10.1016/j.rinma.2021.100239
- Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0
- Rivera, O. G., Allison, P. G., Jordon, J. B., Rodriguez, O. L., Brewer, L. N., McClelland, Z., ... & Hardwick, N. (2017). Microstructures and mechanical behavior of Inconel 625 fabricated by solid-state additive manufacturing. Materials Science and Engineering: A, 694, 1-9.
- Image from Mark Norfolk, Fabrisonic

Microstructure of Various AM Processes
Alloy 625 – Stress Relief, HIP, Solution per AMS 7000

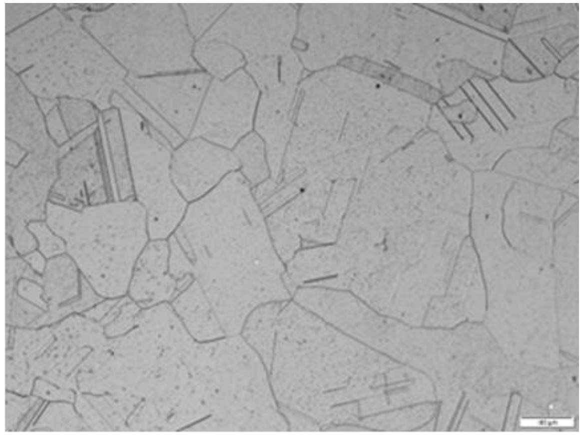
Laser Powder Bed Fusion



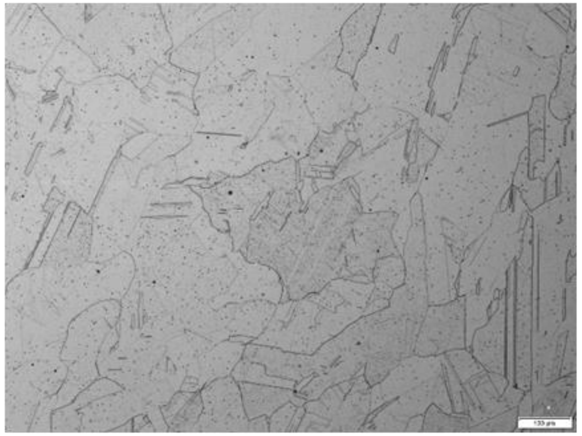
Electron Beam PBF



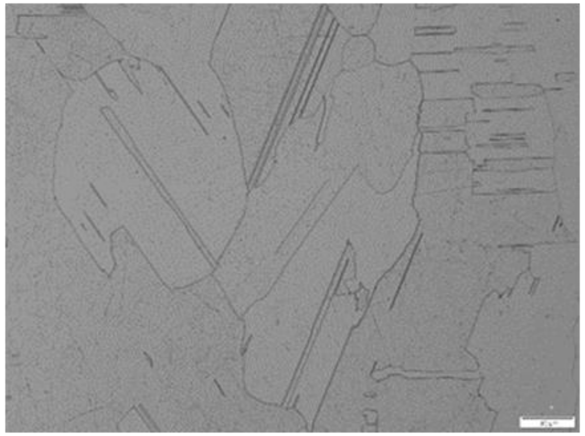
Laser Powder DED (1070 W)



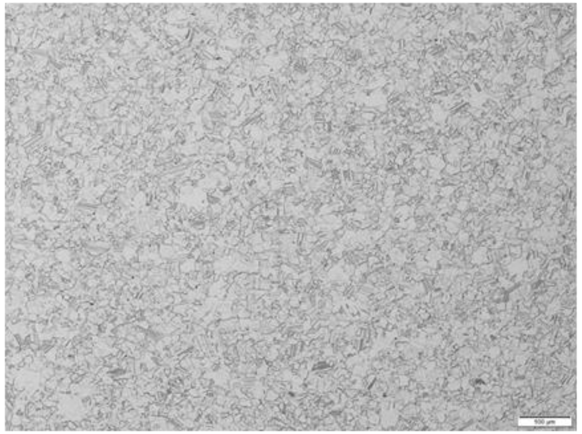
Electron Beam Wire DED



Laser Wire DED



Arc Wire DED



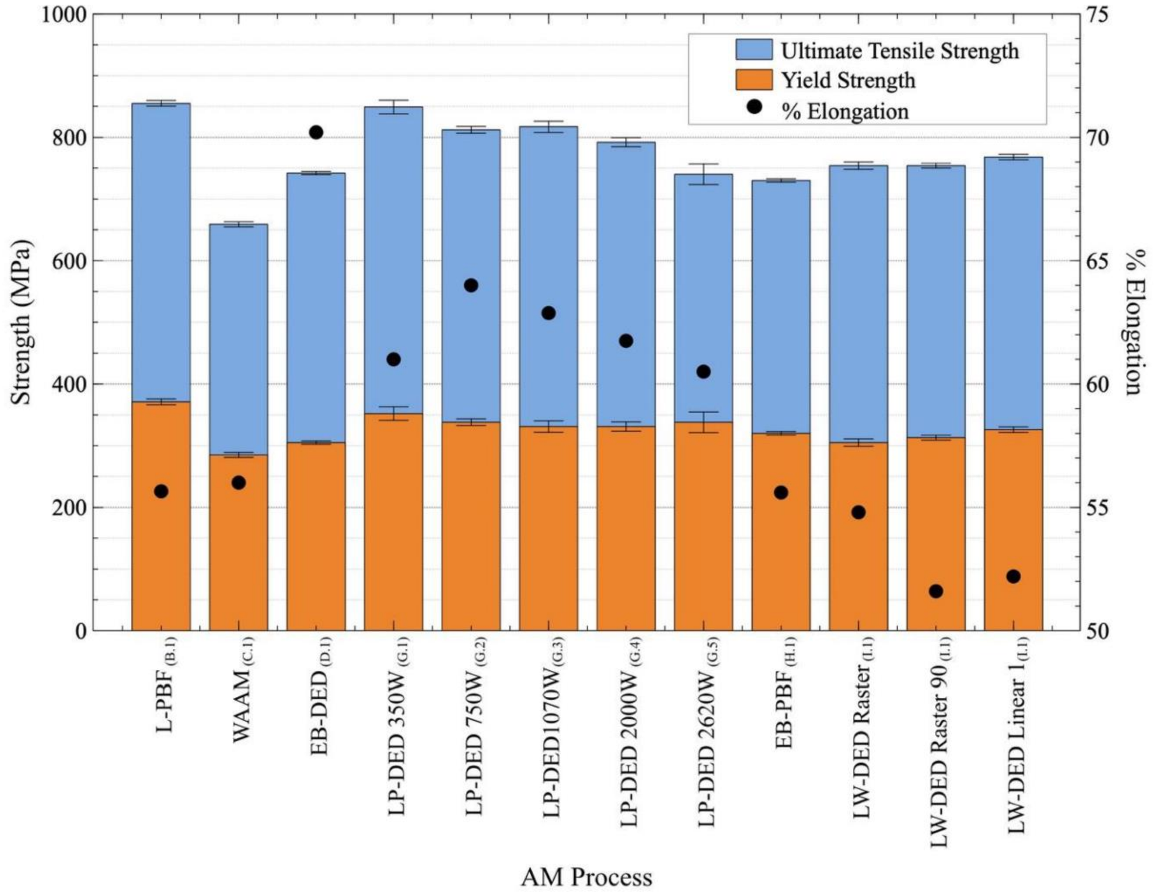
Cold Spray

- Gamon, A., Arrieta, E., Gradl, P.R., Katsarelis, C., Murr, L.E., Wicker, R.B., Medina, F., 2021. Microstructure and hardness comparison of as-built Inconel 625 alloy following various additive manufacturing processes. Results in Materials 12. https://doi.org/10.1016/j.rinma.2021.100239
- Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

Material Properties for Various AM Processes

- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Cold spray….), the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build.
- Each AM process results in different grain distributions, precipitates, and porosity, all of which influence final properties.
- Heat treatments should be developed based on the requirements and environment of the end component use.
- Process, parameters, and feedstock should all be stable before property development.

Alloy 625, Heat Treated per AMS 7000
Room Temperature UTS



*Not design data and provided as an example only

Luna, V.; Trujillo, L.; Gamon, A.; Arrieta, E.; Murr, L.E.; Wicker, R.B.; Katsarelis, C.; Gradl, P.R.; Medina, F. Comprehensive and Comparative Heat Treatment of Additively Manufactured Inconel 625 Alloy and Corresponding Microstructures and Mechanical Properties. *J. Manuf. Mater. Process.* **2022**, *6*, 107. https://doi.org/10.3390/jmmp6050107

AM Alloys Available *(not fully inclusive)*

Ni-Based
Inconel 625
Inconel 713
Inconel 718
Inconel 738
Inconel 939
Hastelloy-X
Haynes 214
Haynes 230
Haynes 233
Haynes 282
Monel K-500
C276
Rene 80
Rene 142
Waspalloy

Fe-Based
SS 17-4PH
SS 15-5 GP1
SS 304
SS 316L
SS 410
SS 420
SS 440
4140/4340
Invar 36
SS347
JBK-75
NASA HR-1

Cu-Based
Pure Cu
GRCop-84
GRCop-42
C18150
C18200
Glidcop
CU110
Monel K500

Co-Based
CoCr/CoCrMo
Haynes 188
Stellite 6, 21, 31

Platinum Group
Ir, Pt, Rh, Ru, Pd, Au, Ag

Refractory
W
WRe
Mo
MoW
MoRe
Ta
TaW
Re
Nb
C103
FS85
High Entropy

Ti-Based
Ti6Al4V
γ-TiAl
Ti-6-2-4-2

Al-Based
AlSi10Mg
A205
F357
1000*
6061*
2024*
7075*
7050*
Scalmalloy*
7A77*

*Reactive-based AM

Data Example For LP-DED AM Haynes 230

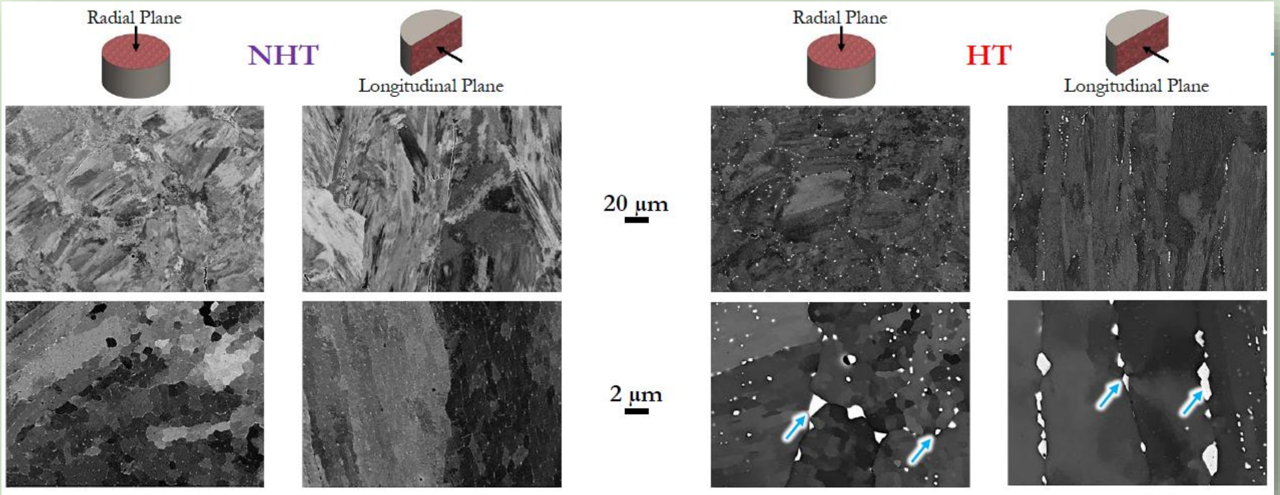
Data from Gradl, Mireles, Protz, Garcia. “Metal Additive Manufacturing for Propulsion Applications”, AIAA Progress Series. (2022). Appendix A.

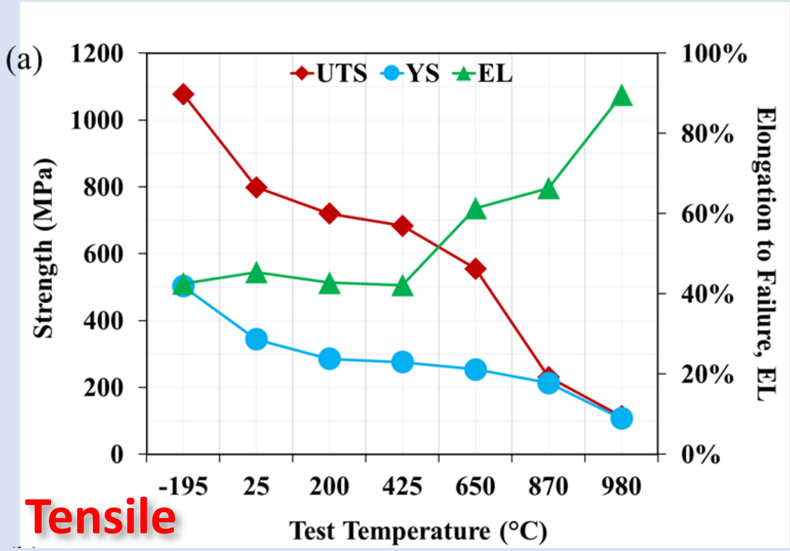
LP-DED Haynes 230

Power (W)	Layer height (µm)	Travel speed (mm/min)	Powder feed rate (g/min)
1070	381	1016	19.10

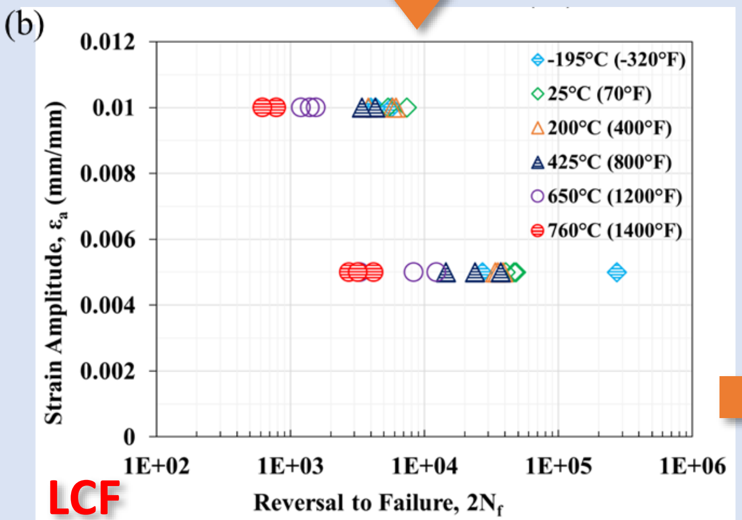
Procedure (Designation)	Temperature (°C)	Time (hrs)	Cooling
Stress Relief (SR)	1066	1.5	Furnace cool
HIP [2]	1163/103 MPa	3	Furnace cool
Solution Annealing (SOL)	1177	3	Argon quench

[2] HIP per ASTM F3301

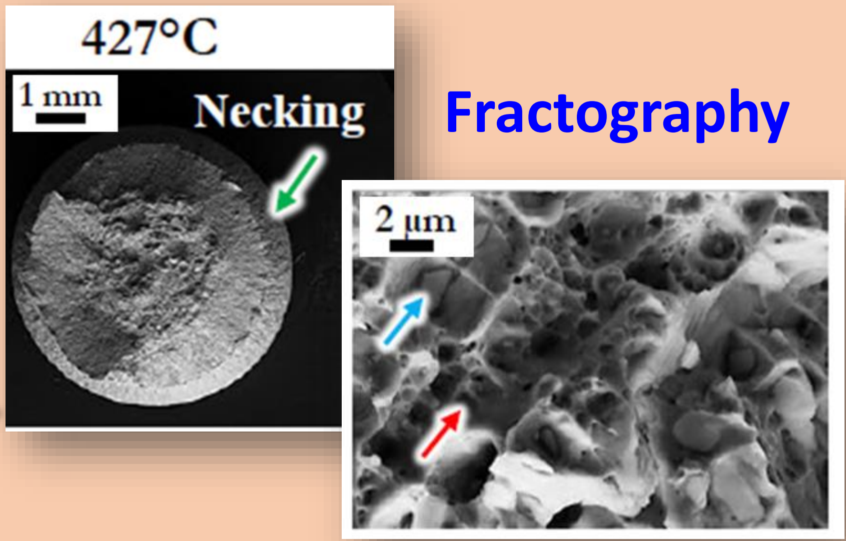




Tensile



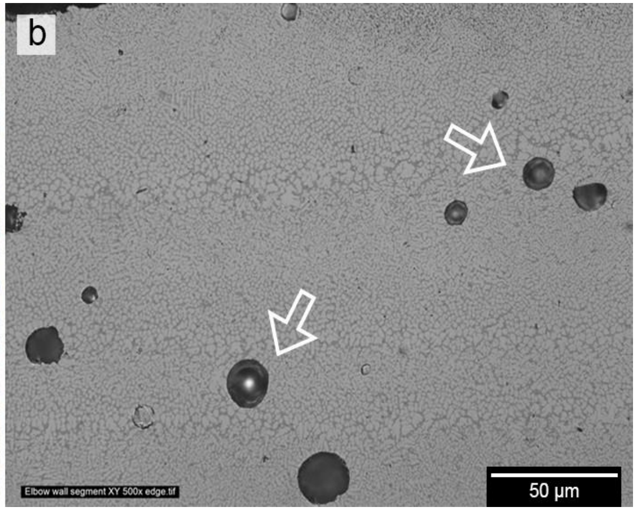
LCF



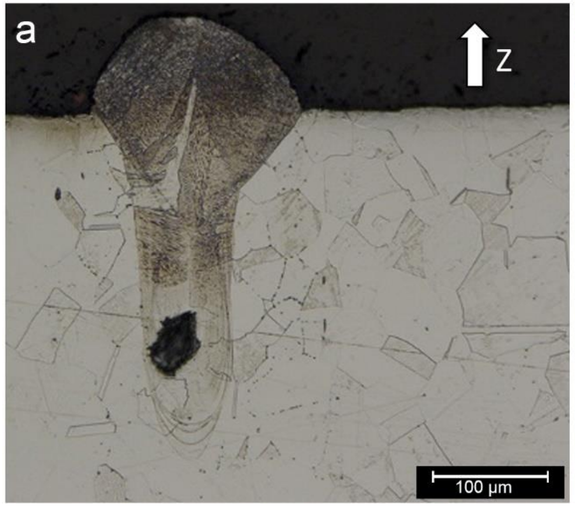
Fractography

Process Defects (Flaws)

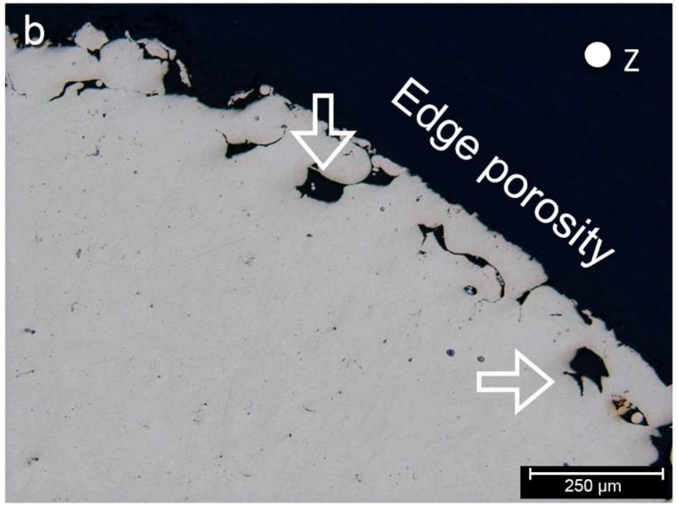
Irregular Lack of Fusion (LOF) volumetric defect
L-PBF Inconel 718



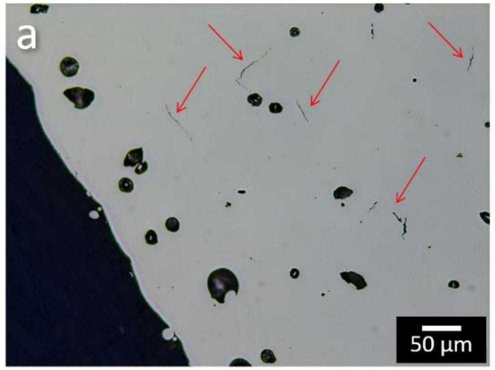
Spherical voids due to trapped gas
L-PBF AlSi10Mg



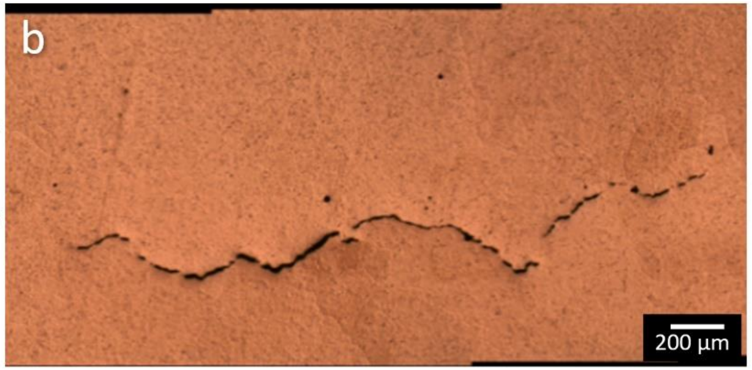
Keyholing due to entrapped vapor
L-PBF



Edge porosity due to improper contour parameters
L-PBF GRCop-42



Microcracks and lack of fusion



Microcracks in XY plane

L-PBF JBK-75

Keyholing reference: King, W. E., Barth, H. D., Castillo, V. M., Gallegos, G. F., Gibbs, J. W., Hahn, D. E., Kamath, C., and Rubenchik, A. M., “Observation of keyhole-mode laser melting in laser powder-bed fusion additive manufacturing,” *Journal of Materials Processing Technology*, Vol. 214, No. 12, Dec. 2014, pp 2915–2925

Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

Feedstock Requirements

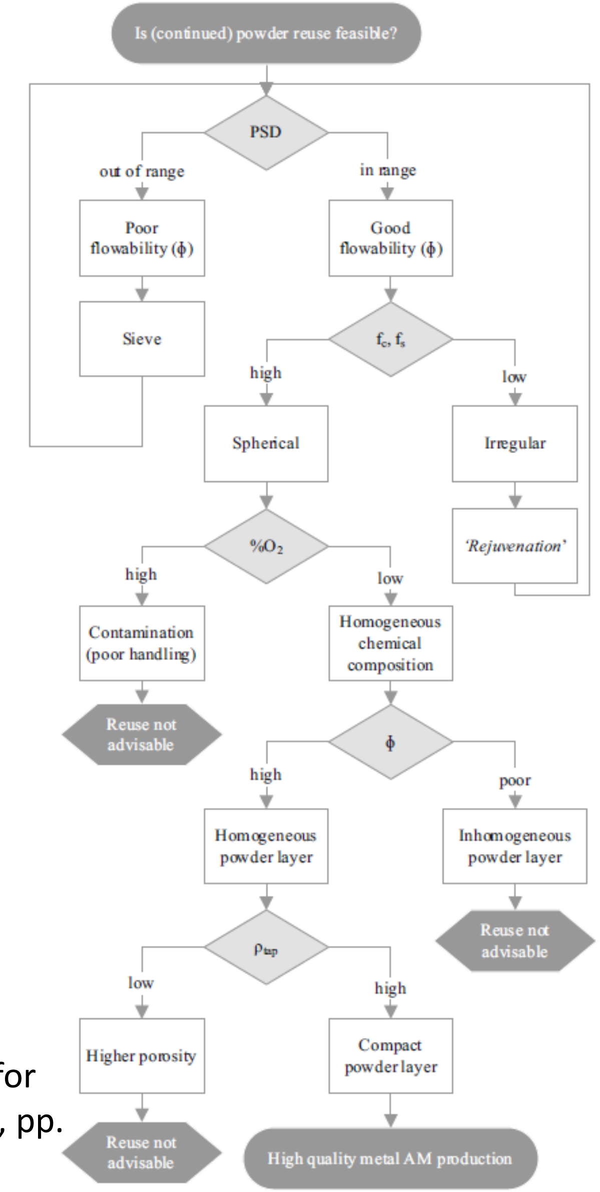
- Feedstock enables AM
- Powder, Wire, and others
- Responsibilities of the “mill” are passed onto the user
  - Chemistry
  - Cleanliness
  - Pedigree
  - Conformance to other standards

Process[a]	Type of Feedstock	Typical Feedstock Size
L-PBF	Powder	10–45 μm
EB-PBF	Powder	45–105 μm
LP-DED	Powder	45–105 μm
AW-DED	Wire	0.8–2 mm dia
LW-DED	Wire	0.6–1.6 mm dia
LHW-DED	Wire	0.8–1.6 mm dia
EBW-DED	Wire	1.14–3.2 mm dia
UAM	Sheet	Varies
AFS-D	Bar, powder	Varies
Cold spray	Powder	10–45 μm
Binder jet	Powder with binder	3–38 μm

Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

Powder Feedstock Characterization: Reuse

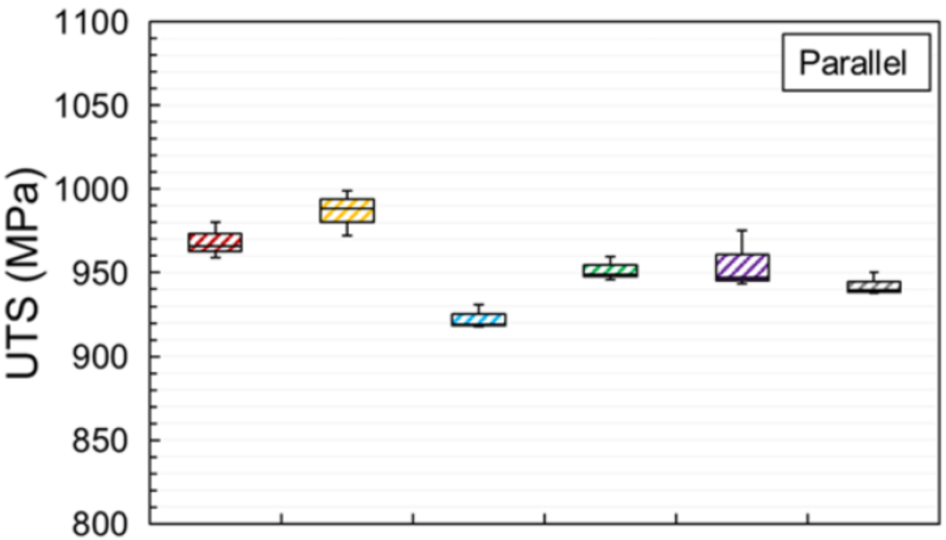
- Powder recycling is an essential aspect to the sustainability and material savings promised by AM
- Most protocols involved blending sieved reused powder with virgin powder.
- Oxygen pickup is the most observed change in reused powder
- Flowability can often be improved with reuse



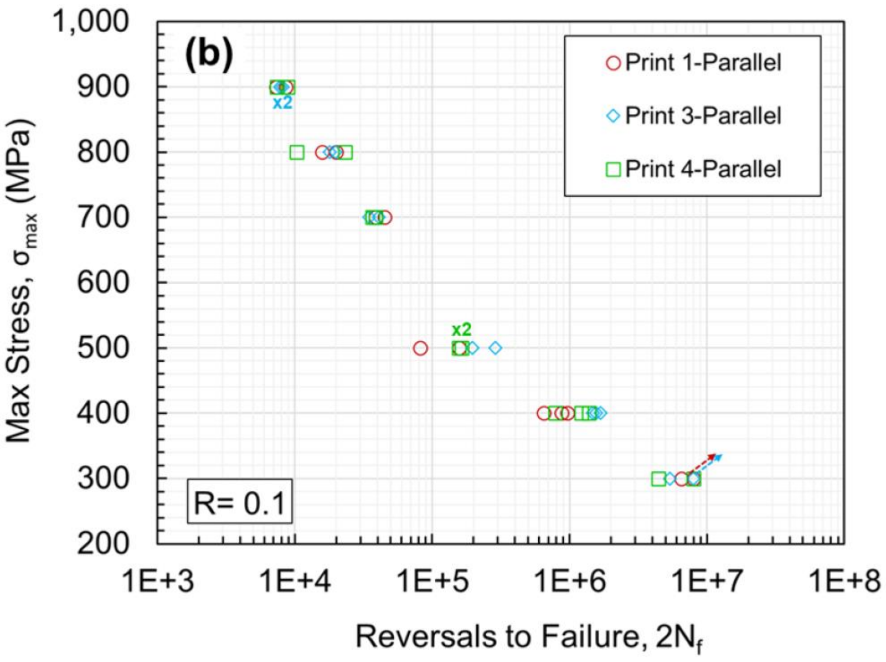
Cordova, L., Campos, M., and Tinga, T. "Revealing the Effects of Powder Reuse for Selective Laser Melting by Powder Characterization." JOM, Vol. 71, No. 3, 2019, pp. 1062–1072. https://doi.org/10.1007/s11837-018-3305-2.

Powder Re-Use (LP-DED Example)

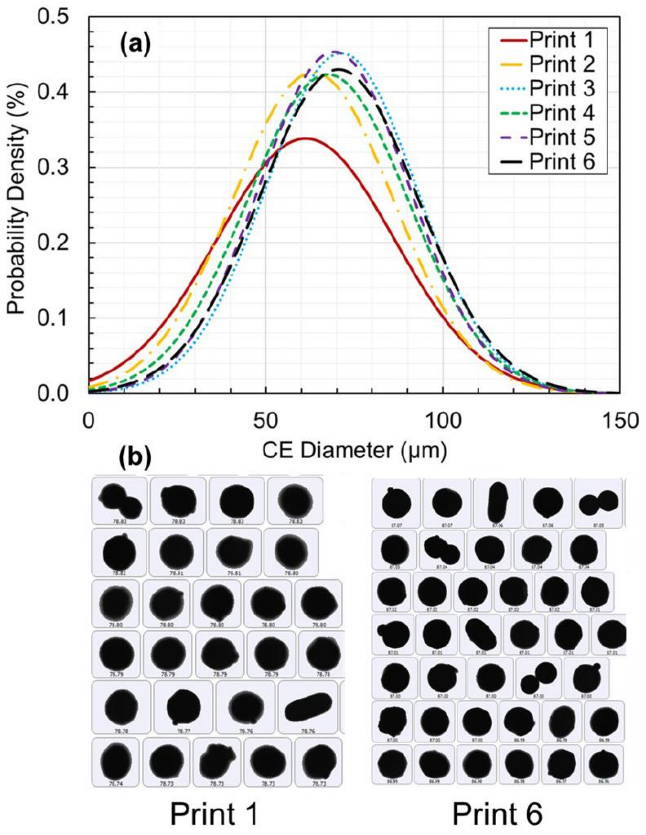
- For AM to be economical, powder must be re-used.
- The life of the powder and properties can be process (build and handling) and alloy dependent.



LP-DED NASA HR-1 Alloy
Tensile

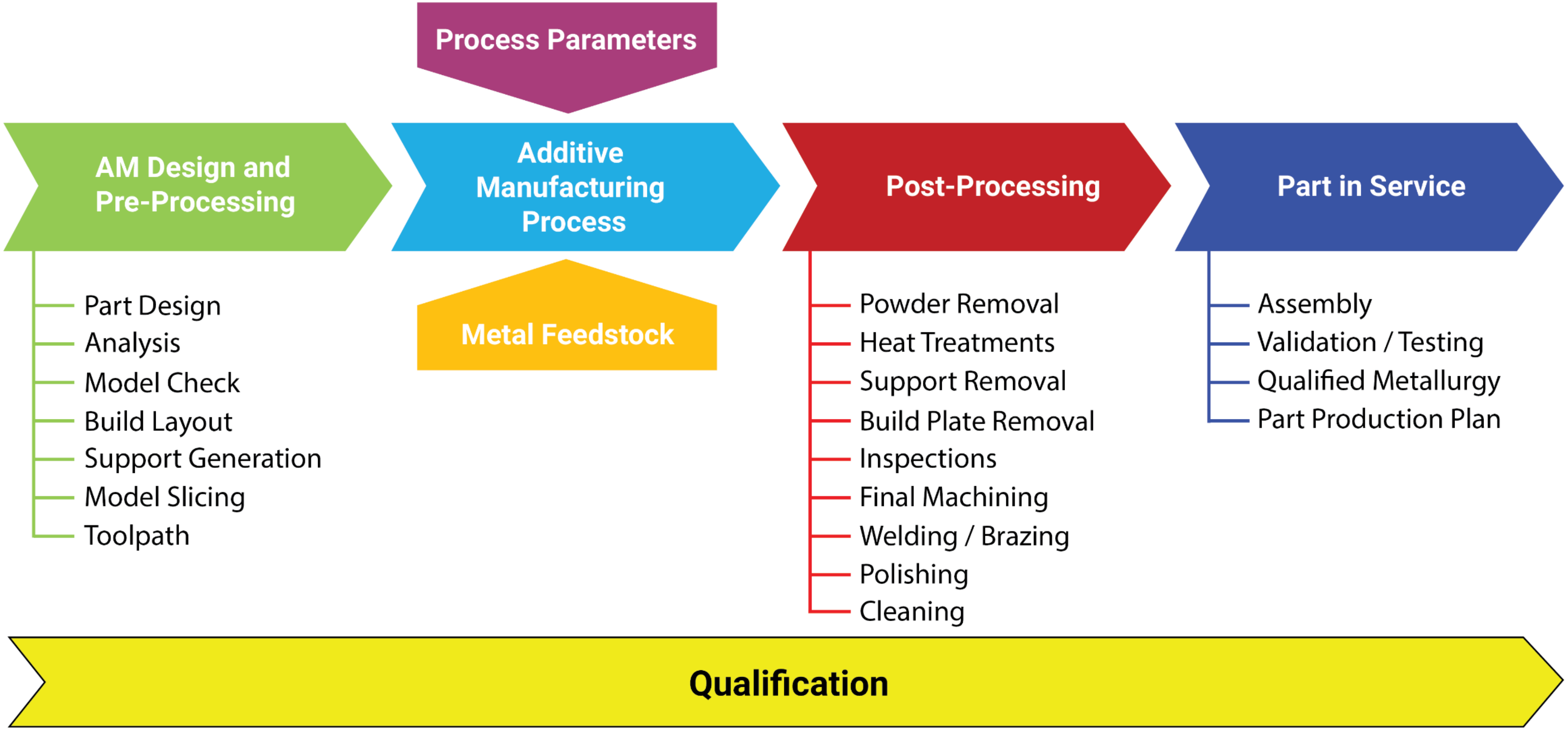


LP-DED NASA HR-1 Alloy
Low Cycle Fatigue



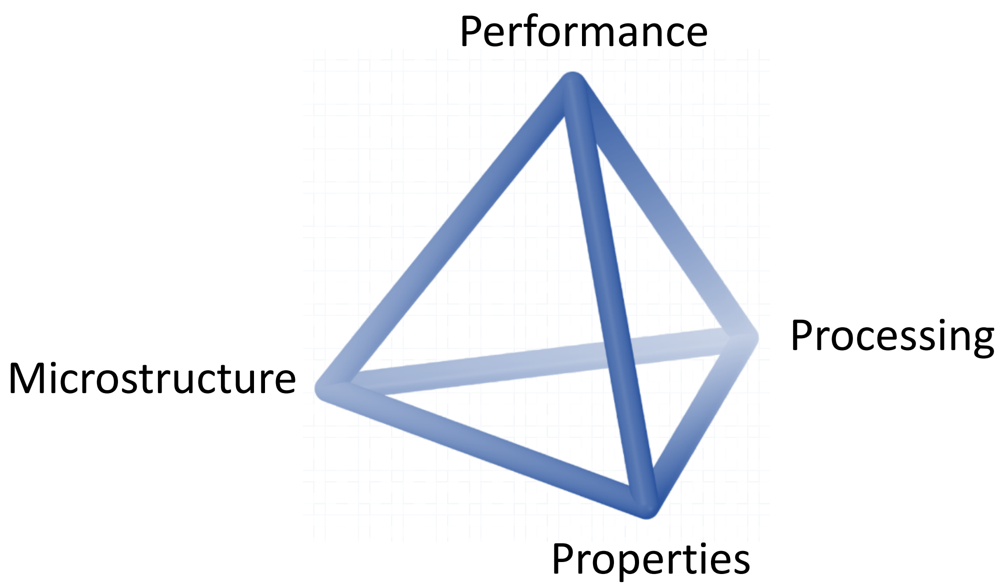
Soltani-tehrani, A., Chen, P., Katsarelis, C., Gradl, P., Shao, S., 2023. Thin-Walled Structures Mechanical properties of laser powder directed energy deposited NASA HR-1 superalloy : Effects of powder reuse and part orientation. Thin-Walled Structures 185, 110636. https://doi.org/10.1016/j.tws.2023.110636

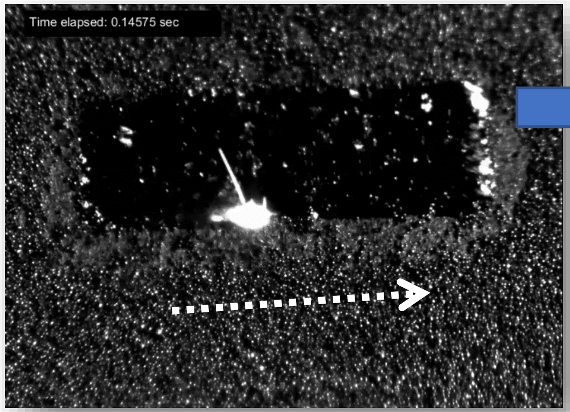
Design for Additive Manufacturing (DfAM)

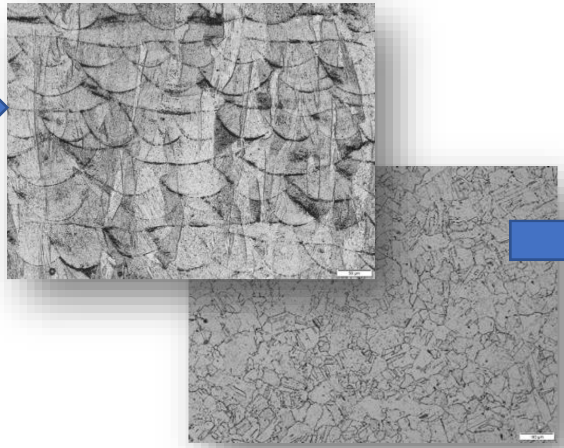


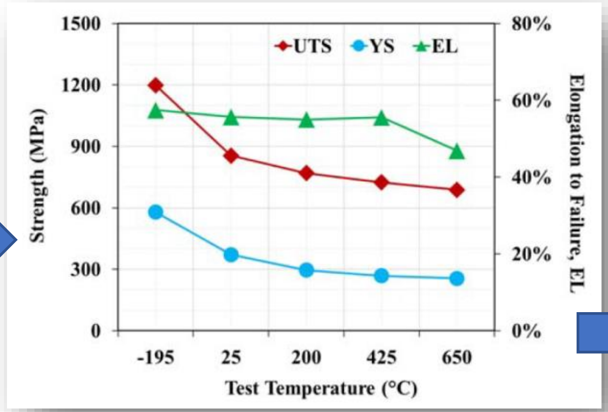
Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

Material Fundamentals are necessary for Component Applications

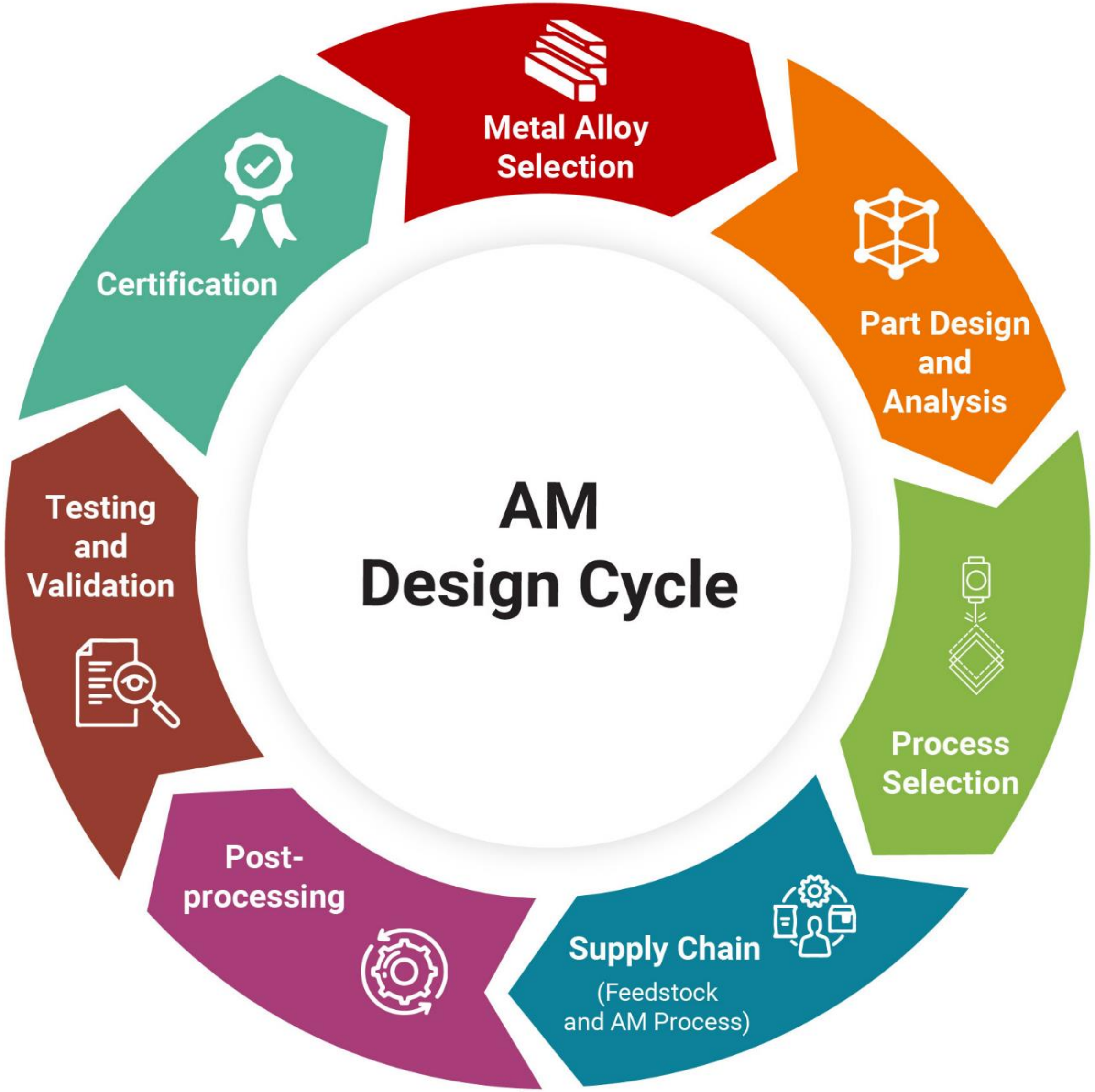








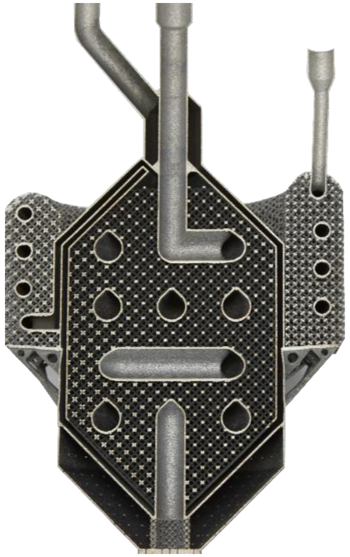
AM Design Cycle



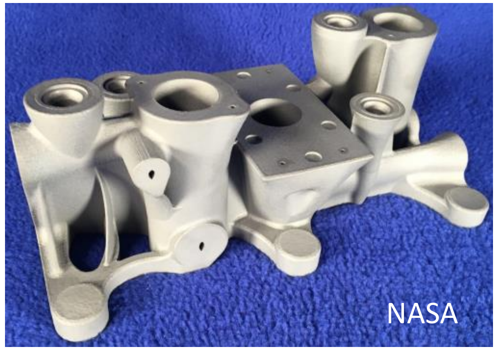
L-PBF DfAM

L-PBF Part Examples

NASA

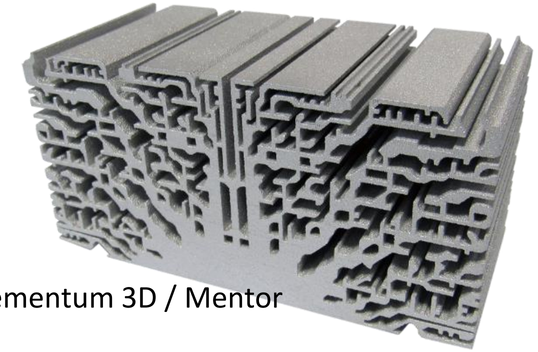


Castheon / ADDman



NASA

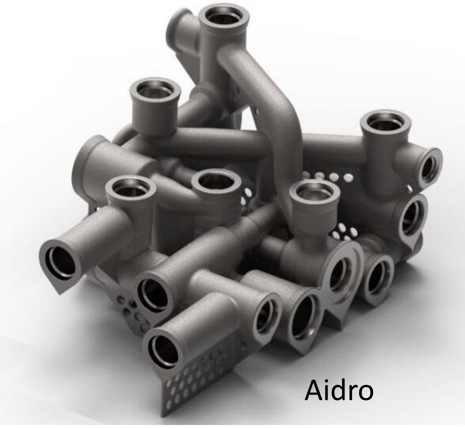
NASA / Aerojet Rocketdyne



Elementum 3D / Mentor

NASA

Cellcore / SLM

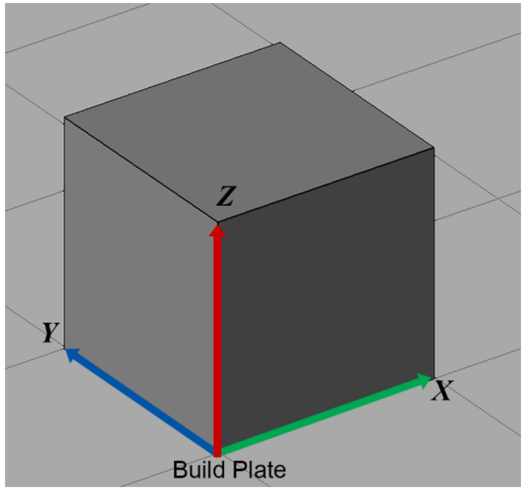


Aidro

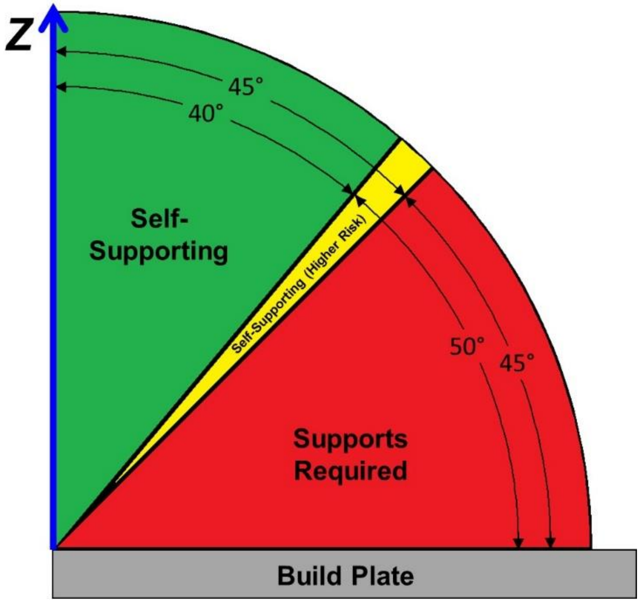
NASA

nTopology

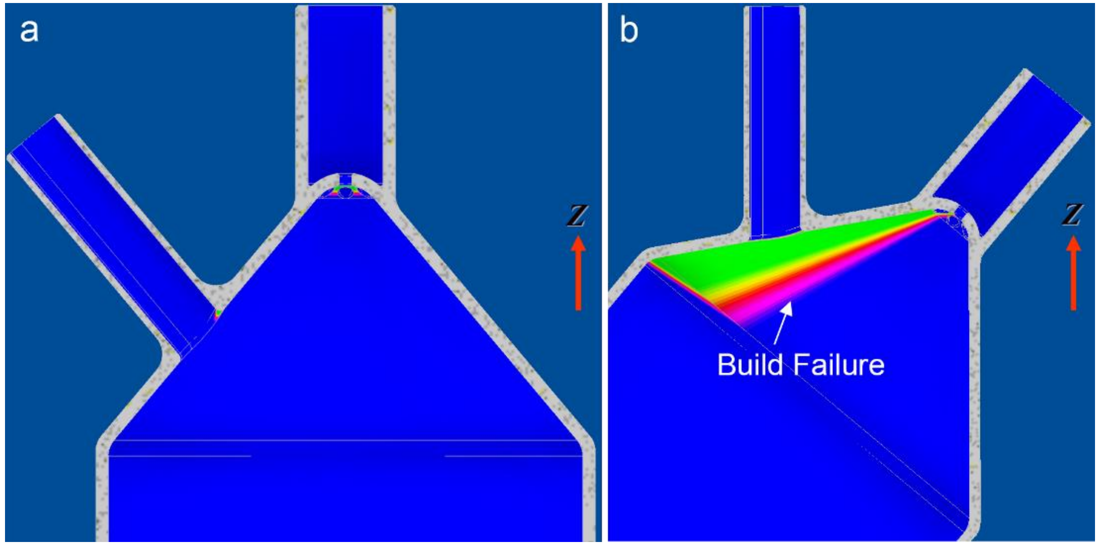
L-PBF DfAM – Coordinates & Overhang Surfaces



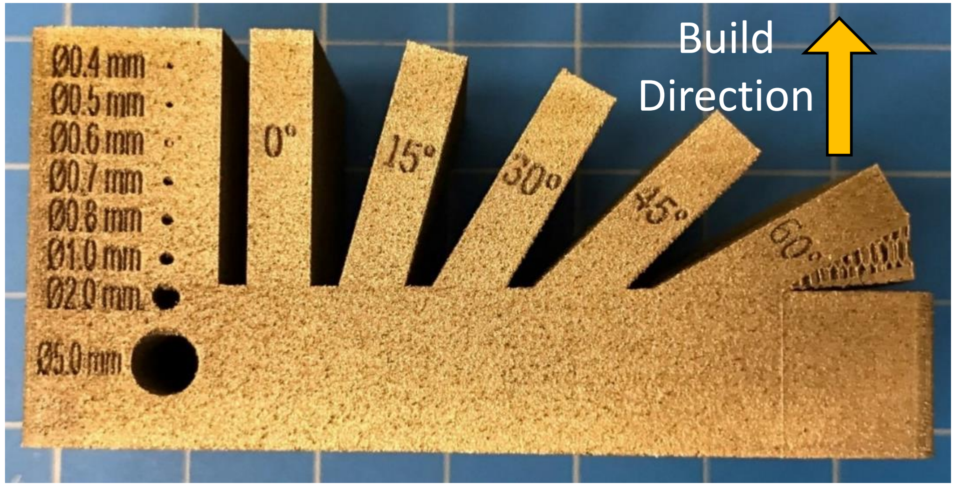
Reference coordinate system



Example of overhang surface region reference to build direction (*Z*)



Unsupported overhang surfaces vs. build direction. a) No unsupported surfaces. b) Unsupported surfaces.

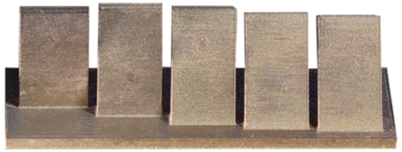


Angle is measured in relation to the build direction, *Z*

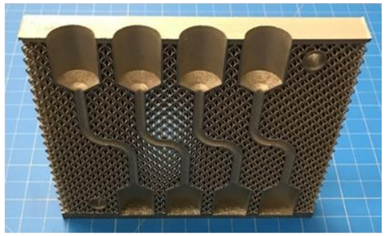
L-PBF Types of AM Features and Standard Build Plates

Test prints are good practice to understand if features feasible


Distance Geometry


Varying Wall Angles

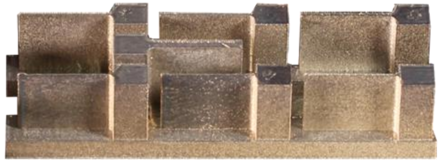

Square Vertical Channels

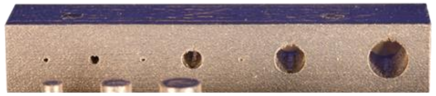

Lattices and Freeform Channels

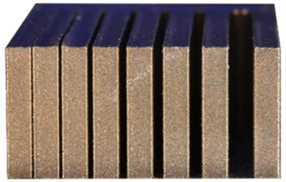

Concentric Hollow Cylinders, Repeating Diameters


Vertical Repeated Holes


Vertical Concentric Holes


Vertical Walls, Varying Thicknesses


Horizontal Holes

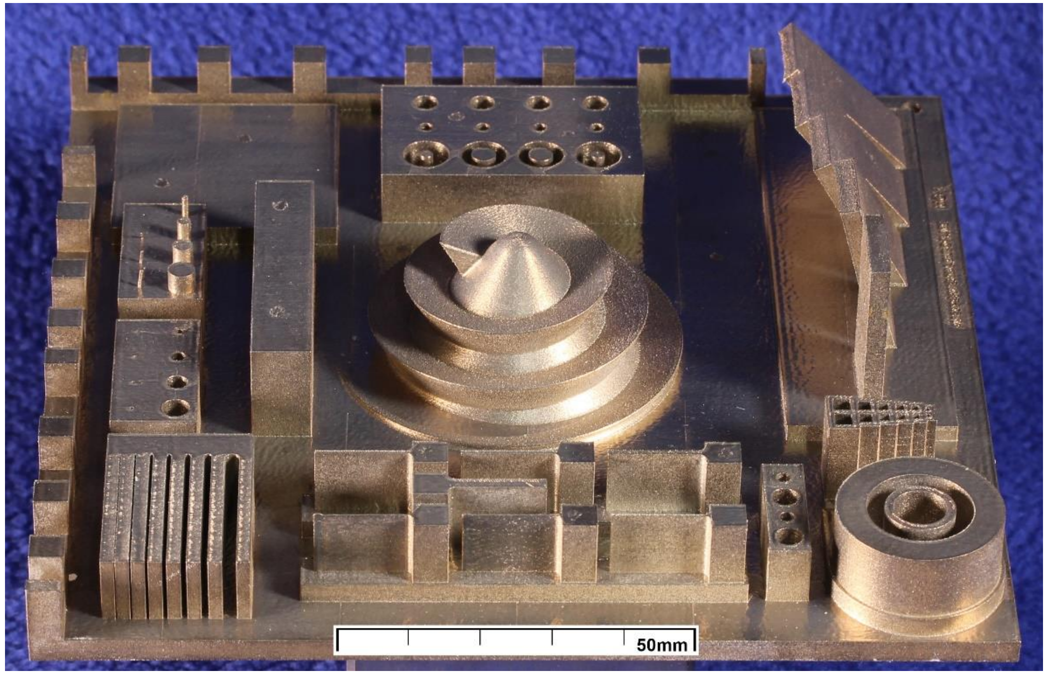

Slot Widths


Vertical Holes

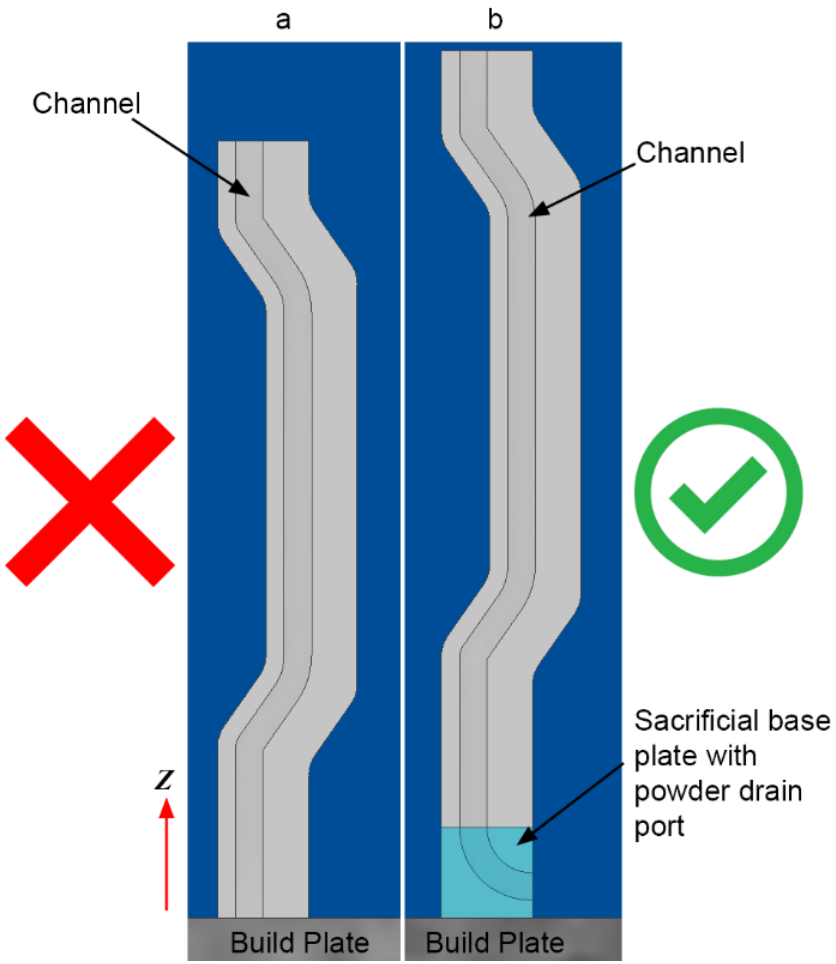

Vertical Protruding Cylinders


Freeform Surfaces

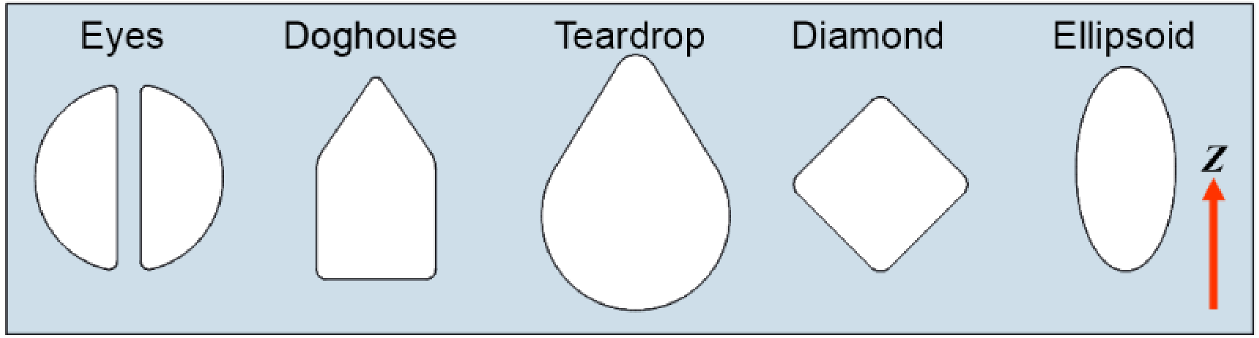

Vertical Repeated Holes



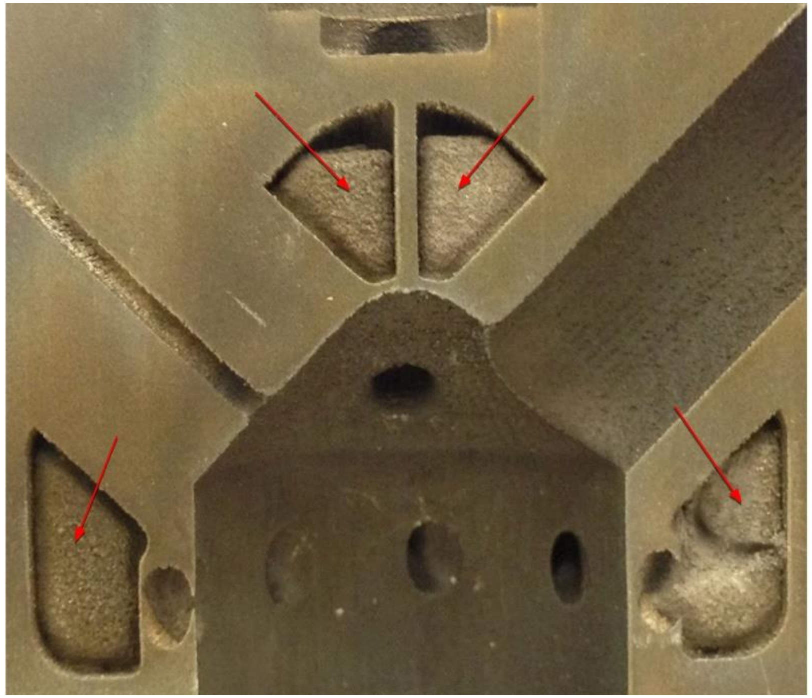
L-PBF DfAM – Holes & Drain Ports



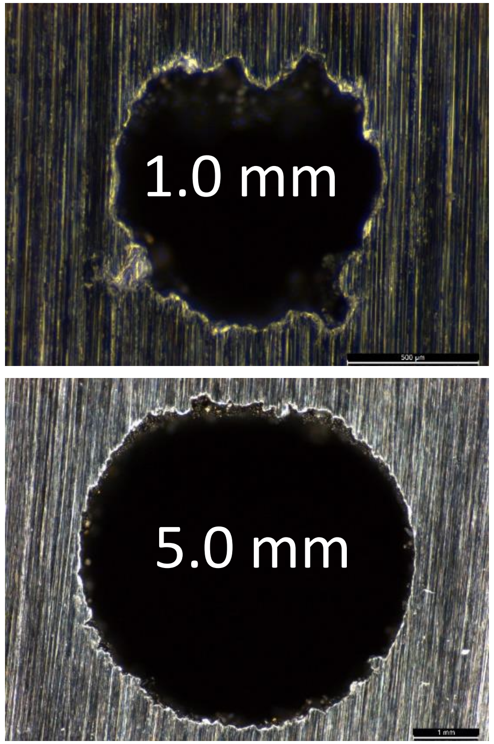
a) Channel terminating at the build plate. b) base plate with powder drain port.



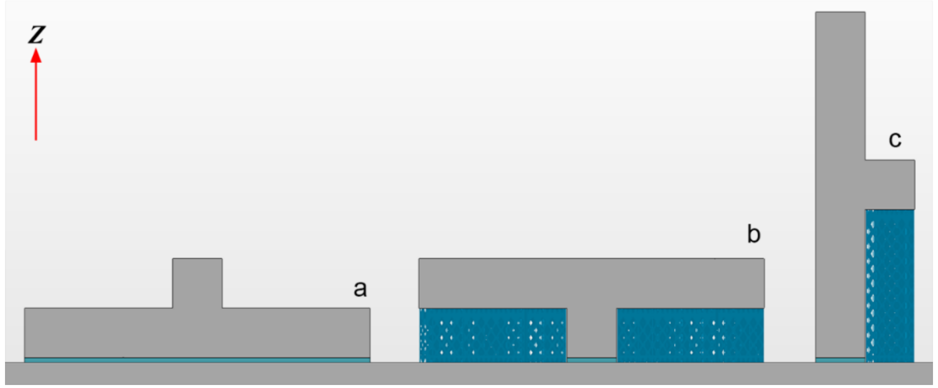
Self-supporting hole geometries.



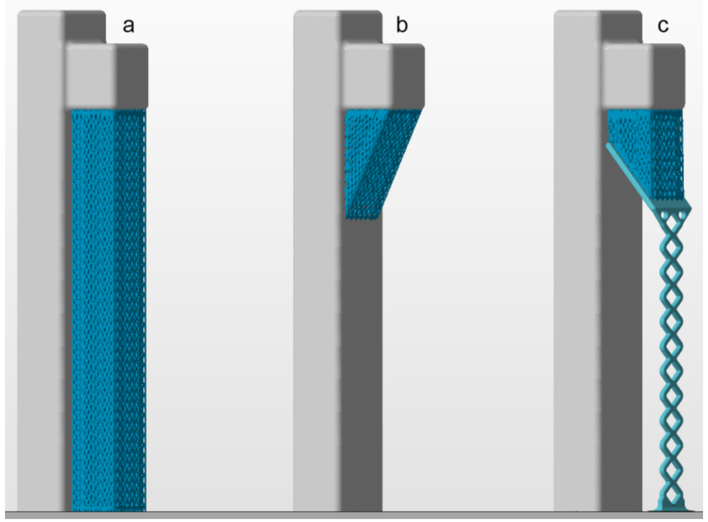
Cross-sectional cut of a part with trapped powder that sintered during stress-relief heat treatment.



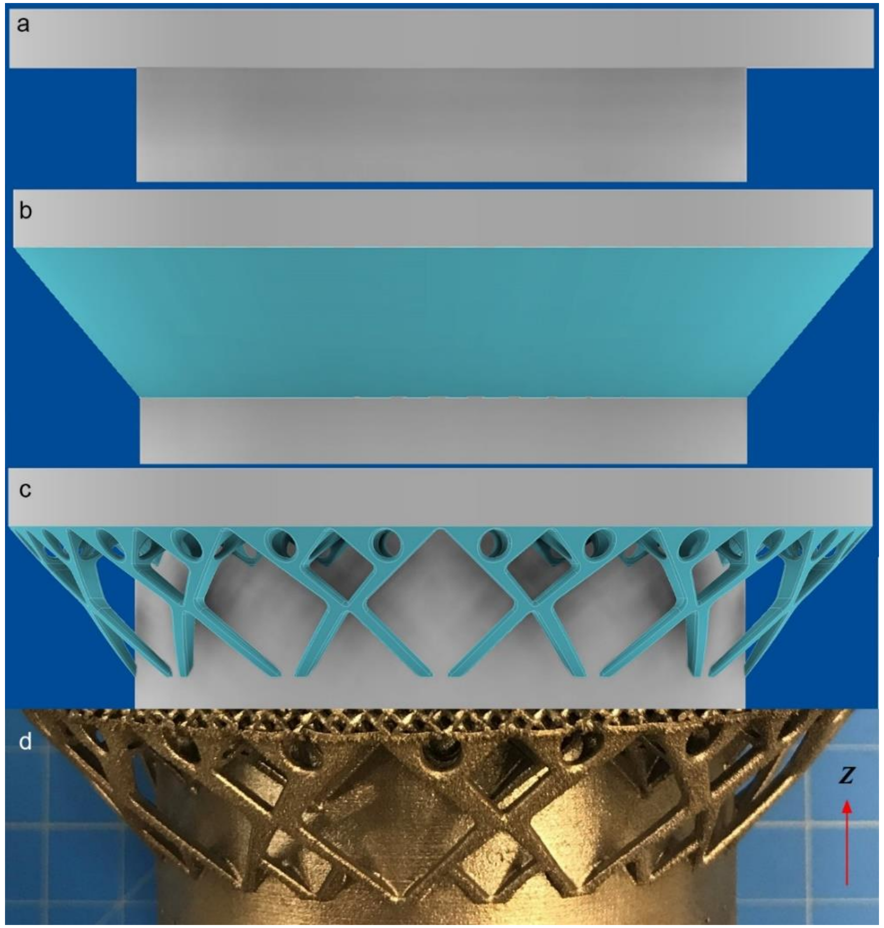
L-PBF DfAM – Supports



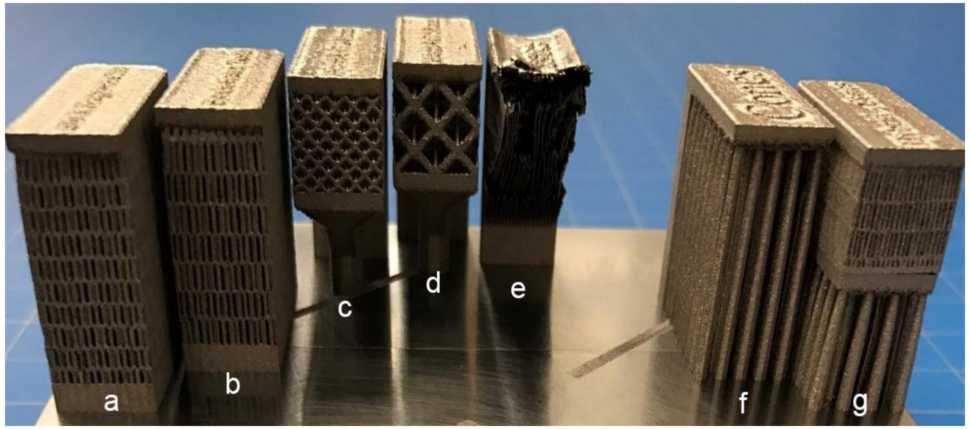
Placement and volume of support structures (blue volumes) are highly dependent on part orientation.



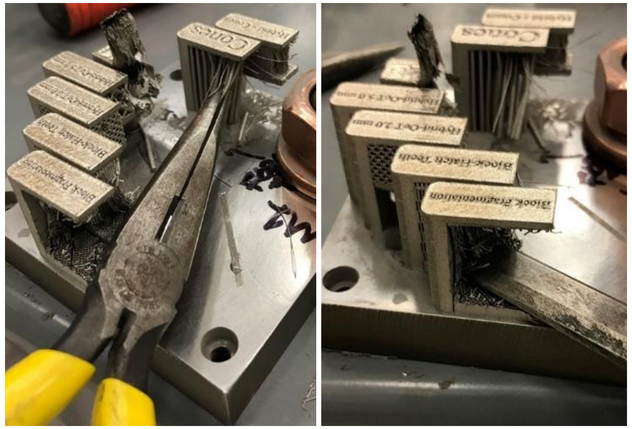
Perforated block supports a) full length, b) 30° angle, and c) projected onto a user designed scaffold.



Comparison of a) unsupported overhang flange, b) 40° sacrificial support, c) crown support, and d) IN718 crown support generated by L-PBF AM.



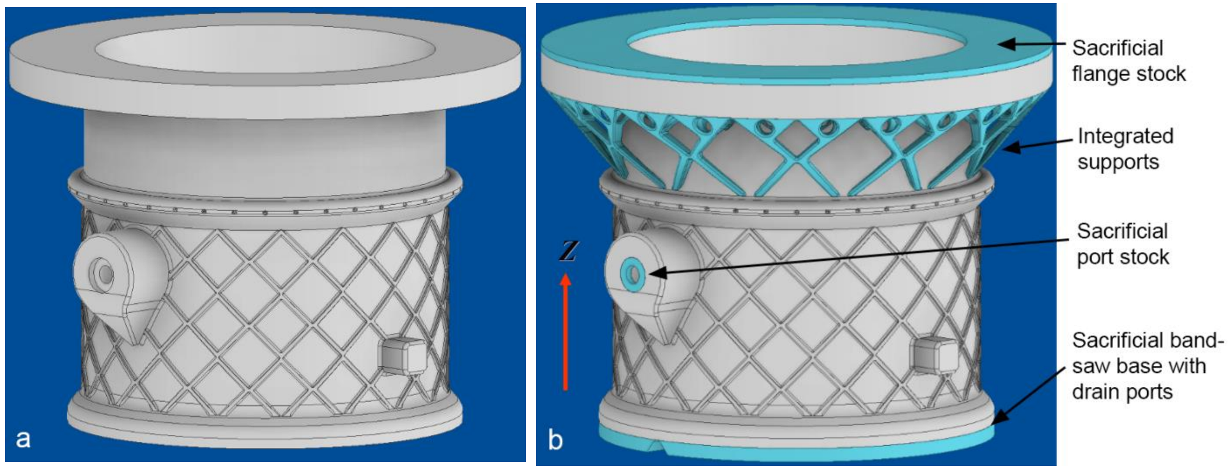
L-PBF AM support structure examples.



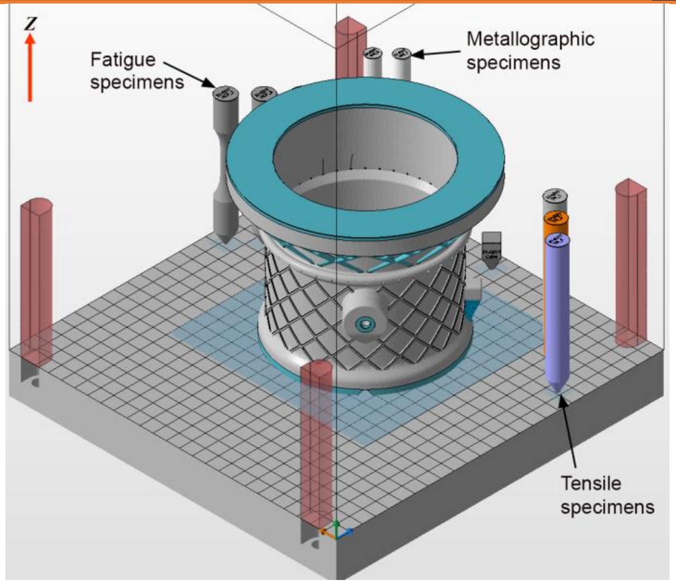
Manual support removal using hand tools.

Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

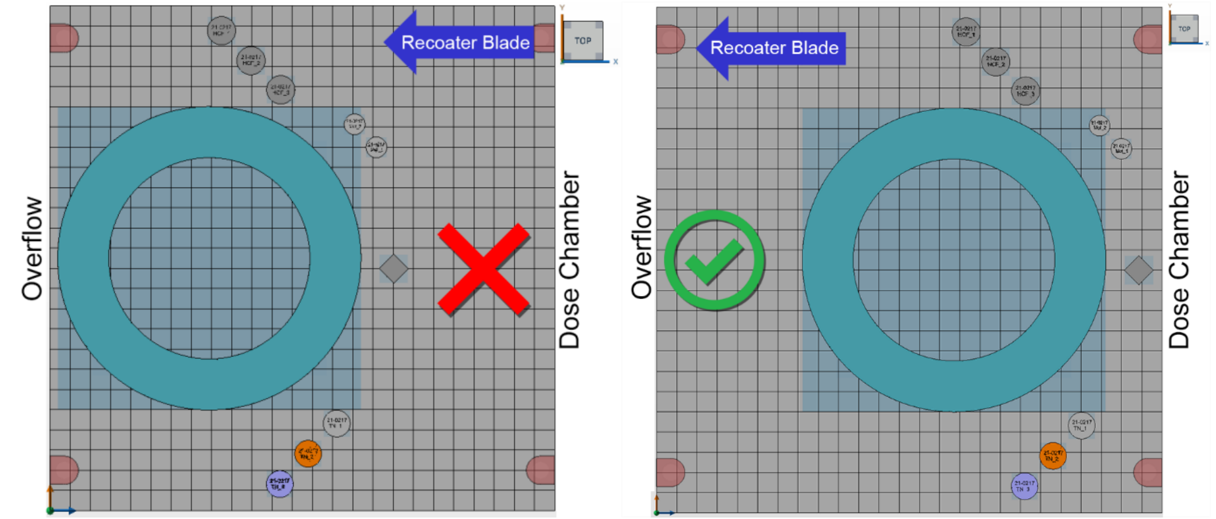
L-PBF DfAM – Case Study



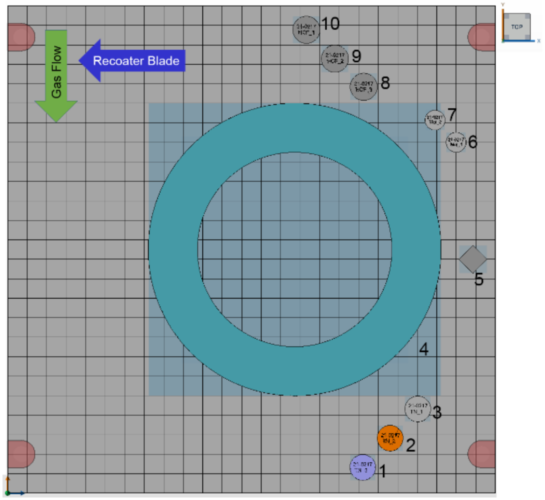
Part a) in final machined condition and b) with integrated supported, stock added to interfaces, and drain ports.



Build layout of part, support structure, and serialized specimens.



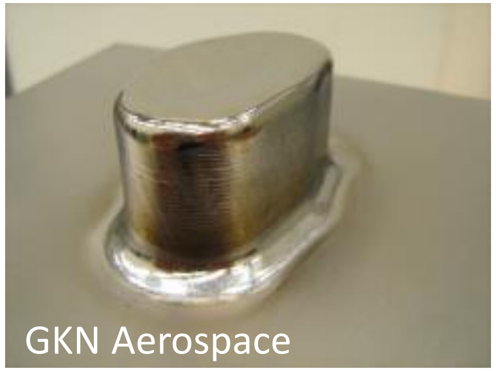
Component placement relative to dose chamber and recoater blade path.



Build layout top view with part positions and scan order optimized.

DED DfAM

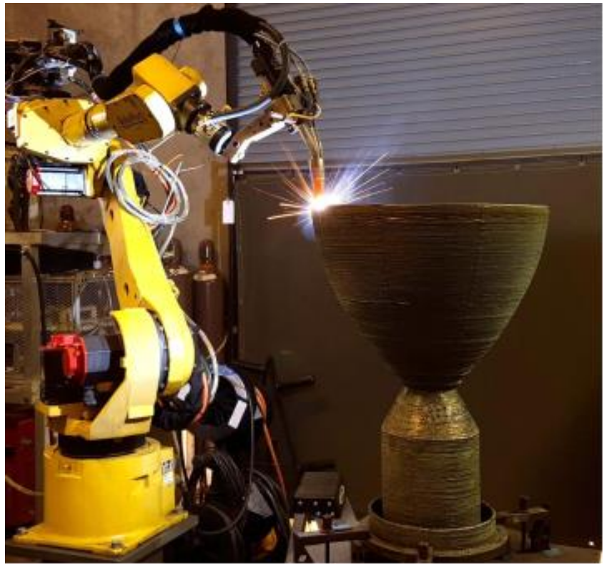
DED DfAM – Examples of Geometries

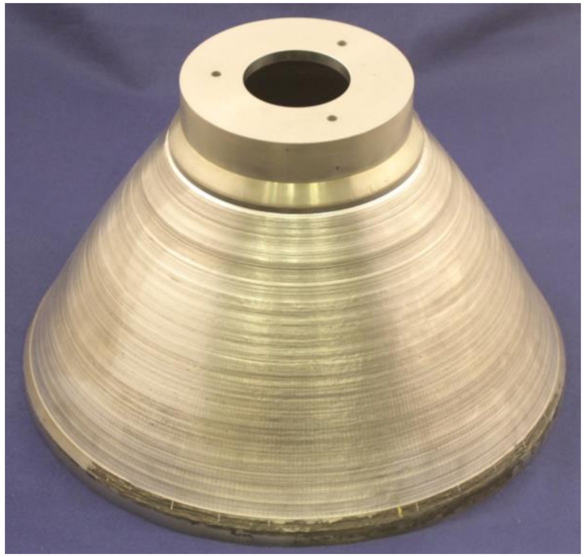


GKN Aerospace

RPMI

DM3D/NASA





DM3D/NASA

RPMI

RPMI/NASA

Freedom in DED design and deposition strategies

Ability to use multiple axes for complex features fabricated locally

RS25 Powerhead demonstrator using LP-DED under NASA SLS Artemis Program (NASA/RPMI)

Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

Design for DED Considerations

Substrate
- Size, Material, Temper
- Integral or Sacrificial?

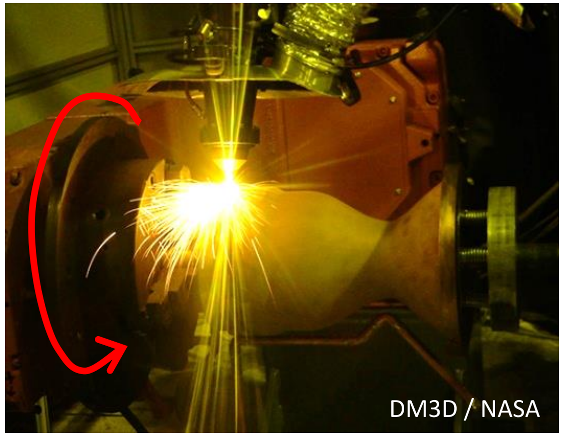
Material
- Chemistry and form
- Material feedstock effect on surface finish

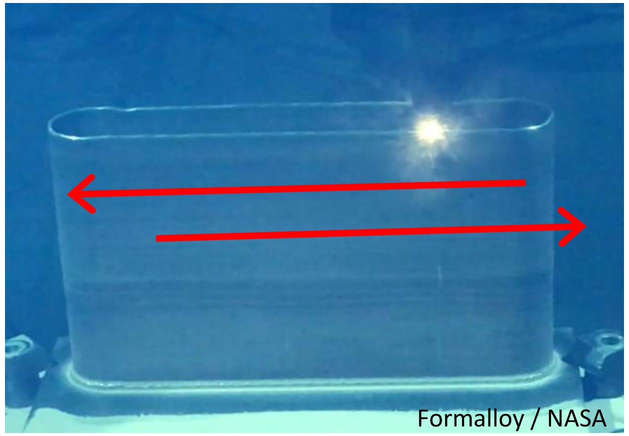
Deposition Strategy and Parameters
- Melt pool size and bead width/height
- Motion platform degrees of freedom and self-supporting angles
- Start / Stop / Transition locations and impact on properties

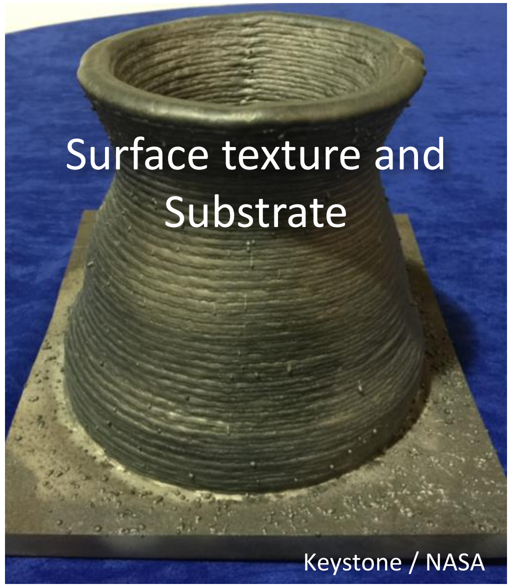
Machining
- Fixturing and datum locations

Inspection
- Surface interface with NDE and/or geometry compatibility

Example: Deposition Strategies

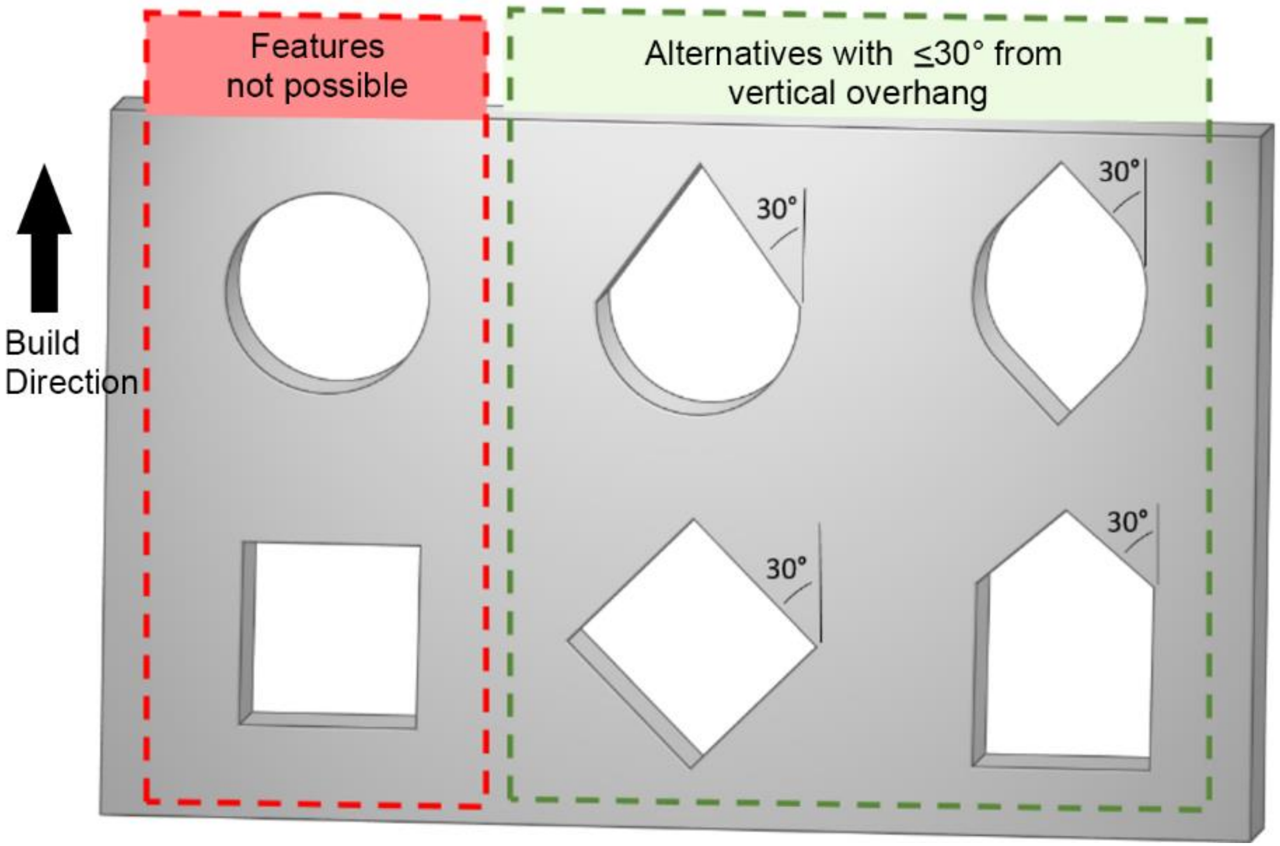


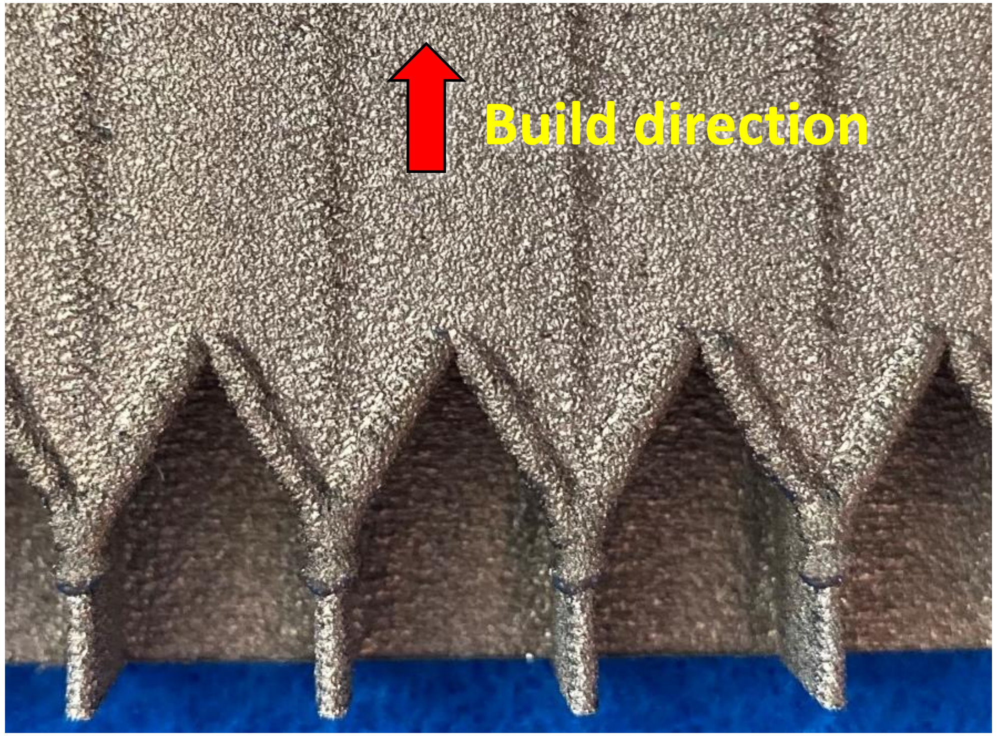




From: Making and Breaking the Rules for DED, Laura Ely and Paul Gradl, ASTM ICAM 2022.

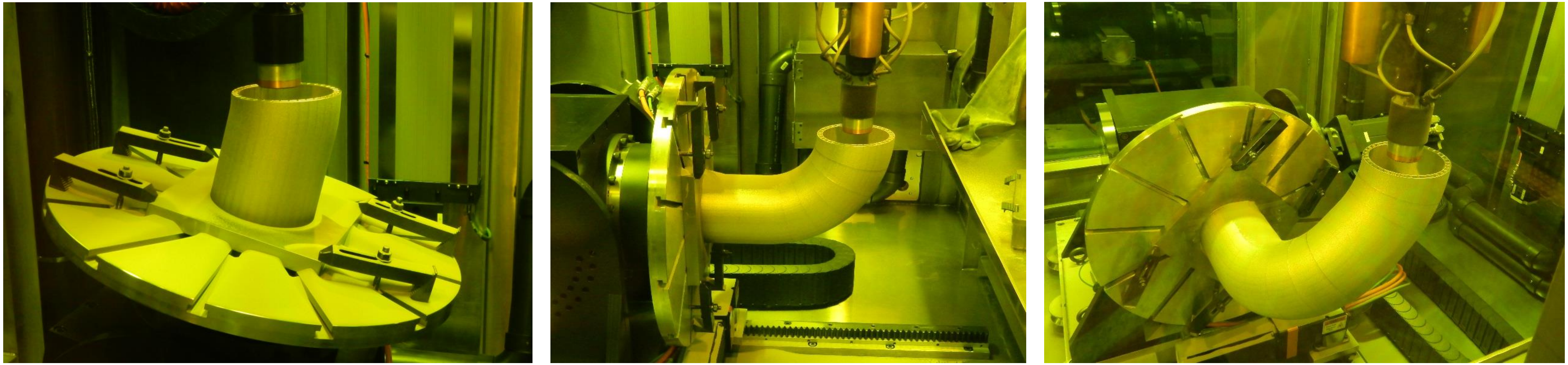
Similar types of holes as L-PBF must be considered when designing for DED



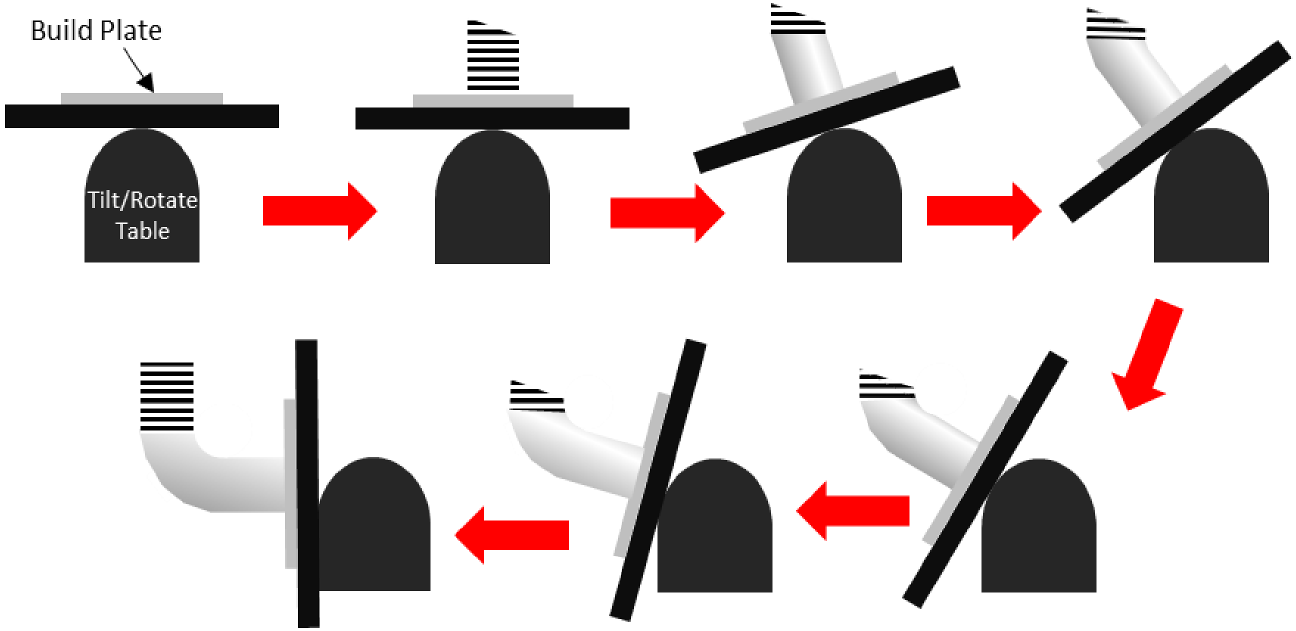


Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

DED DfAM – More axes gives more design freedom



Courtesy: RPMI



Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

Post-Processing – General Process Flow

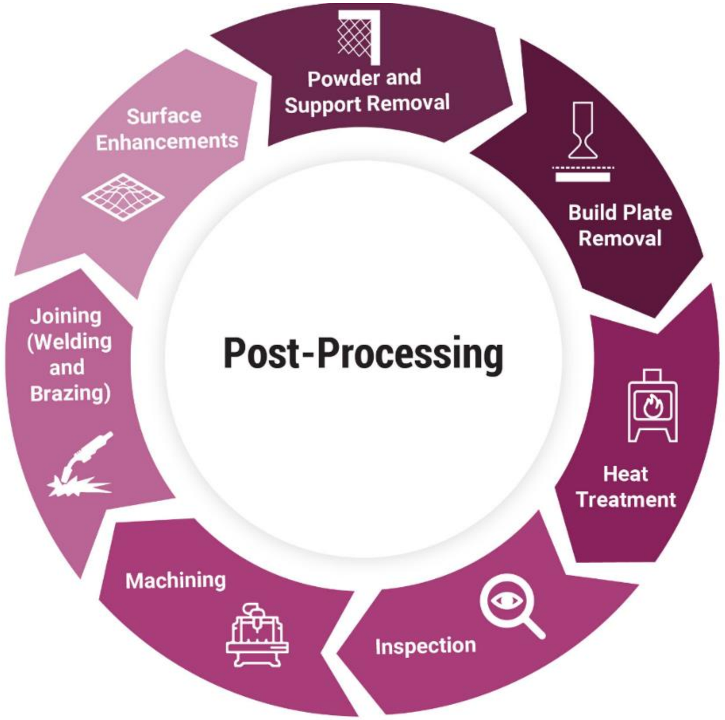
Powder Removal or Part Cleanup → **Support, Build Plate, or Stock Removal** → **Heat Treatments (Thermal Processing)** → **Final Processing and Inspections**

Powder Removal or Part Cleanup
- Powder Removal
- Verification
- Cleaning of Residual Powder

Support, Build Plate, or Stock Removal
- Removal of Supports
- Build Plate Removal
- Excess Stock Removal

Heat Treatments (Thermal Processing)
- Stress Relief
- Hot Isostatic Pressing (HIP)
- Homogenization
- Solutionizing
- Aging

Final Processing and Inspections
- Inspections
- Final Machining
- Polishing
- Welding
- Brazing



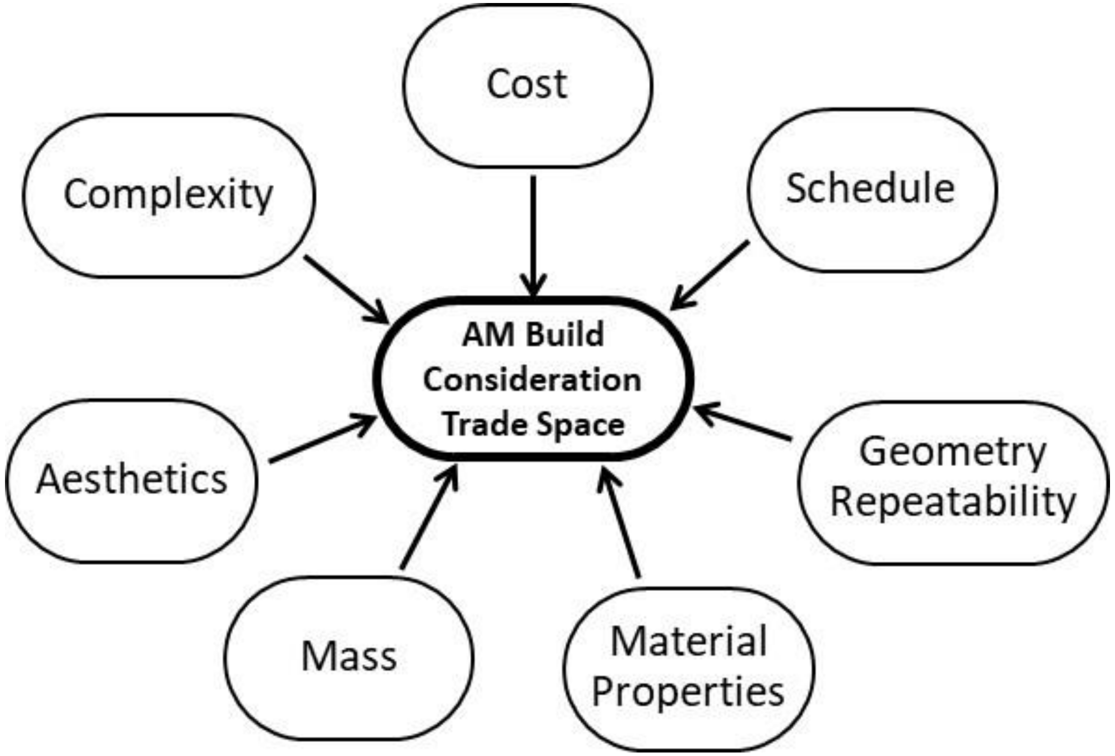
Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

Some Key Questions for Design and Post-Processing

- Are there internal cavities?
- Does the part have drain ports or openings to allow for powder removal?
- What technique(s) will be used for powder removal?
- How is powder removal verified?
- Will a support structure be used in the build or designed into the part?
- Are there downstream operations that require fixtures or tooling to integrate in the design?
- What type of distortion might be expected from the process and how can one properly design for it?
- How is the part removed from the build plate?
- What forces are being imparted during post-processing operations?
- Are adequate stock and proper datums included for part removal and post-machining?
- What kind of post-process machining, welding, brazing, or assembly needs to occur after the print?
- Does the part incorporate the correct welding or brazing joint design?
- What heat treatments are required, and what risk do they pose to the part?
- What is the proper sequence of heat treatments?
- What material properties are required for the end-use application?
- What inspections (full or partial, volumetric, surface, geometric) are required to verify integrity?
- Is the design conducive to these inspections?
- What surface texture is needed for the final application? [i.e. 2D directional roughness (Ra), average maximum profile height (Rz), average maximum valley depth (Rv), average areal roughness (Sa), surface maximum height (Sz), surface skewness (Ssk), directional waviness (Wa).]
- Are surface finish requirements uniform across the part or limited to specific locations (e.g., interfaces)?

“Post-processing” is really “the process”

To successfully build parts to integrate into a system and meet the properties required, post-processing is required



Post-Processing	Process Step	Resultant Application
Heat Treatment	HIP, Solution, Annealing, Aging	Mechanical properties, thermophysical properties, high density, grain uniformity, etc.
Surface Finishing	Chemical Milling, Abrasive Flow Machining, Chemical Mechanical Polishing, Mechanical Honing	Aesthetics, pressure drop, mass flow alteration, fatigue life, corrosion resistance, etc.
Condition	Final Machining, Joining, Cleaning, Inspection	Geometric dimensioning and tolerancing (GD&T), exposure to environment, integration with subsystem, quality Improvement, etc.

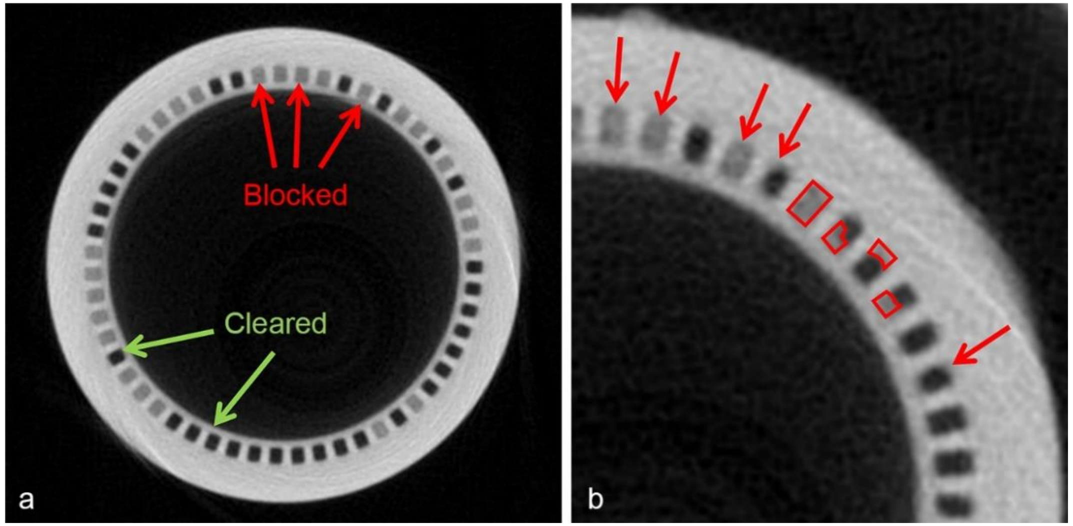
Post-Processing Summary

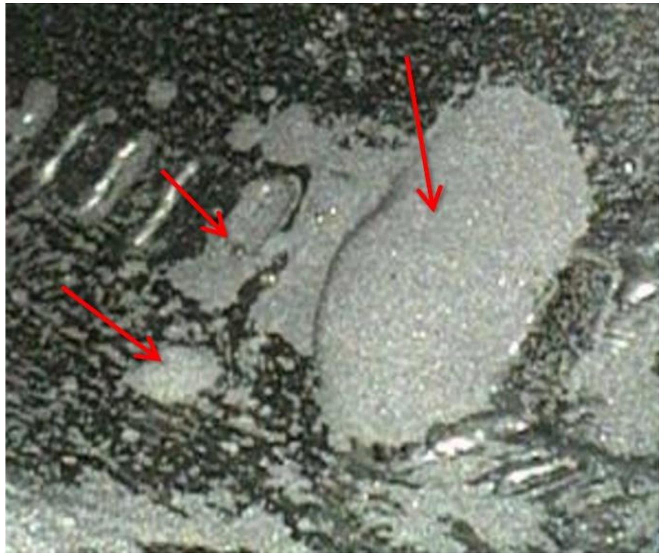
	Powder Removal and Verification	Support Removal*	Stress Relief**	Build Plate Removal	Heat Treatment Required?	Post-Curing	Final Machining ***
Laser Powder Bed Fusion (L-PBF)	Y	Y	Y	Y	Y	N	O
Electron Beam Powder Bed Fusion (EB-PBF)	Y	Y	N	Y	Y	N	O
Blown Powder Directed Energy Deposition (BP-DED)	Y	Y	Y	Y	Y	N	Y
Arc-Deposition DED	N	N	Y	Y	Y	N	Y
Laser Hot-wire DED	N	N	Y	Y	Y	N	Y
Electron Beam DED	N	N	Y	Y	Y	N	Y
Laser Wire DED	N	N	Y	Y	Y	N	Y
Ultrasonic	N	N	N	N	O	N	Y
Friction Stir	N	N	N	N	O	N	Y
Coldspray	N	N	N	Y	O	N	Y
Binder Jet	Y	O	N	N	Y	Y	O

Y = Requires operation
N = Does not require
O = May Require

Is powder removed? ...Are you sure?

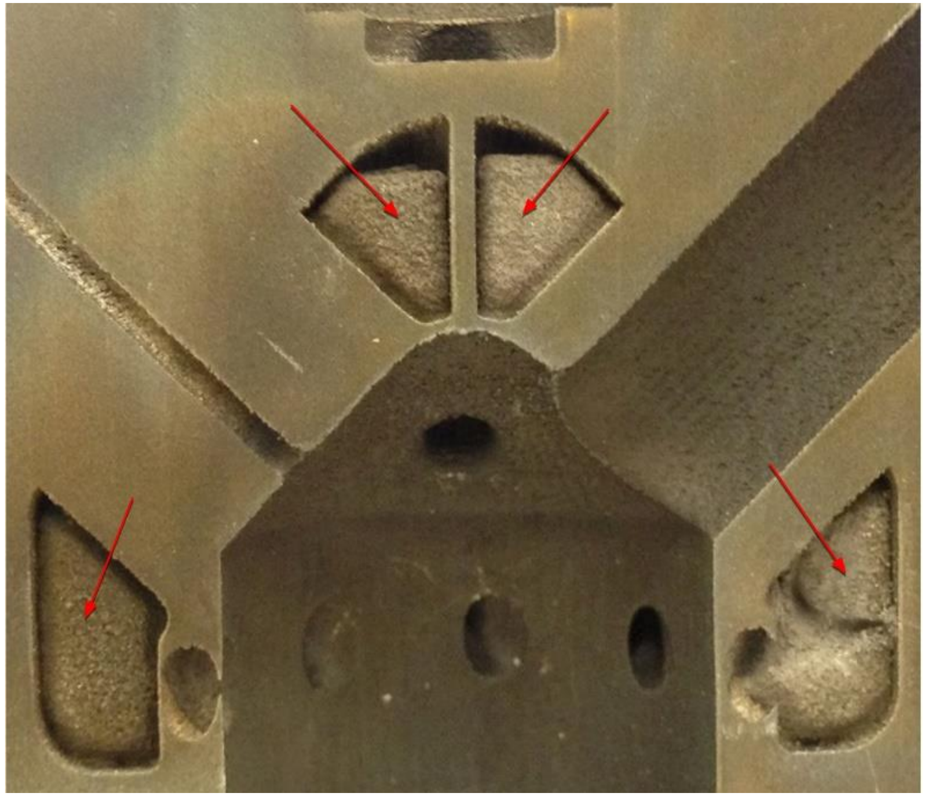
Powder observed in channels after CT





Borescope inspection of internal features

Internal cavities with sintered powder after stress relief – not properly designed for removal



Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

Table 5.2: NDE Applications and Limitations

+, strong capability; 0, limited capability; -, no capability

Method	Metrology	Surface defects	Volumetric defects	Main strength	Main weakness
Visual inspection	0	0	–	Quick check for major problems	No quantitative measurements
Coordinate measurement machine (CMM)	+	–	–	Allows for dimensional inspections	No internal characterization; does not allow for detailed surface characterization
Laser profilometry	+	0	–	Characterize roughness	No internal characterization
Structured light scanning	+	0	–	Check dimensions, generate three-dimensional model	No internal characterization

(continued)

Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

Courtesy: Erin Lanigan / NASA MSFC

Nondestructive Evaluation (NDE): Flaws

Table 5.2: NDE Applications and Limitations

+, strong capability; 0, limited capability; -, no capability

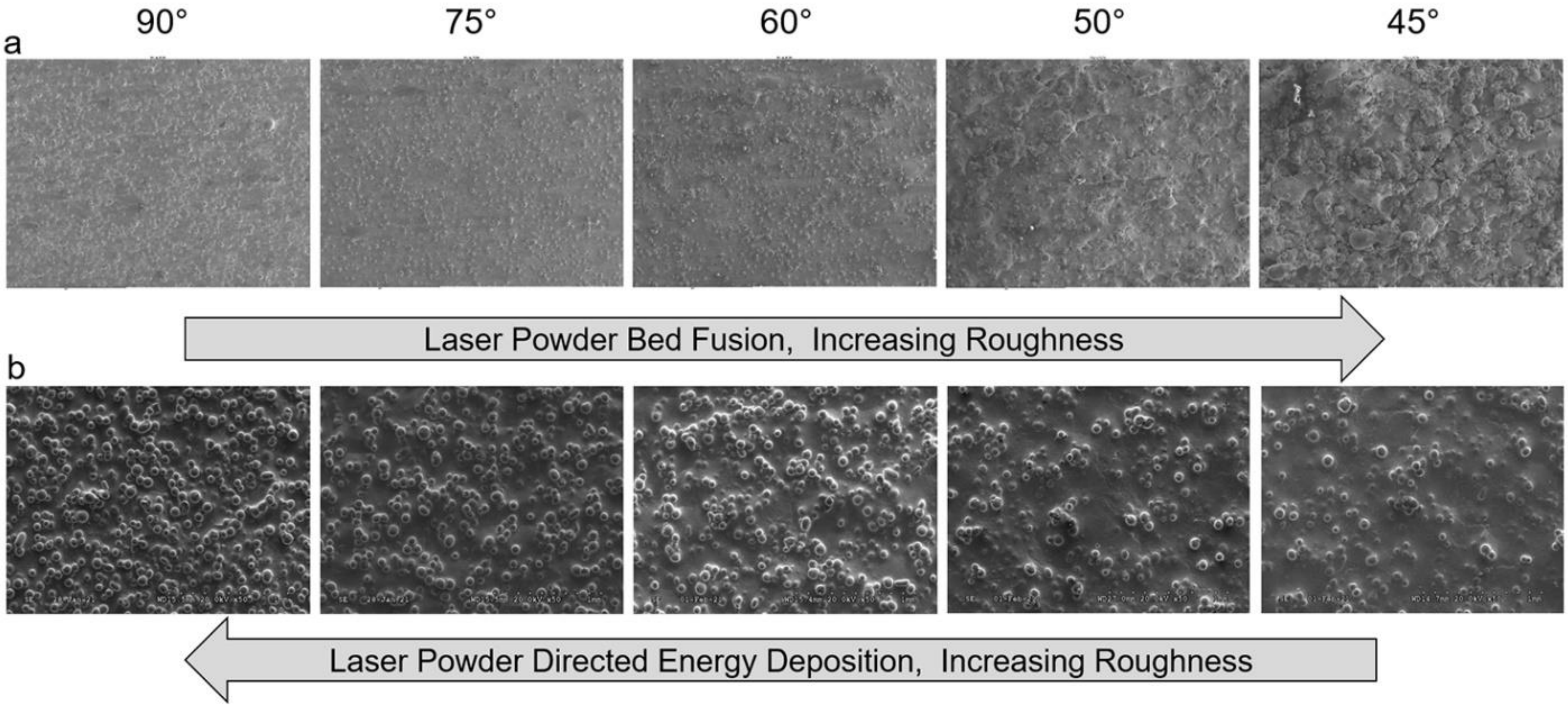
(continued)

Method	Metrology	Surface defects	Volumetric defects	Main strength	Main weakness
Radiography	0	0	+	Volumetric defects, changes in density	Interpreting complexity, detecting tight cracks
CT	+	0	+	Three-dimensional reconstruction of volumetric defects	Characterizing surface, detecting tight cracks
Ultrasonic inspection	–	0	+	Volumetric defects, linear defects	Surface access, quality changes, defect detection varies with depth
Dye penetrant	–	+	–	Surface-breaking defects, cracks	Requires smooth as-built surface or machining
Eddy current	–	+	0	Surface and near-surface (subsurface) defects	Limited to electrically conductive materials
Magnetic particle inspection	–	0	–	Surface defects	Limited to ferromagnetic materials, smooth surface
Thermography	–	0	0	Surface and subsurface defects	Interpreting complexity, limited depth
Resonance	–	0	0	Overall defect state, part comparisons	Locating defects, understanding extent

Courtesy: Erin Lanigan / NASA MSFC

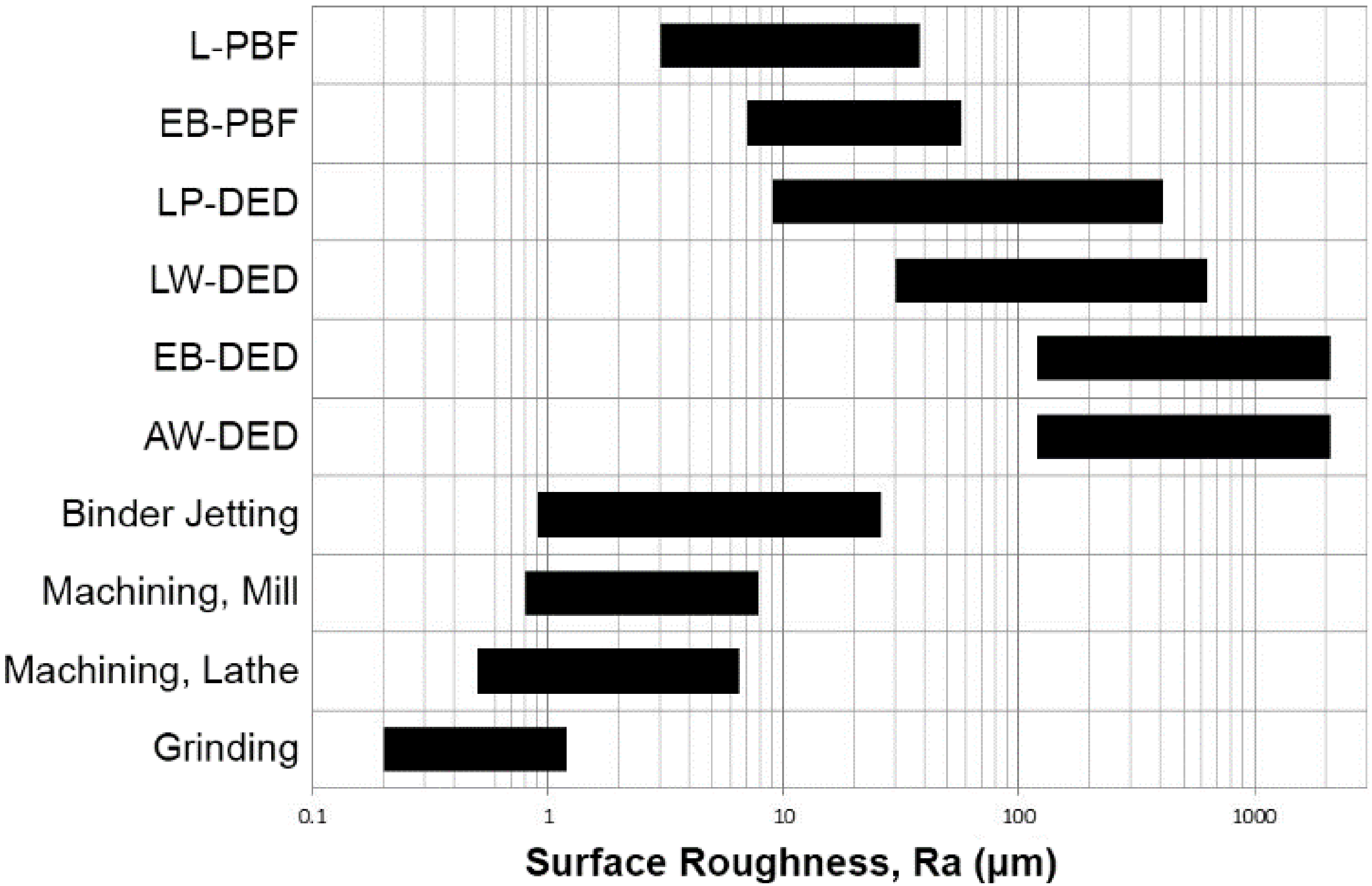
Surface Texture of AM

Surface texture (waviness, roughness, form) varies based on build process and build orientation



Gradl, P., Cervone, A., Colonna, P., 2023. Influence of build angles on thin-wall geometry and surface texture in laser powder directed energy deposition. Materials & Design 234, 112352. https://doi.org/10.1016/j.matdes.2023.112352

Surface Conditions from different processes



Caveat: Surface condition highly variable based on process, material, parameters, build orientation

Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

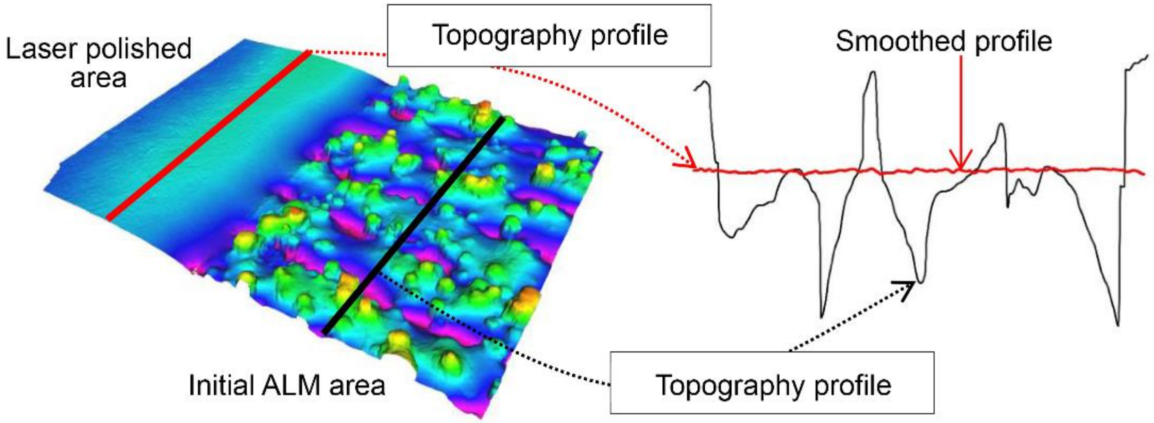
Surface Enhancements and Polishing

	Polishing feature applicability	
Process	**External surfaces**	**Internal surfaces**
In-process smoothing (contours)	+	+
Chemical milling	+	+
Chemical Mechanical Polishing	+	+
Abrasive flow machining	+	+
Media suspension methods	+	–
Dissolvable / surface sensitization	+	0
Powder enhanced slurry plating	0	0
Electrochemical machining (ECM) or electropolishing (EP)	+	0
Secondary laser polishing (in-process or post)	+	–
Manual polishing (honing, buffing, burnishing)	+	–
Grit blasting	+	–
Thermal deburring	–	–
Coatings	+	0
Peening methods	+	–
Magnetic abrasive finishing (MAF)	0	+

Note: +, potential for maturation and/or demonstrated; –, significant challenges exist; 0, unknown and further development required.

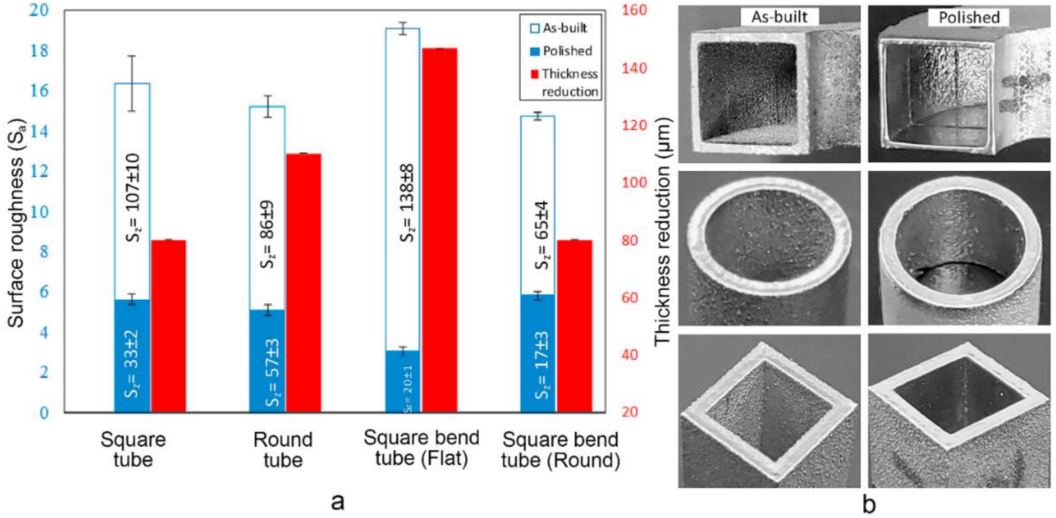
Surface Enhancements

Laser polishing

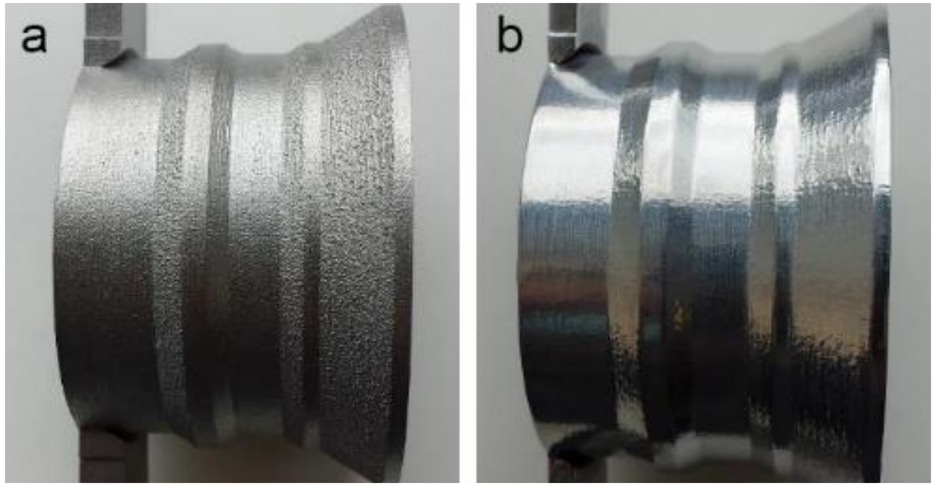


- As-built
- Chemically Milled
- Electrochemical Machining
- Chemical Mechanical Polishing

Electrochemical Polishing



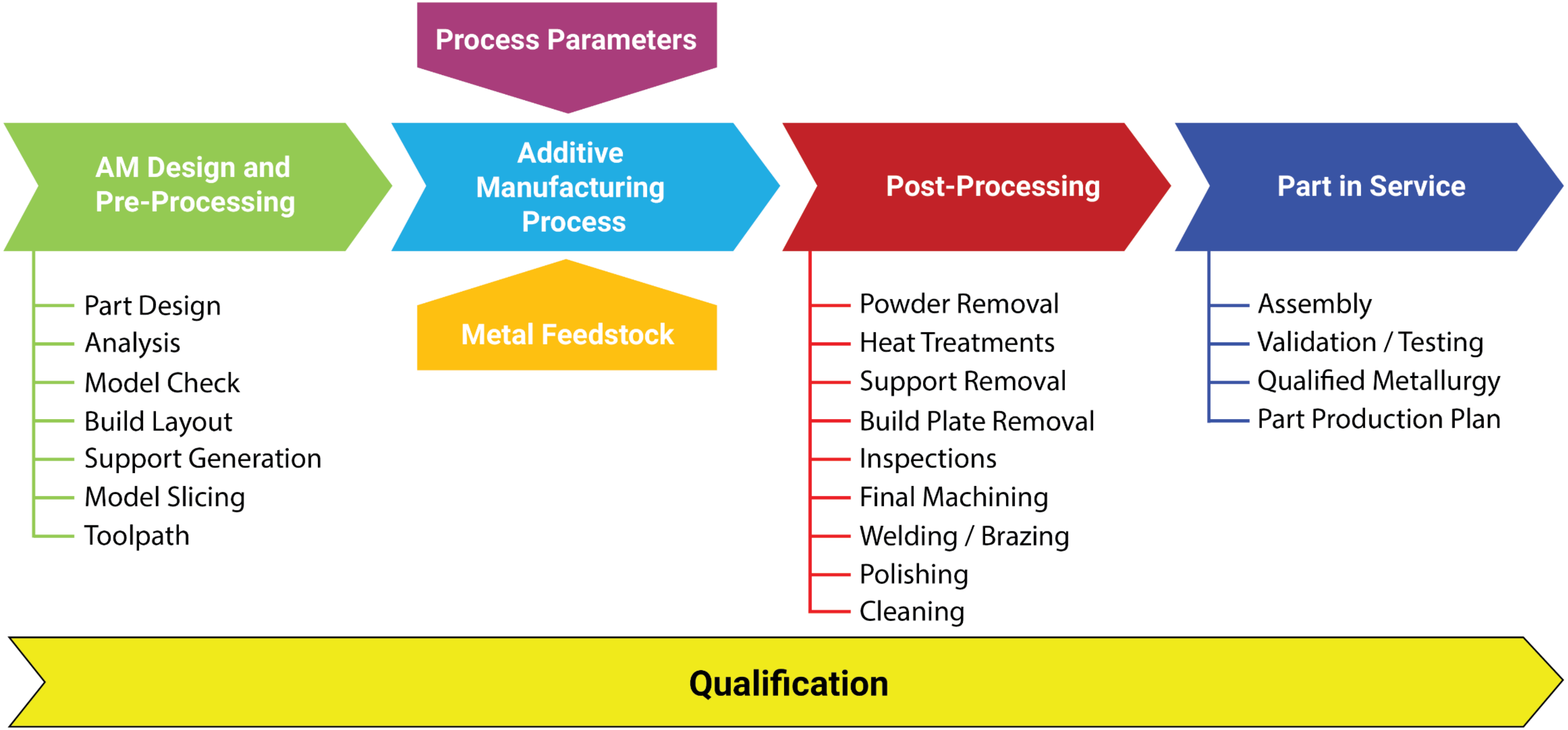
Abrasive Flow Machining



Feedstock and Post-build Processing Summary

- Feedstock is critical and all aspects should be carefully tracked (chemistry, size distribution, flowability, morphology, reuse, etc).
- Post-processing is just part of the process and will be necessary for most all components.
- Post-processing must be planned for in the initial design stage.
  - Powder unpacking
  - Powder removal and cleaning
  - Build plate and support removal
  - Heat treatments
  - Machining
  - Cleaning
  - Joining (Welding, brazing and diffusion bonding)
  - Inspections and NDE
  - Surface enhancements (or polishing techniques)

Design for Additive Manufacturing (DfAM)



Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

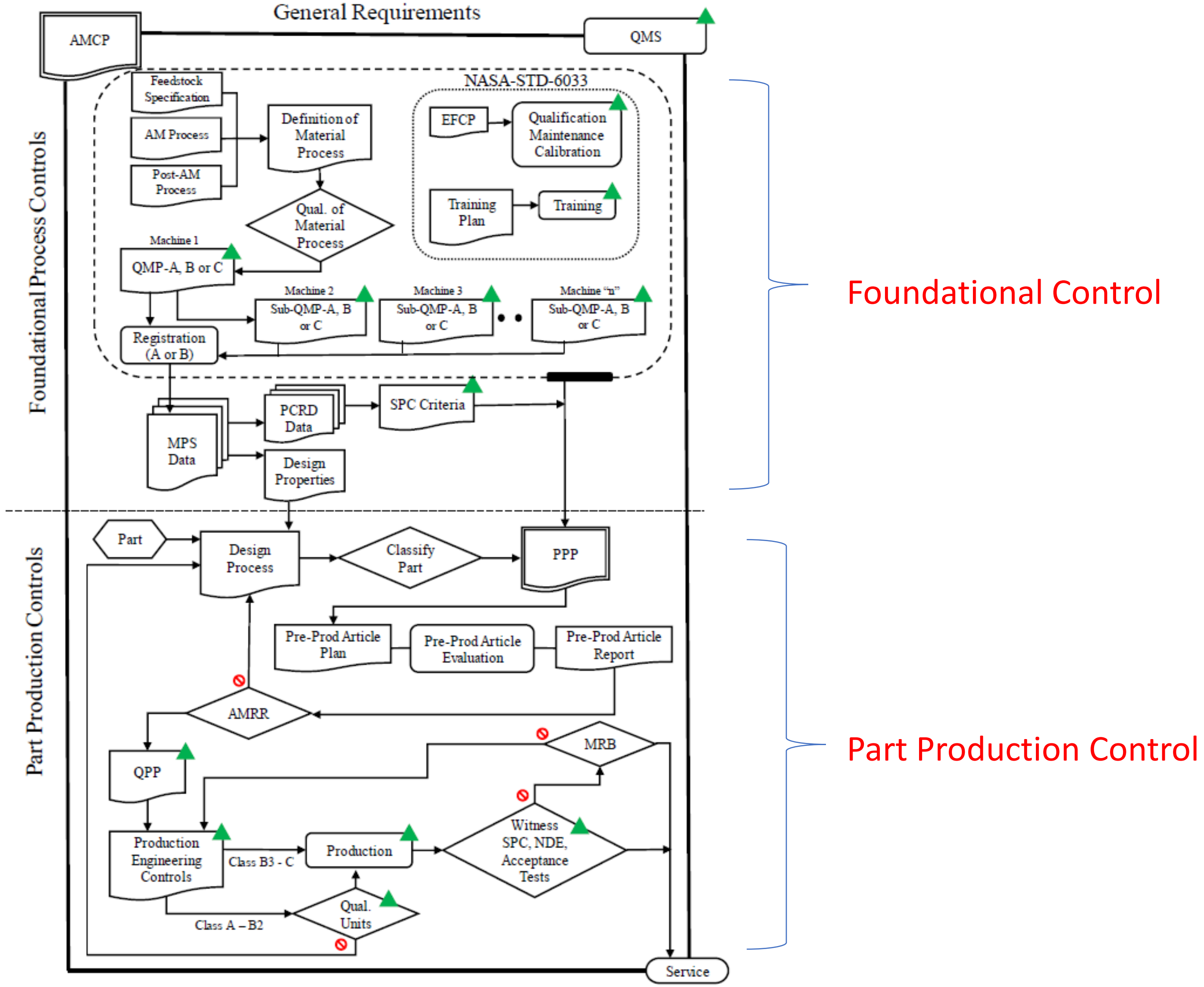
Qualification – Framework of 6030 Requirements

What should I worry about?

How should I define and control them?

Who and When should work them?

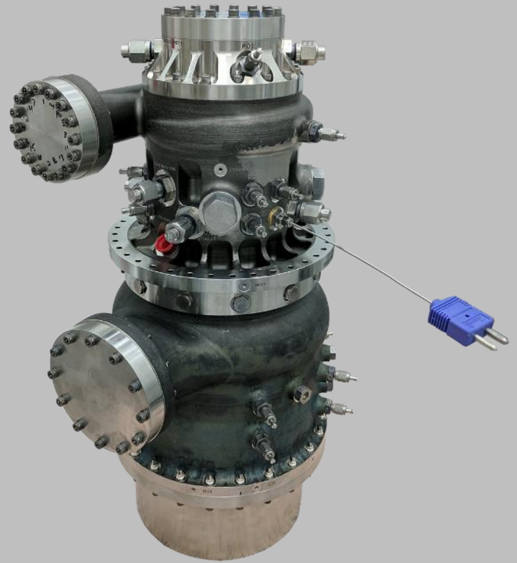
How NASA should be aware and approve of them?



115 "shall" requirement statements in 6030; 31 "shall" statements in 6033

Qualification and Certification (based on NASA)

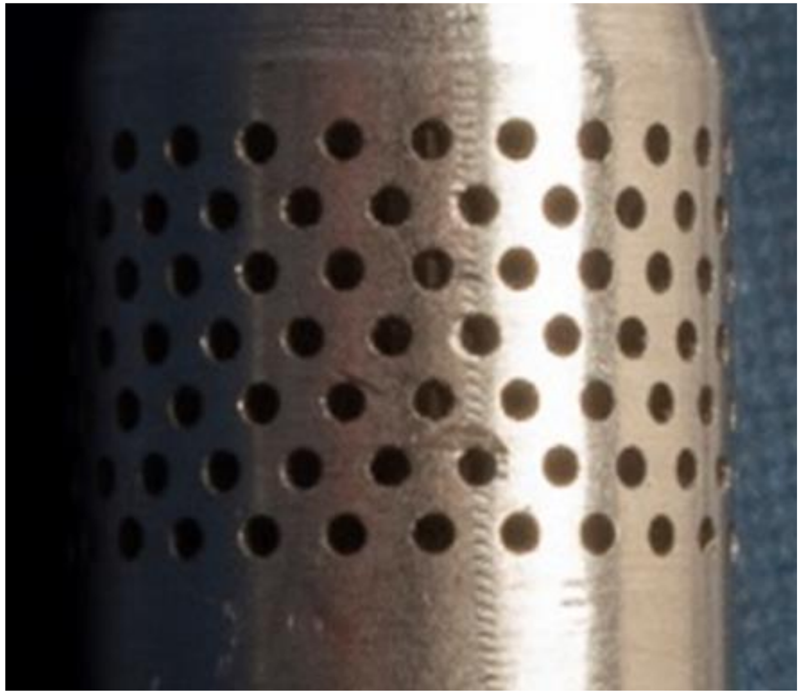
- Define a manageable, systematic, and consistent approach to AM to allow the Agency to evaluate risk and make consistent decisions regarding the certification of designs and hardware.
- Integrate the AM process in a manner compatible with existing governing Agency standards.
- Enforce discipline and systematic rigor throughout the AM process, from design to part.
- Avoid defining the specifics of AM processes; instead define methodologies for qualifying and controlling the processes.
- Accommodate the use of internal and open industry standards as appropriate.
- Provide NASA with opportunities for insight to gauge quality, completeness, and rigor through a well-defined and predictable set of reviewable products governing the AM process.



Select Application Case Studies

Case Study #1 – Fine Features

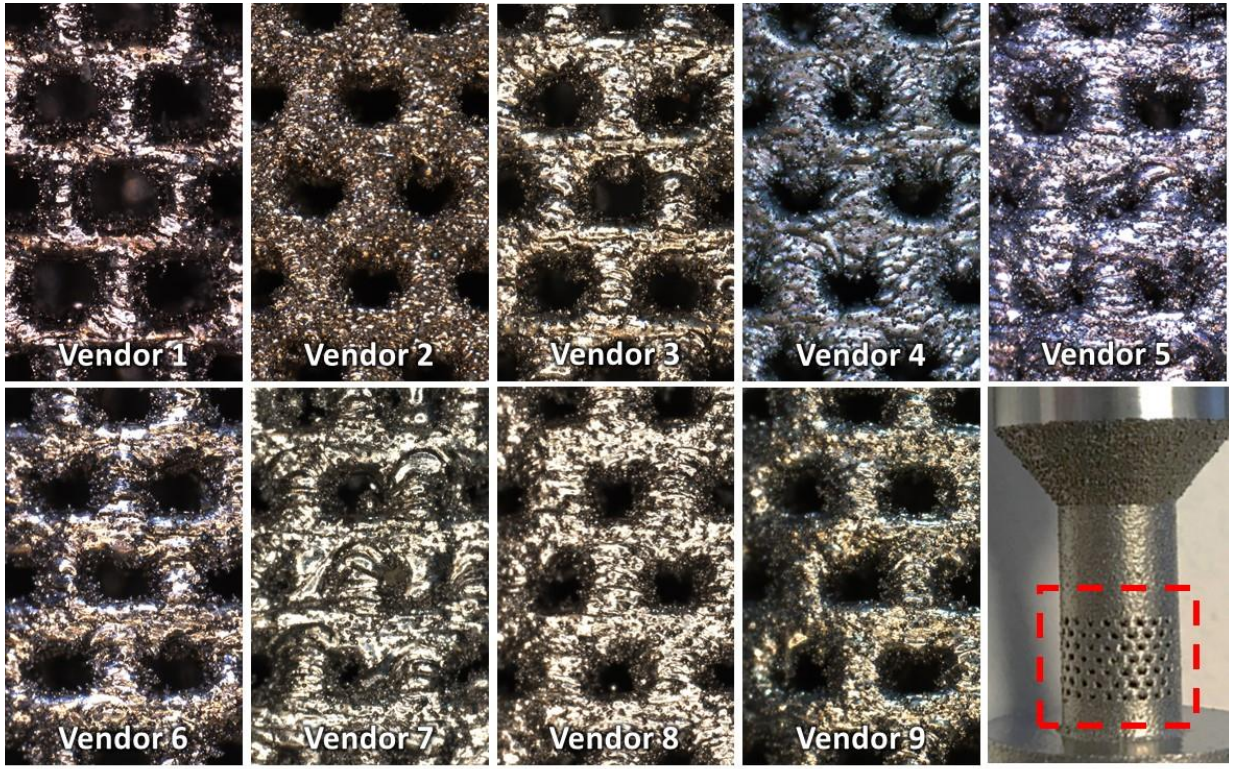
- Single element injector
- 168 small radial filter holes per element
- Built by 9 commercial vendors using the same model in 2019

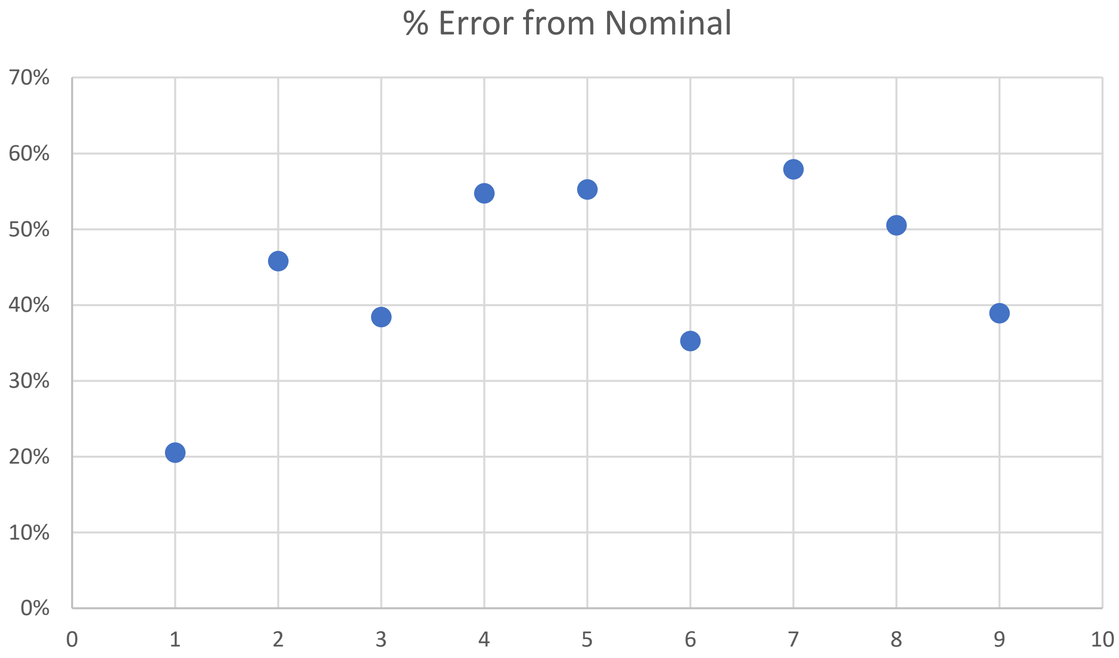


A traditionally machined sleeve filter used as baseline

Case Study #1

Error from nine vendors ranged from 21% to 55%





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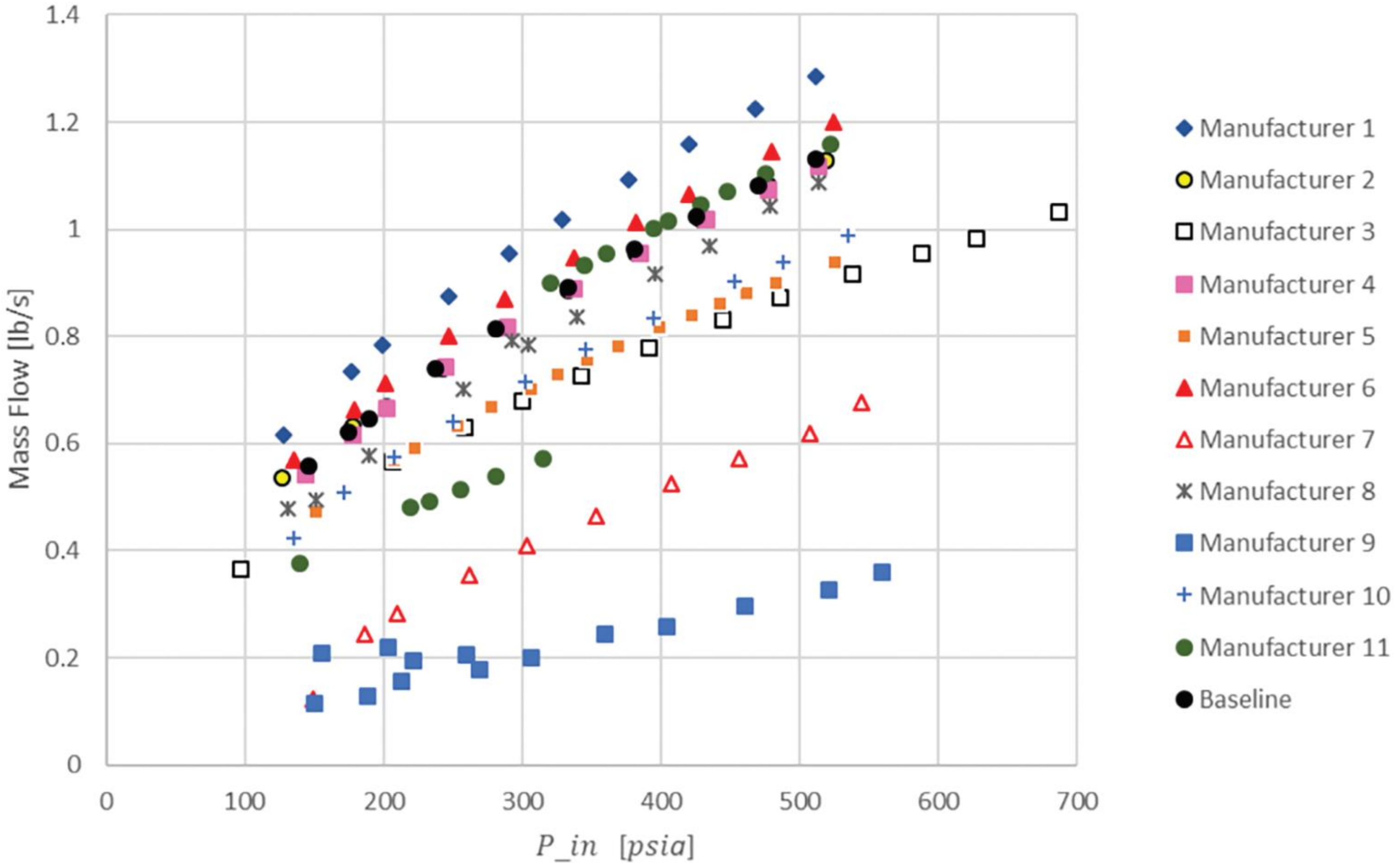
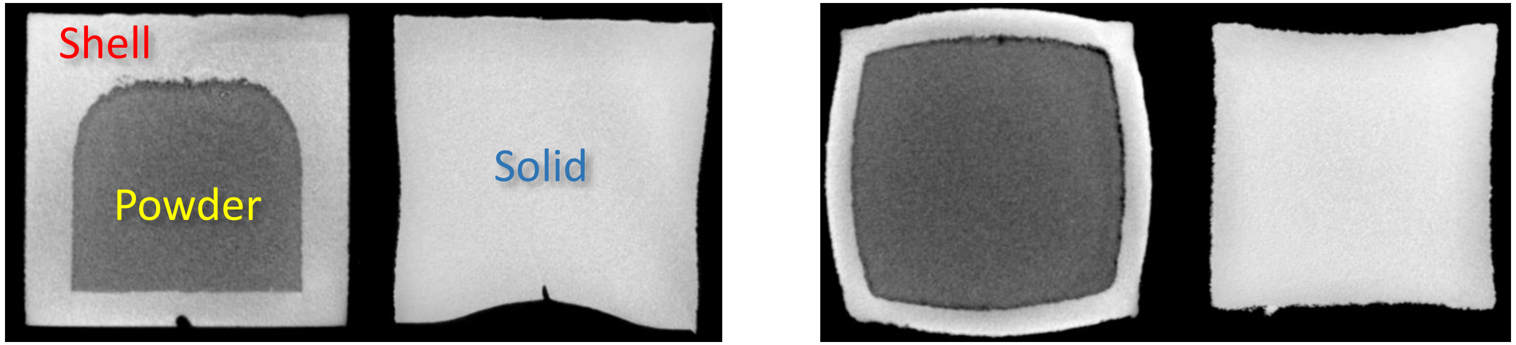
Case Study #1

Water mass flow rate of the fuel circuit for 11 AM elements with comparison to baseline injector element

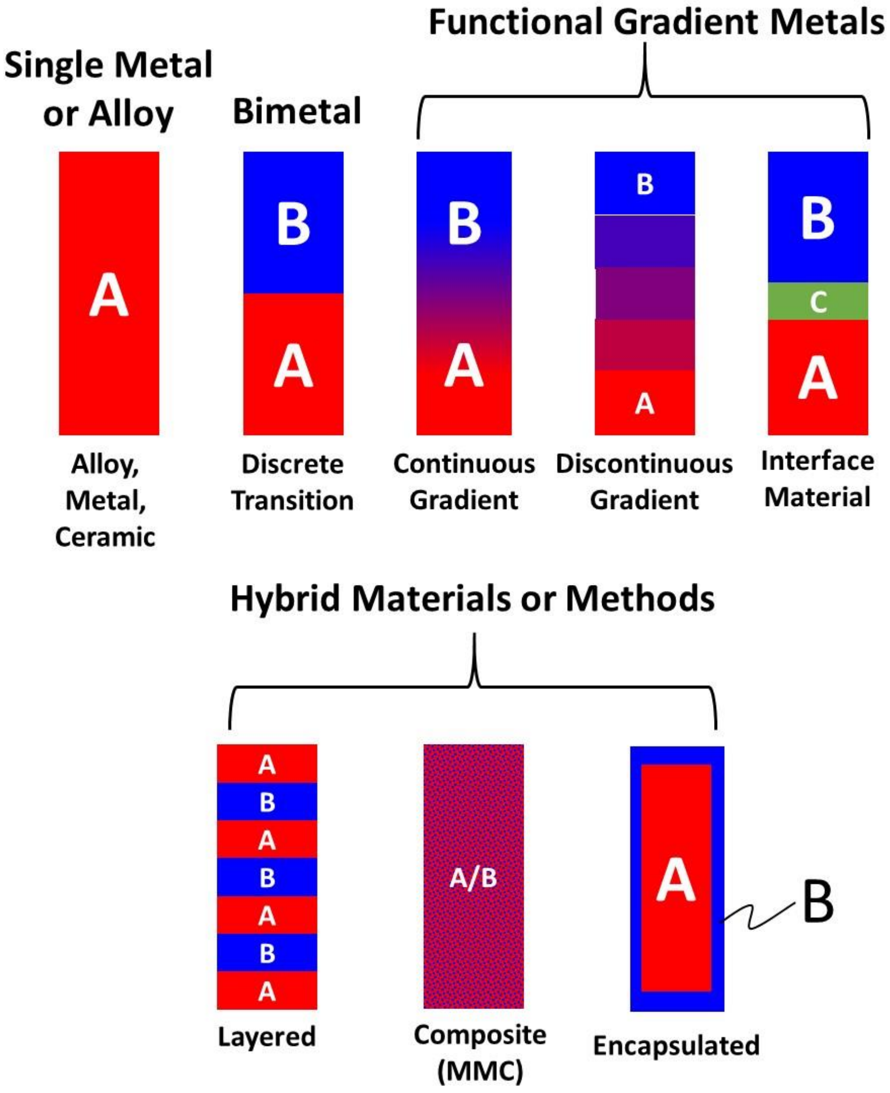


Bimetallic, Multi-metallic, and Hybrid Builds

- Much of AM is focused on single alloys or processes, where further opportunities exist to optimize performance.
  - Weight reduction (higher strength to weight).
  - Use of materials as required locally based on various properties.
- Hybrid methods may include ceramics or unique processing for improved efficiency.



Hybrid Methods -- Encapsulated: shell and powder with HIP consolidation



Du Plessis, A., Yelamanchi, B., Fischer, C., Miller, J., Beamer, C., Rogers, K., Cortes, P., Els, J., and MacDonald, E., "Productivity enhancement of laser powder bed fusion using compensated shelled geometries and hot isostatic pressing," *Advances in Industrial and Manufacturing Engineering*, Vol. 2, May 2021, paper 100031, https://doi.org/10.1016/j.aime.2021.100031.

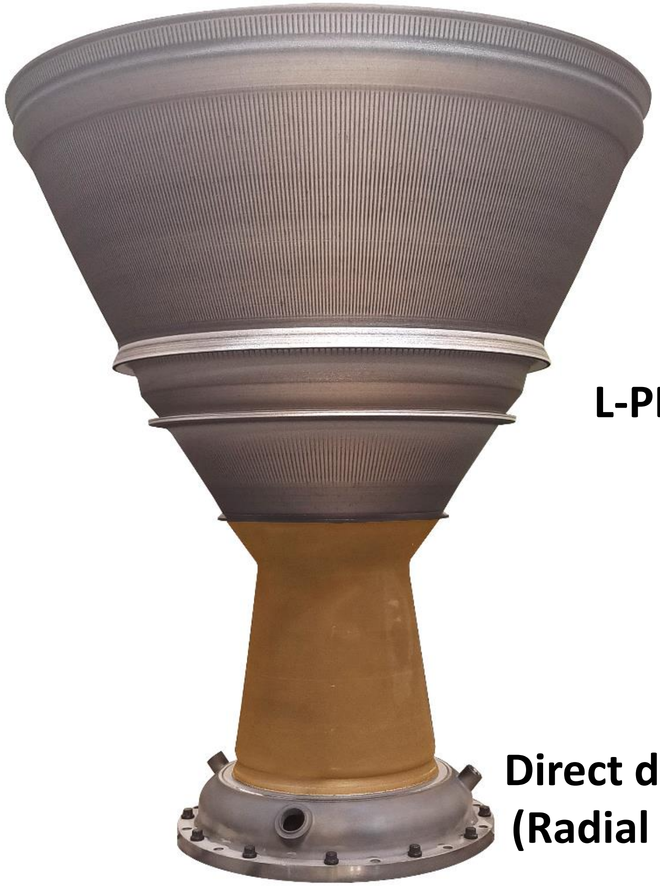
Hofmann, D. C., Kolodziejska, J., Roberts, S., Otis, R., Dillon, R. P., Suh, J.-O., Liu, Z.-K., and Borgonia, J. P., "Compositionally graded metals: A new frontier of additive manufacturing," *Journal of Materials Research*, Vol. 29, No. 17, 2014, pp. 1899–1910.

Multi-metallic and multi-process hardware development

Credit: RPMI / NASA

L-PBF Liner / LP-DED Jacket

L-PBF Liner / Coldspray Jacket



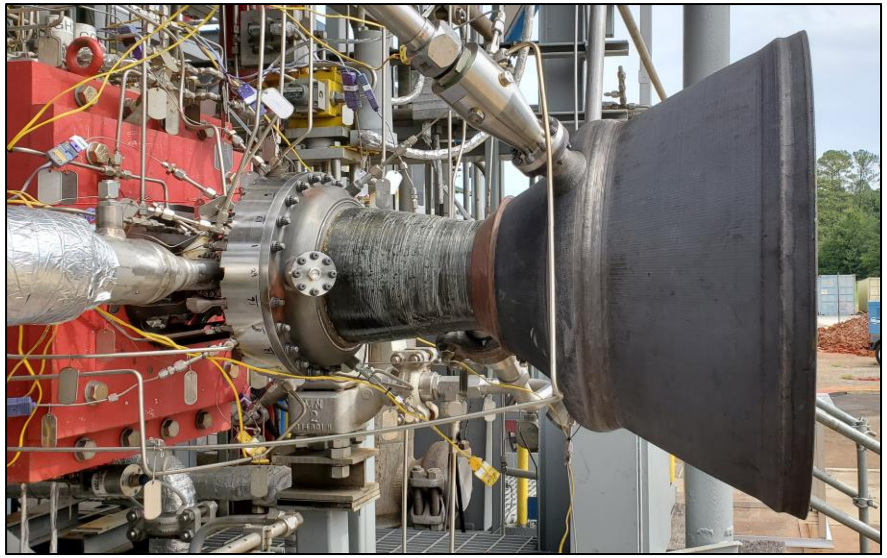
Direct deposit LP-DED nozzle (Radial and Axial Bimetallic)

L-PBF Liner / EBW-DED Jacket

L-PBF GRCop-42 to Inco 625

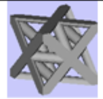
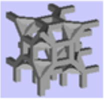
Case Study #2 – Bimetallic AM

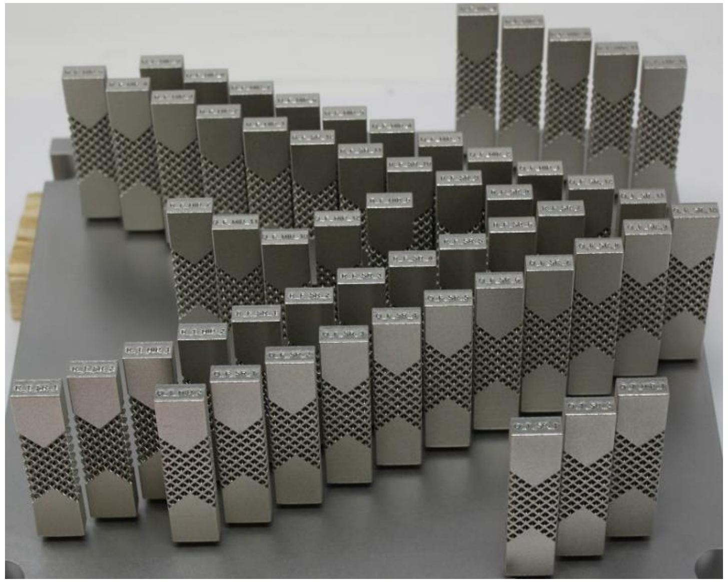
- Implementation of novel AM technologies at 40,000 lbf thrust class TCA testing as part of the RAMPT project
  - L-PBF GRCop-42 chamber liner
  - Radial bimetallic LP-DED NASA HR-1 builds (manifold buildup and cladded structural jackets)
  - Axial bimetallic LP-DED NASA HR-1 nozzle with integral channel wall cooling



Lattice Topology Selection

- Highly dependent on application and operating environment.
- Standard libraries or custom topologies.
- Screening start with file size / generation time then printability.
- Specimen design optimization.
- Characterize desired thermal and/or mechanical properties.

Lattice Topology	Image	Cube Size (mm)	Unit Cell (mm)	Number of Unit Cells	STL Generation Time (s)	STL File Size (KB)	L-PBF AM Trial Outcome	Notes
Octet Truss - 30 %RD		10x10x10	10	1	1	62	Print	Candidate to further evaluation. Pass.
		10x10x10	1	1000	3	22052	Print	Candidate to further evaluation. Pass.
Rhombi Octa Dense		10x10x10	10	1	1	106	Print	Excessive generation time. Disqualifed.
		10x10x10	1	1000	420	51510	Fail	Excessive generation time. Failed print trial. Disqualifed.
Rhombi Octa Light		10x10x10	10	1	1	44	Fail	Failed print trail. Disqualifed.
		10x10x10	1	1000	90	29956	Fail	Excessive generation time. Disqualifed.
Rhombic Dodecahedron - 20 %RD		10x10x10	10	1	1	93	Print	Candidate to further evaluation. Pass.
		10x10x10	1	1000	180	21444	Print	Excessive generation time. Disqualifed.



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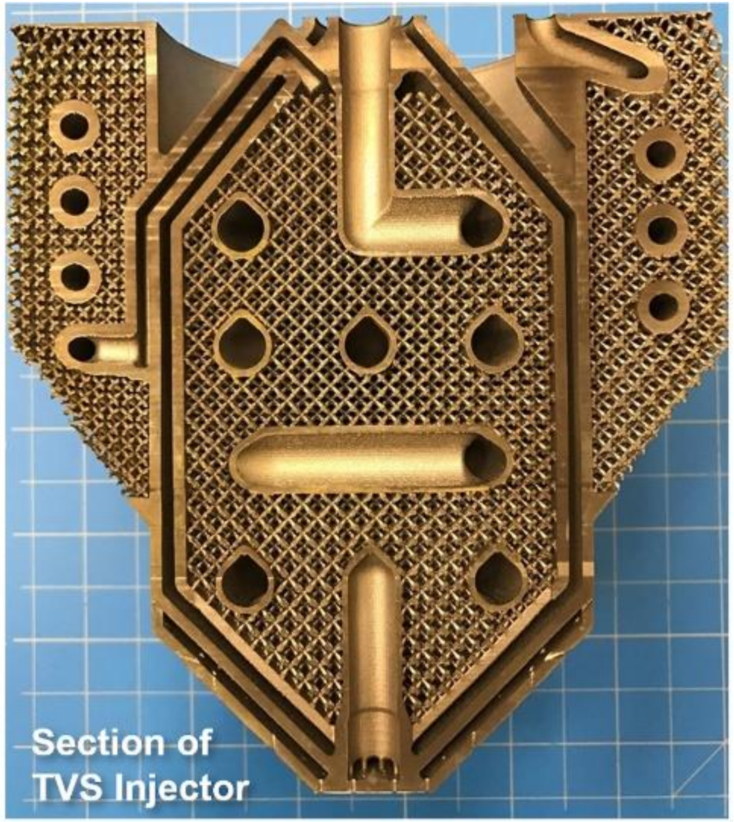
Case Study #3 – Functional Lattices, TVS Injector

- Thermodynamic vent system (TVS) injector with liquid, two-phase, and gas flow – heat exchanger, injector, and condenser integrated



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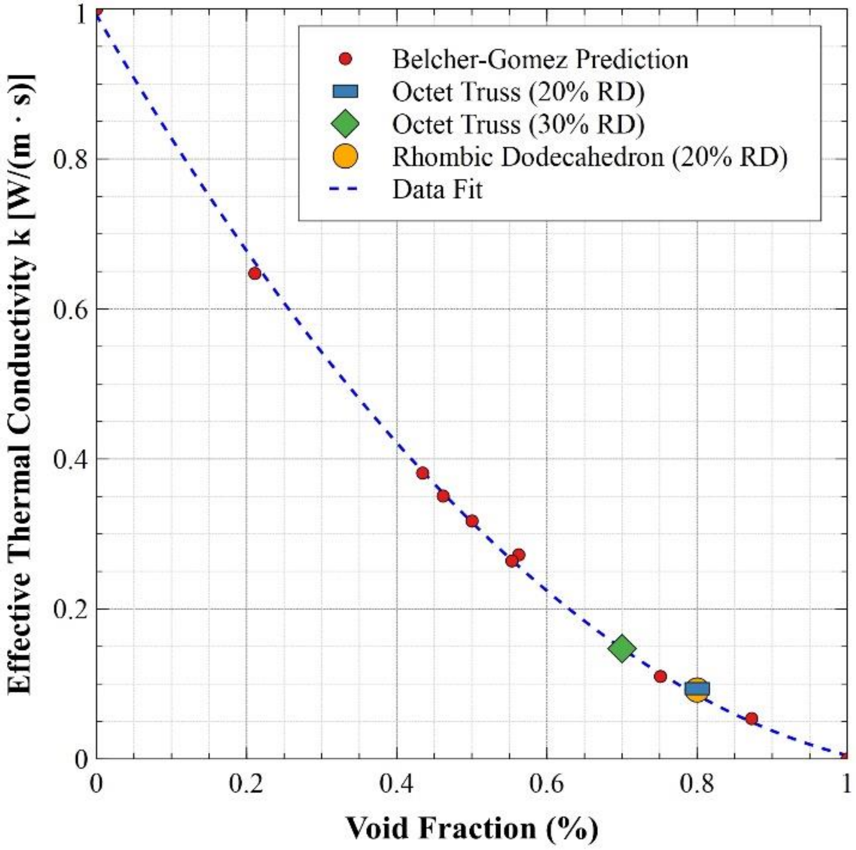
Application Case Study – Thermal Isolation using AM

- Minimize conductive heat transfer using various lattice structures.
- Weight reduction of 40% and thermal conductivity reduced to 10% of fully dense designs



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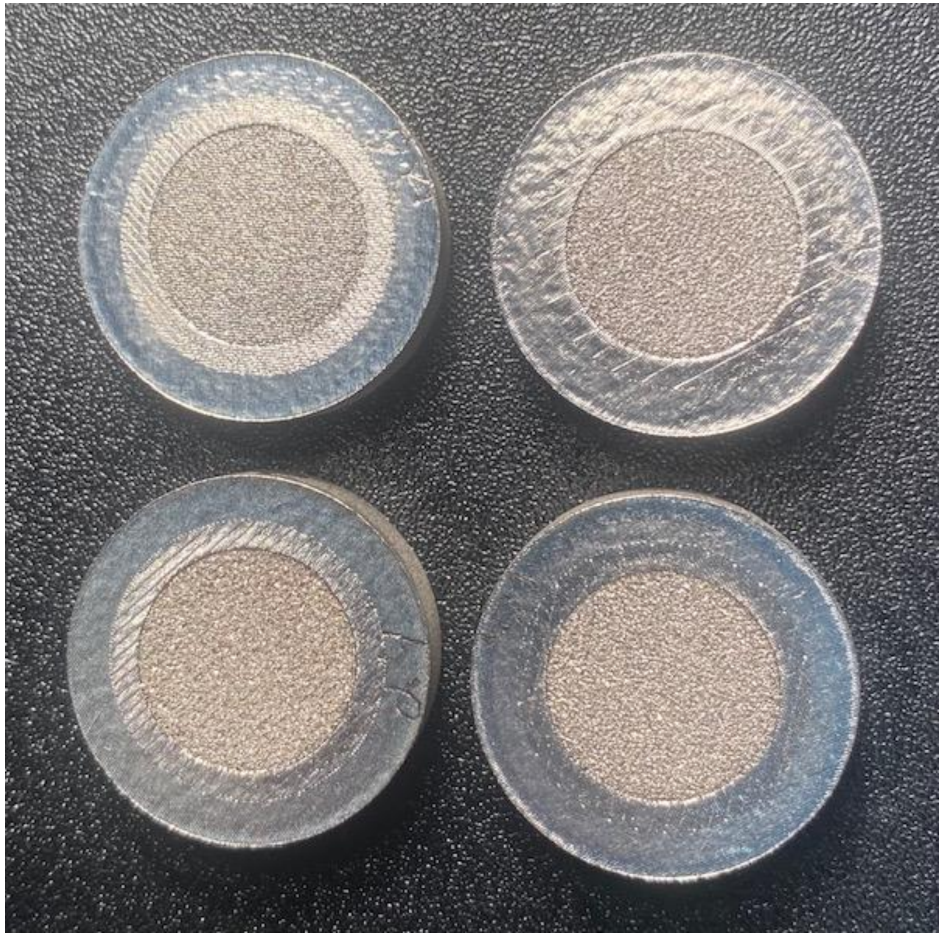
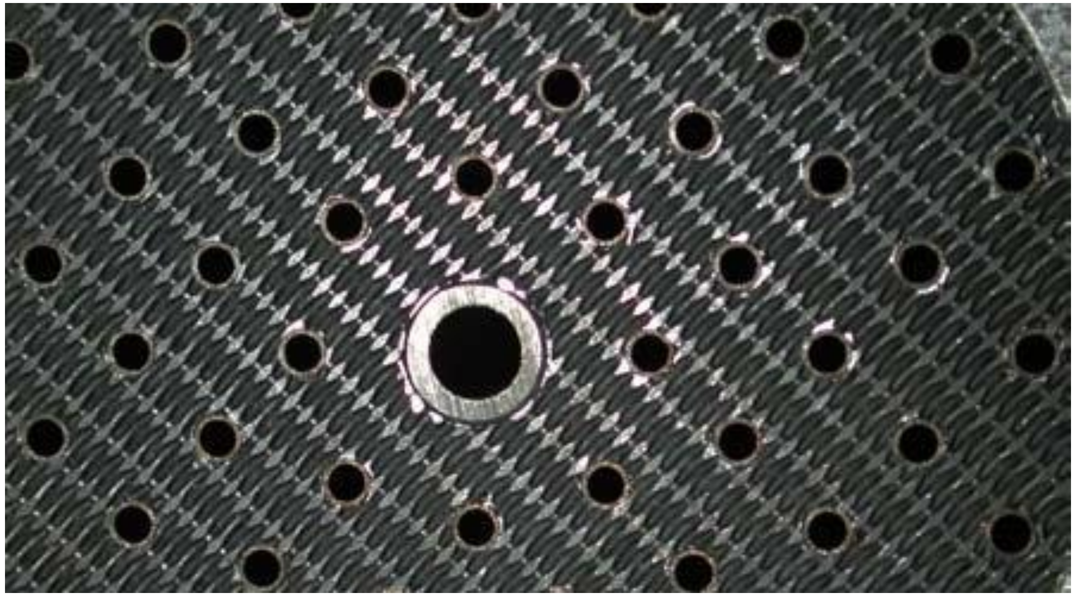
Case Study #4 – Porous AM

- Porous AM for transpiration cooling of rocket engine components
- NASA SBIR with Masten and several industry developments
- Internal development at MSFC ongoing
- For various build parameters, how do porosity and permeability change
- Pressure drop vs. mass flow rate data
- Structural properties unknown



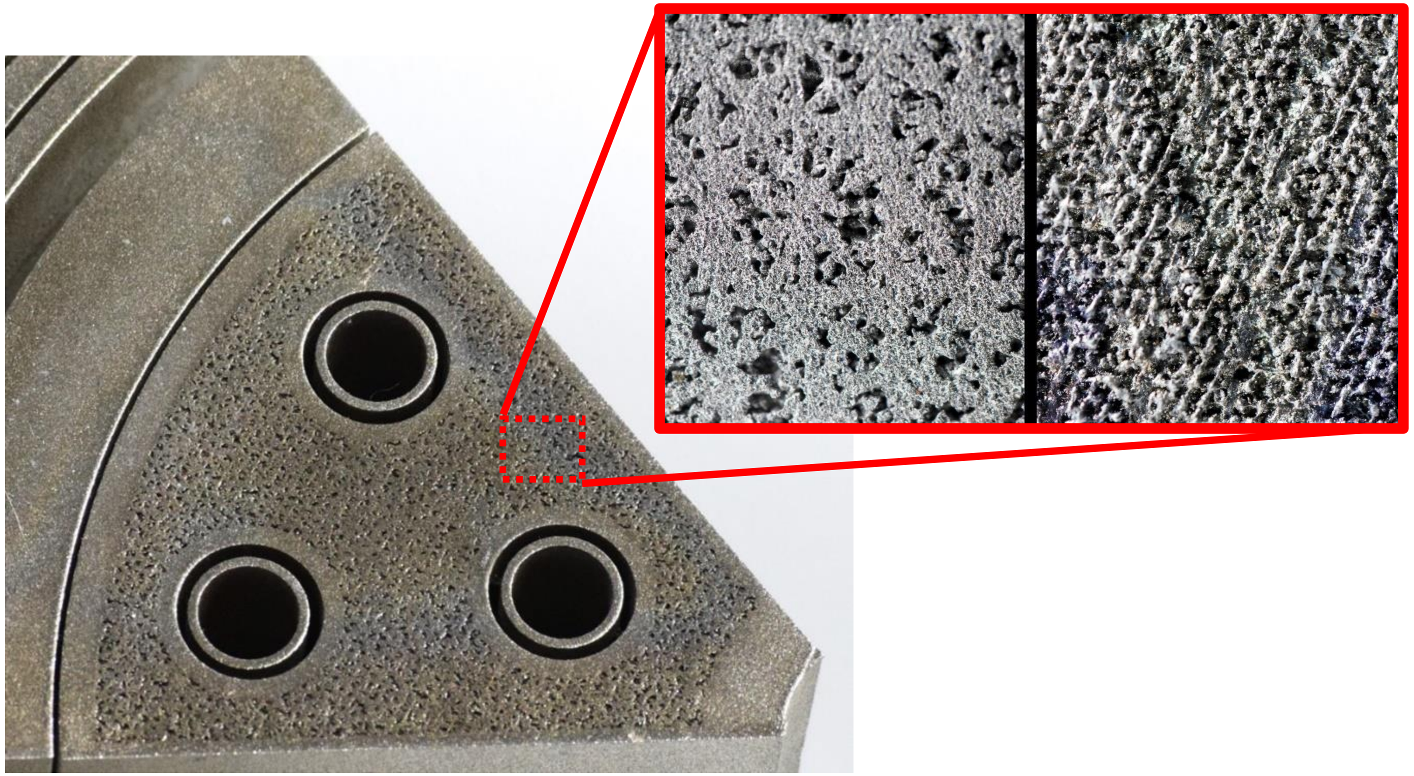
Porous flow sample pucks with solid outer ring for sealing

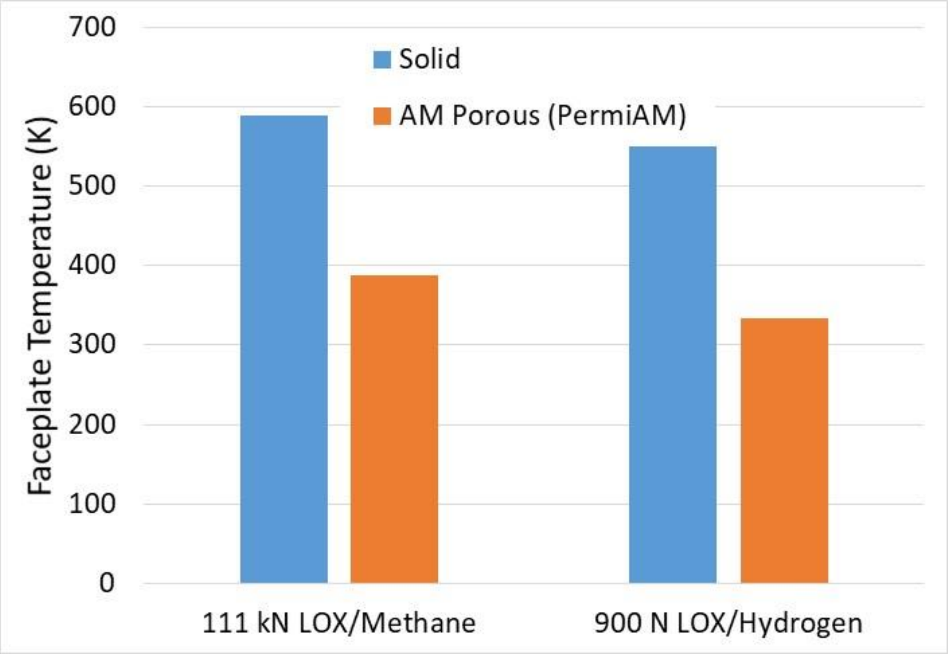


Traditional Rigimesh for faceplate cooling

Application Case Study – Transpiration Cooling

- Creating intentional porosity to allow for transpiration cooling in high heat flux components.
- Replaces solid surfaces or Rigimesh structures with (localized) permeable AM as part of the build.





35-40% reduction in wall temperatures

Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, Metal Additive Manufacturing for Propulsion Applications, 1st ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2022. https://doi.org/10.2514/4.106279

NASA led book on Metal Additive Manufacturing

https://arc.aiaa.org/doi/book/10.2514/4.106279

Online version and hardcopy available

P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022). *Metal Additive Manufacturing for Propulsion Applications*. AIAA Progress in Astronautics and Aeronautics Book Series. https://arc.aiaa.org/doi/book/10.2514/4.106279

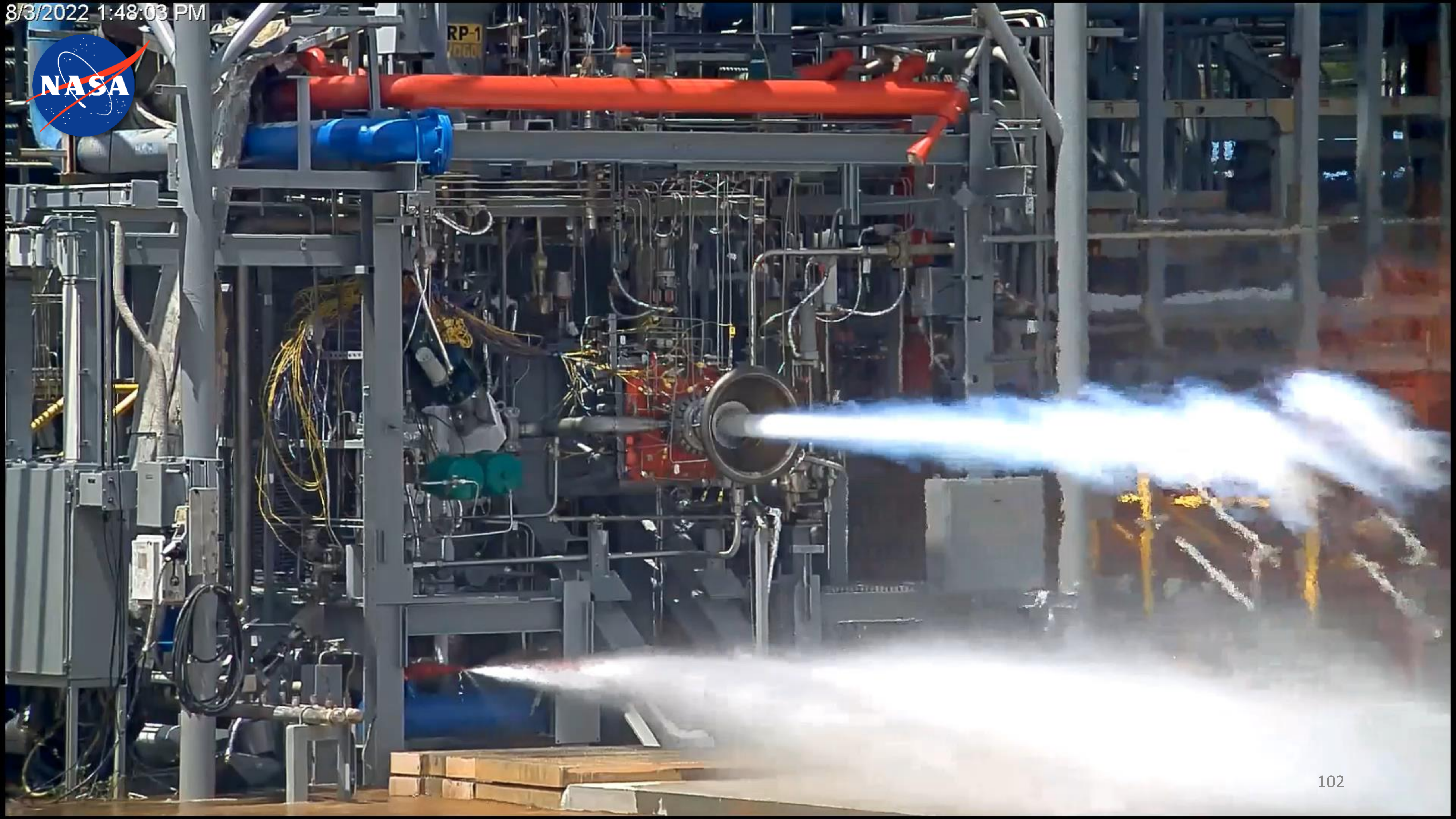
Additive manufacturing (AM) processes are proving to be a disruptive technology and are grabbing the attention of the propulsion industry. AM-related advancements in new industries, supply chains, design opportunities, and novel materials are increasing at a rapid pace. The goal of this text is to provide an overview of the practical concept-to-utilization lifecycle in AM for propulsion applications.

Some key takeaways for metal AM…

- The design and build process will be iterative.
- AM materials are different from wrought.
  - Process => microstructure => property => performance
  - Anisotropy exists and need to include in design allowables.
- Traceable and high-quality feedstock is essential for good builds.
- Post-processing is essential for proper integration into a system.
- Design with **<u>all</u>** process steps in mind – post-processing is **<u>not</u>** an after thought and you must design for up front.
  - Remove powder and verify before any heat treatments or immersing the part (ie. EDM or band saw for build plate removal).
  - Heat treatment is now your responsibility (not the mill).
  - Complexity is the inverse of inspectability.

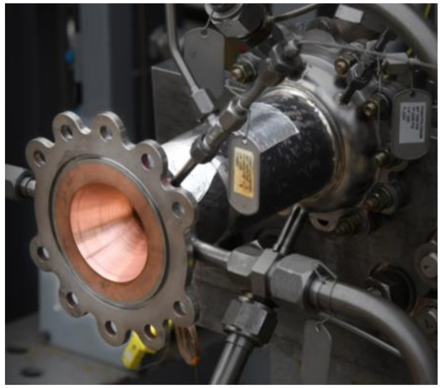
Some key takeaways for metal AM…

- The best DfAM designs eliminate supports, however this is not always possible so explore options and not just computer generated.
- Witness specimens are integral to your part quality and should be designed and specified in your build.
- Ensure proper datum placement for down stream processing.
- AM surface texture is both a detriment and opportunity.
- Qualification is integral to the entire process and upfront planning can save significant effort when implementing.

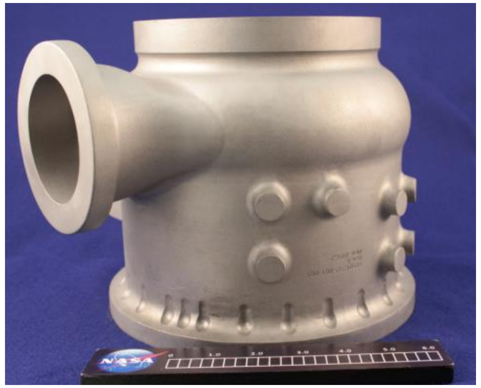

8/3/2022 1:48:03 PM
NASA
RP-1

Summary

- Various AM processes have matured for aerospace applications each with unique advantages and disadvantages.
- AM is not a solve-all; consider trading with other manufacturing technologies and use only when it makes sense.
- **Complete understanding of the design process, build-process, feedstock, and post-processing is critical to take full advantage of AM.**
- Additive manufacturing takes practice!
- AM is evolving and imagination is the limit.





Contact:

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Photo: NASA/Ben Smegelsky

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- Long Life Additive Manufacturing Assembly (LLAMA) Project
- Space Launch System (SLS) Program
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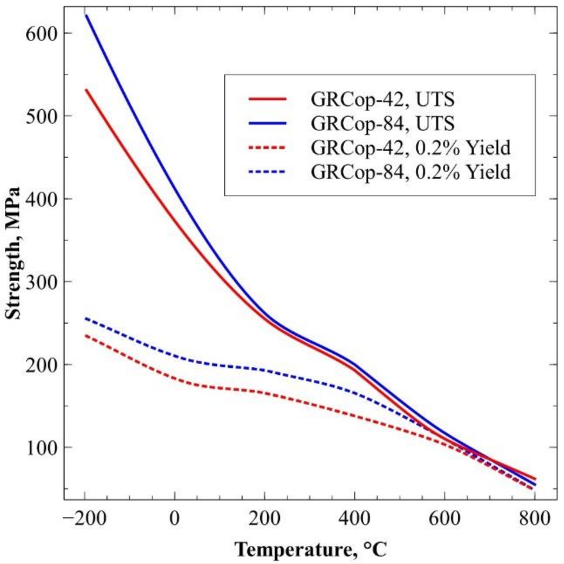
- Drew Hope
- Martin Annett
- Lynn Machamer
- RPM Innovations (RPMI)
- Tyler Blumenthal
- DM3D
- GE Research
- Bhaskar Dutta
- REM Surface Engineering
- Powder Alloy Corp
- AP&C
- Formalloy
- Auburn University (NCAME)
- Ben Williams
- Marissa Garcia
- Tim Smith / GRC

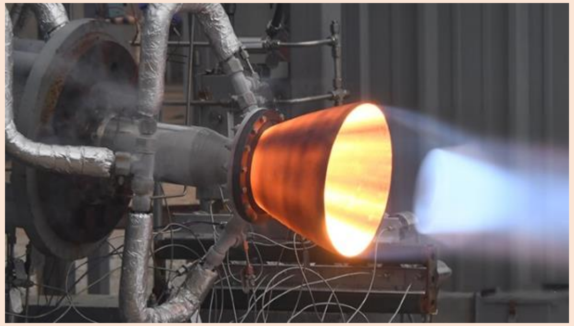
  Christopher Kantzos / GRC
- Tal Wammen
- Tom Teasley
- Scott Chartier
- Test Stand 115 crew
- Kevin Baker
- Matt Medders
- Adam Willis
- Nunley Strong
- Zach Taylor
- Matt Marsh
- Darren Tinker
- Dwight Goodman
- Will Brandsmeier
- Jonathan Nelson
- Bob Witbrodt
- Shawn Skinner
- Will Evans
- John Ivester
- Will Tilson
- Jim Lydon
- Brian West
- Gabe Demeneghi
- David Ellis / GRC
- Judy Schneider / UAH
- David Myers / MSFC EM21
- Scott Ragasa / MSFC EM21
- Sturbridge Metallurgical Services
- Product Evaluation Systems
- IMR Test Labs
- Robert Amaro / AMTT
- Ron Beshears
- James Walker
- Steve Wofford
- Johnny Heflin
- Mike Shadoan

  Keegan Jackson
- Many others in Industry, commercial space and academia

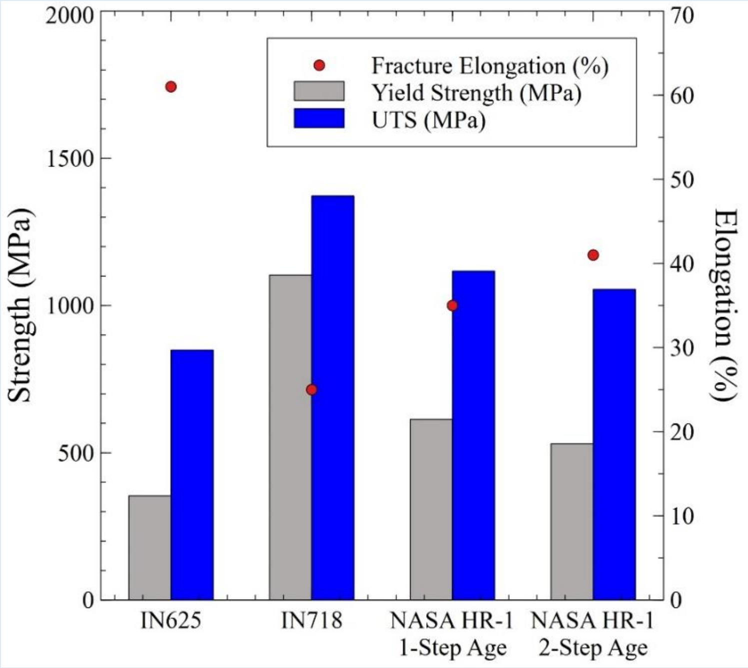
AM Enabling New Alloy Development

GRCop-42, High conductivity and strength for high heat flux applications

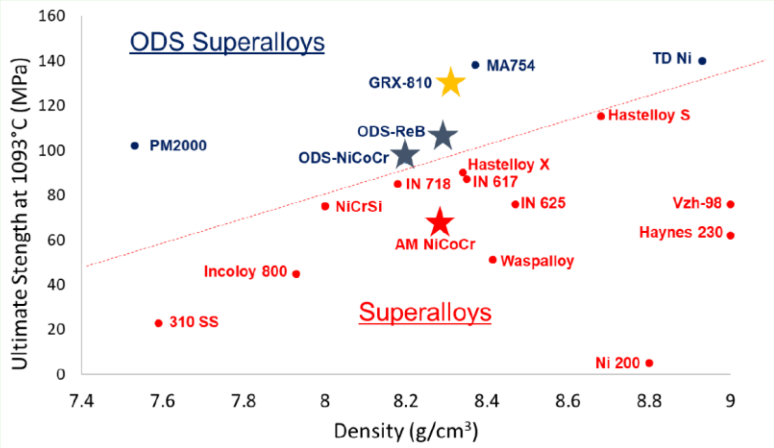




NASA HR-1, high strength superalloy for hydrogen environments



GRX-810, high strength, low creep rupture and oxidation at extreme temperatures



Ref: Tim Smith, Christopher Kantzos / NASA GRC