Additive Manufacturing (AM) for Propulsion Component and System Applications

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NASA Marshall Space Flight Center
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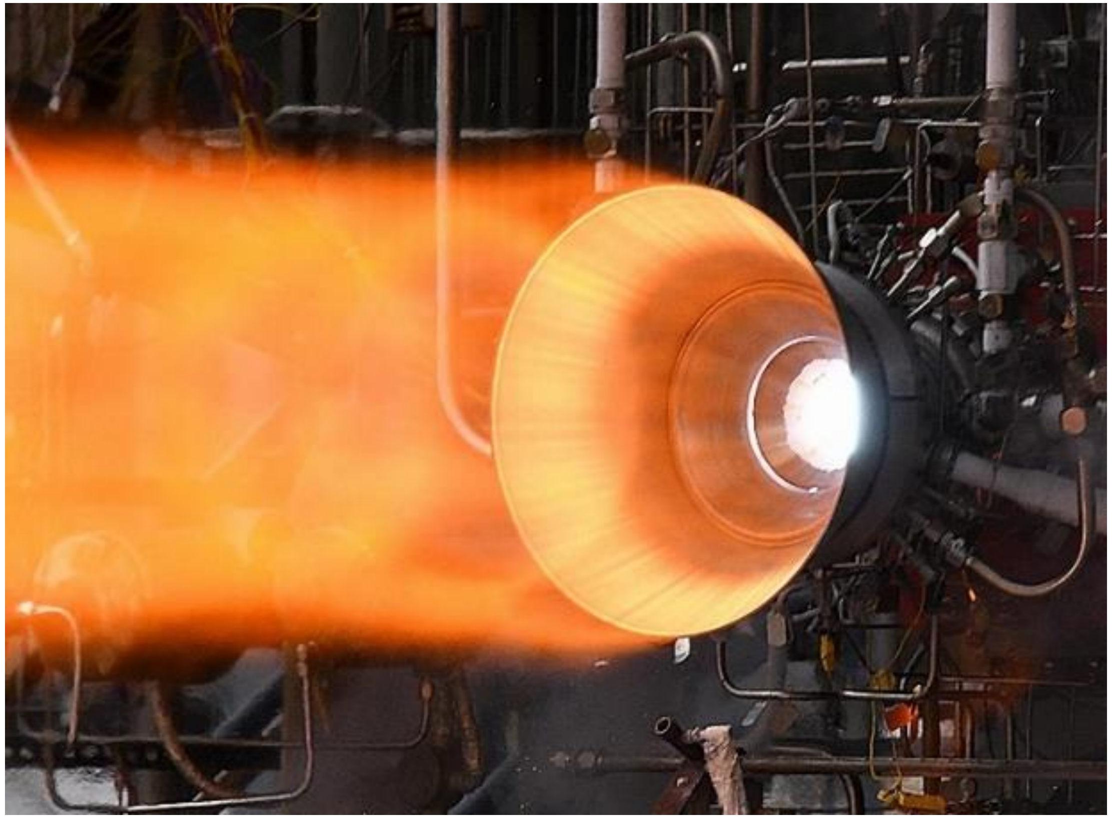
Introduction and Agenda

- Introduction of Metal AM for Propulsion
- Case Study using L-PBF
- Case Study using DED
- Overview of Metal AM Processes
- Trades among various AM techniques
- Large Scale DED Process Overviews
- Other topics in AM Advancement
- Advancements in Post-Processing
- Refractory Alloy Development



Hot-fire testing of bimetallic additively manufactured combustion chamber using **Electron Beam DED** Jacket

Terminology

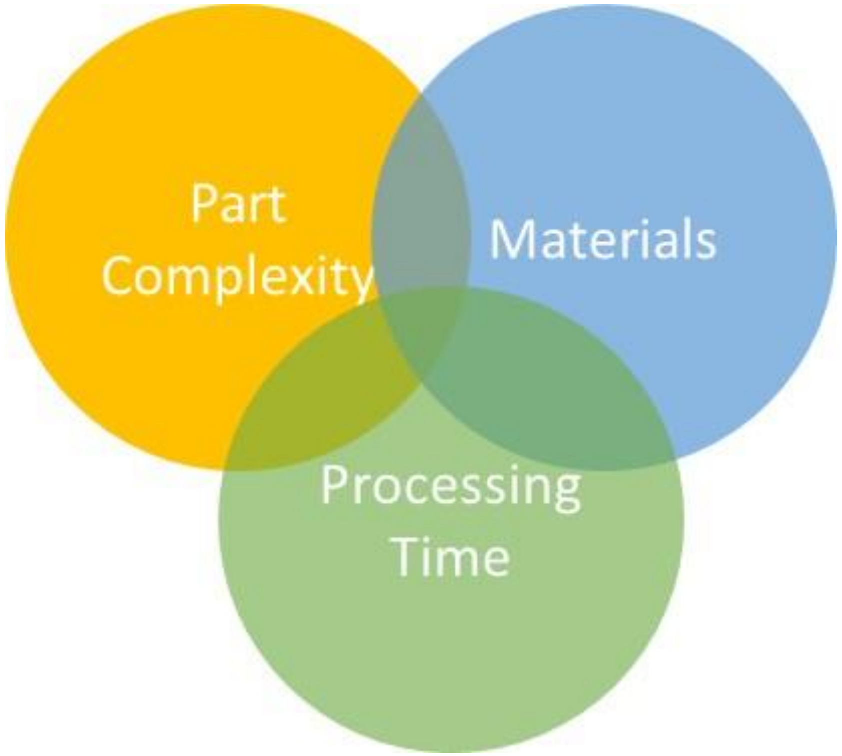
Course will focus exclusively on metal additive manufacturing

- AM = Additive Manufacturing
- DED = Directed Energy Deposition
- LP-DED = Laser Powder DED
- LW-DED = Laser Wire DED
- AW-DED = Arc Wire DED
- EB-DED = Electron Beam DED
- L-PBF = Laser Powder Bed Fusion

- Metal Additive Manufacturing - Build, print, grow, AM, *fabricate*…

Why use AM? (Rocket Engines)

- Metal Additive Manufacturing provides 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

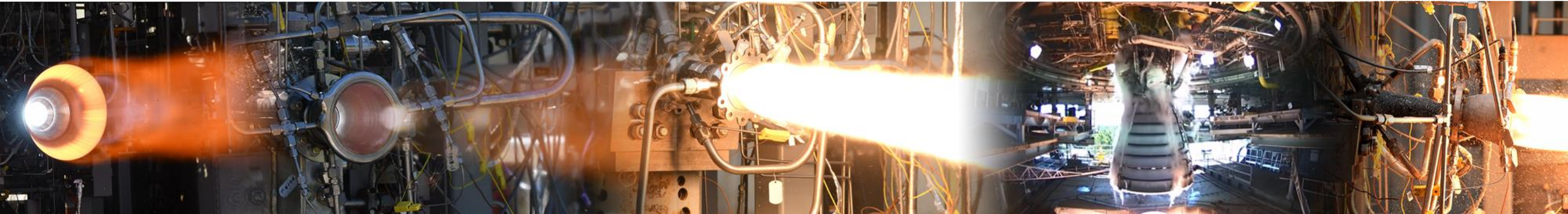


Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

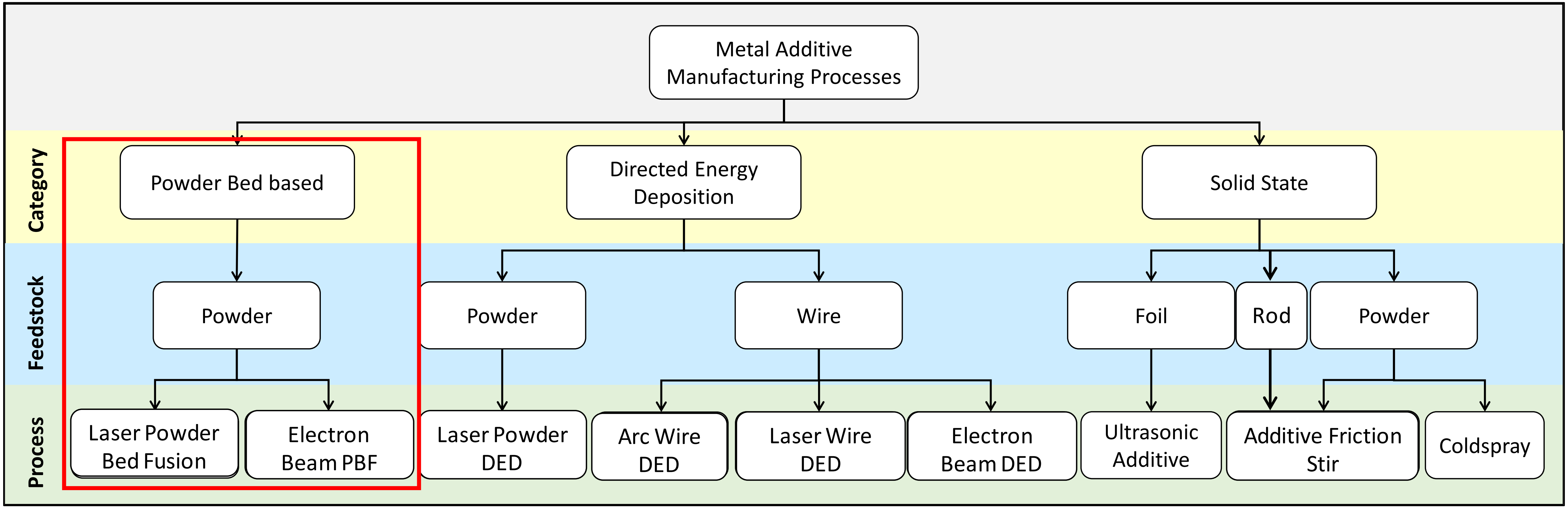
Laser Powder Bed Fusion (L-PBF)
Copper Alloys and Multi-Alloy

Directed
Energy
Deposition

L-PBF of complex components, new alloy developments for harsh environment



Metal AM Technologies - Overview



*Does not include all metal AM processes

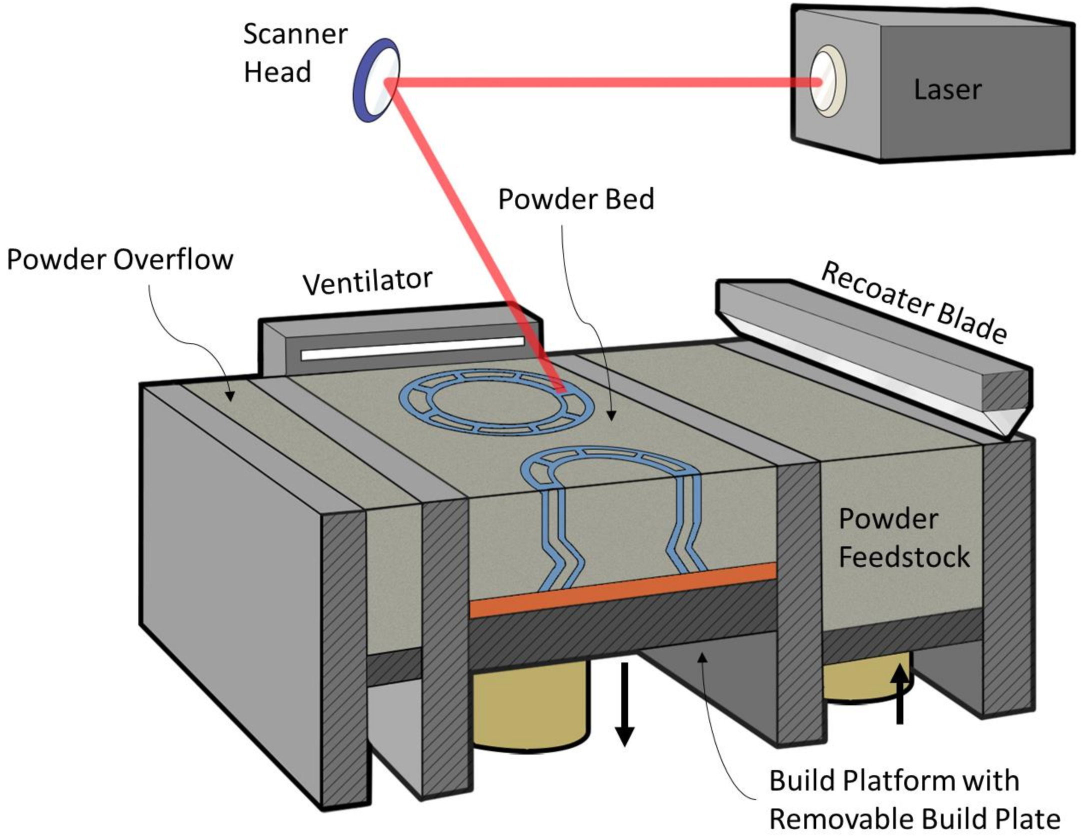
__Based on Ref:__

- Gradl, P.R., Mireles, O., Andrews, N. "Introduction to Additive Manufacturing for Propulsion Systems. 10.13140/RG.2.2.13113.93285
- 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).
- Ek, K., "Additive Manufactured Metals," Master of Science thesis, KTH Royal Institute of Technology (2014).

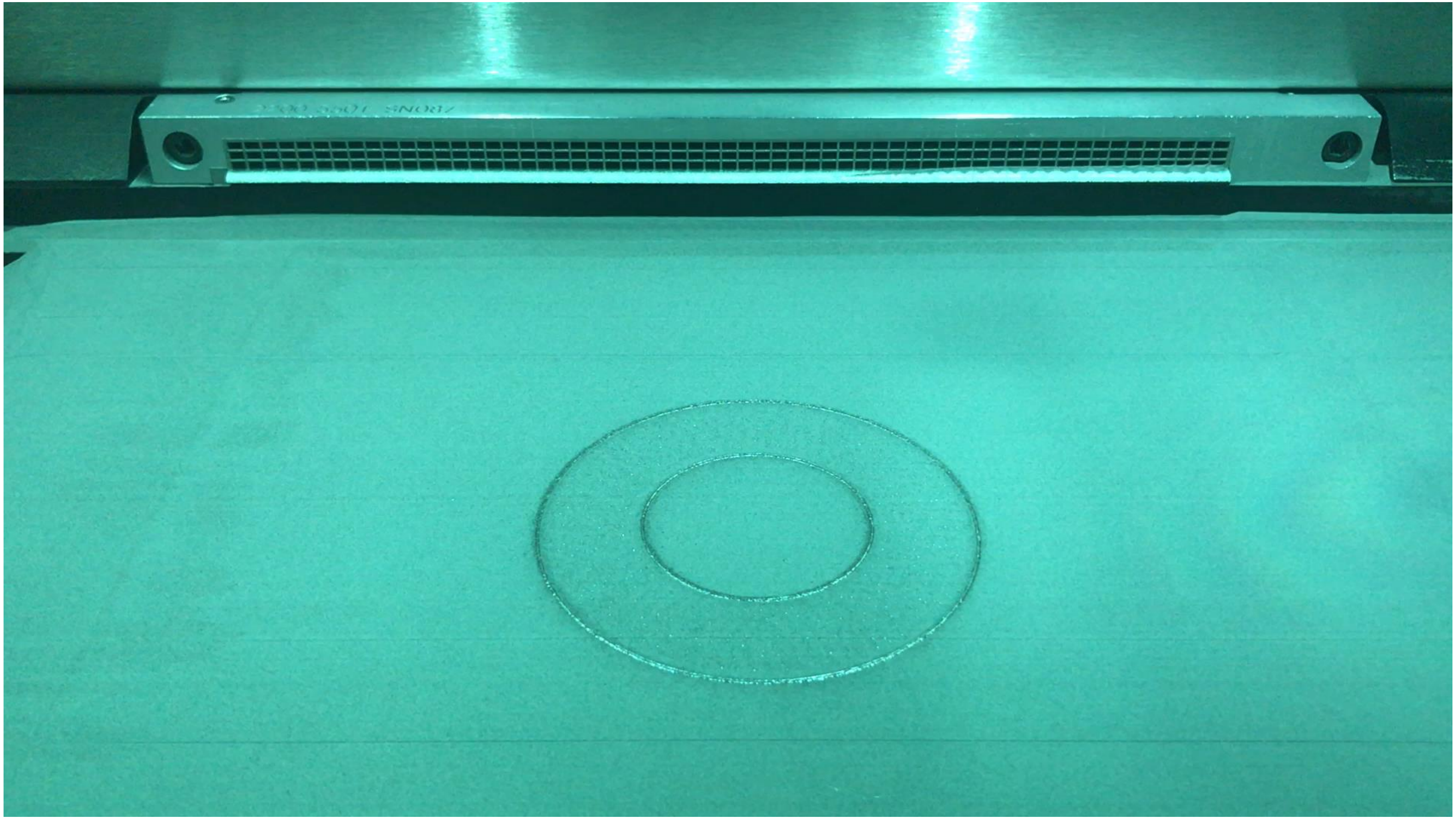
Laser Powder Bed Fusion

- **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.



Laser Powder Bed Fusion (L-PBF)



NASA Development with L-PBF

Cost Evolution for Copper-Alloy Additive Chambers

Traditional Manufacturing

12-18 mos / $310k

AM Development

6-8 mos / $200k

Evolving AM

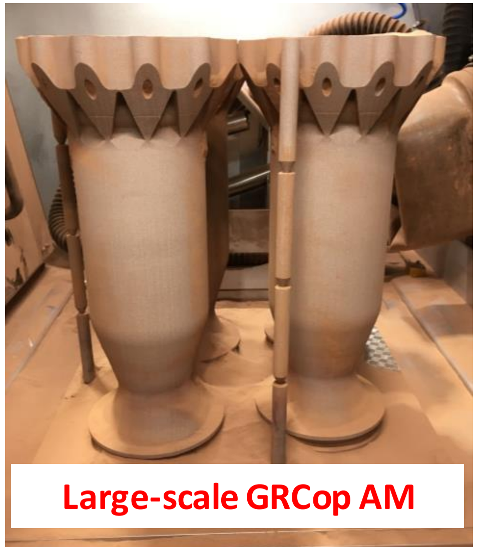
3-5 mos / $125k

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

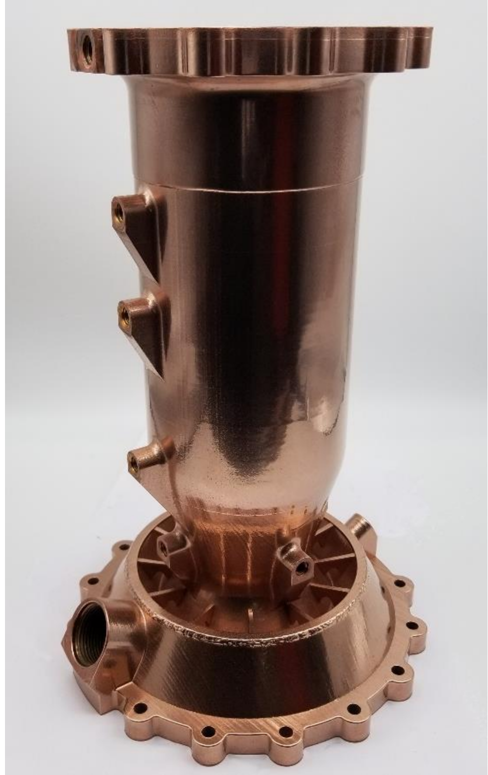
L-PBF GRCop-alloy Combustion Chambers

Multi-Alloy Additive

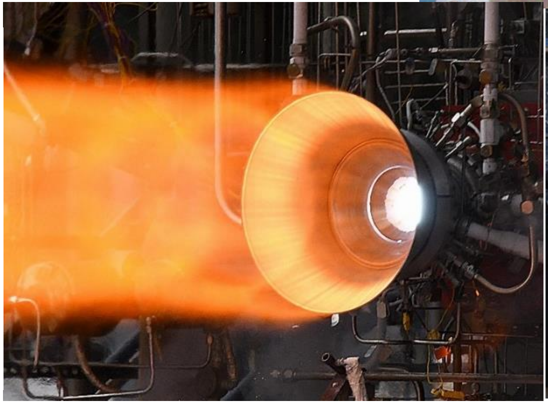
Combine L-PBF and DED

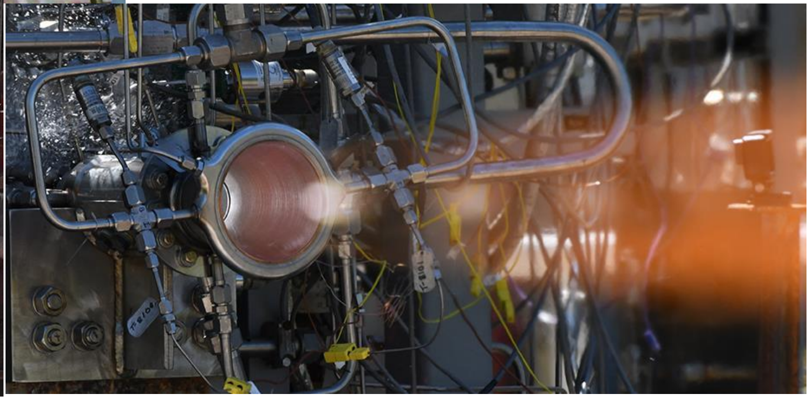


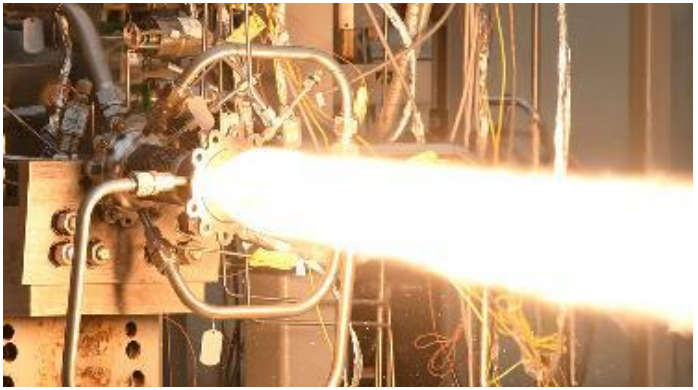
Large-scale GRCop AM



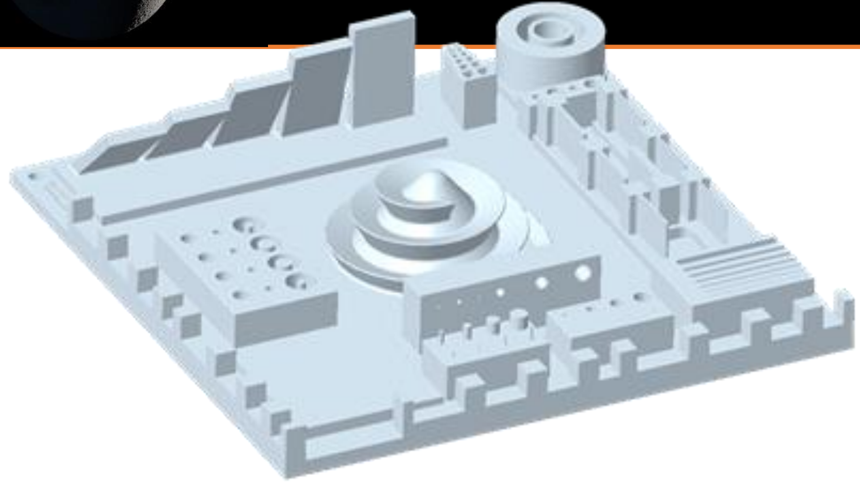
~12” Dia / 14” height

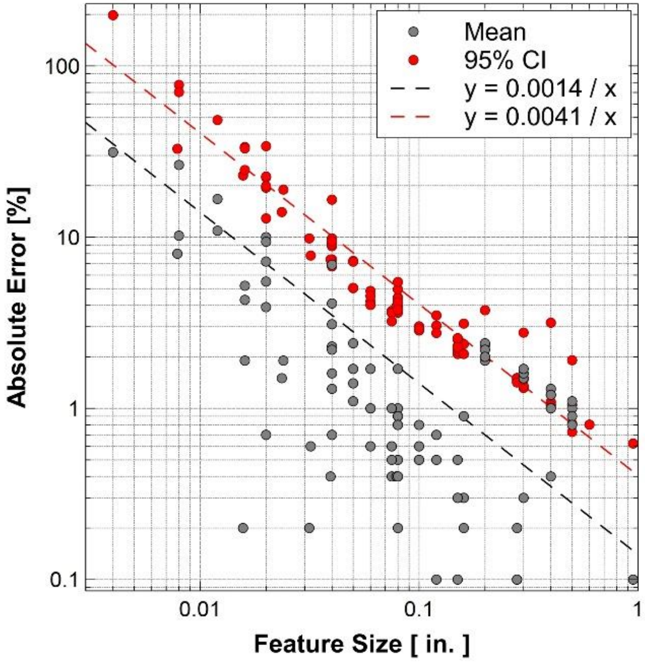


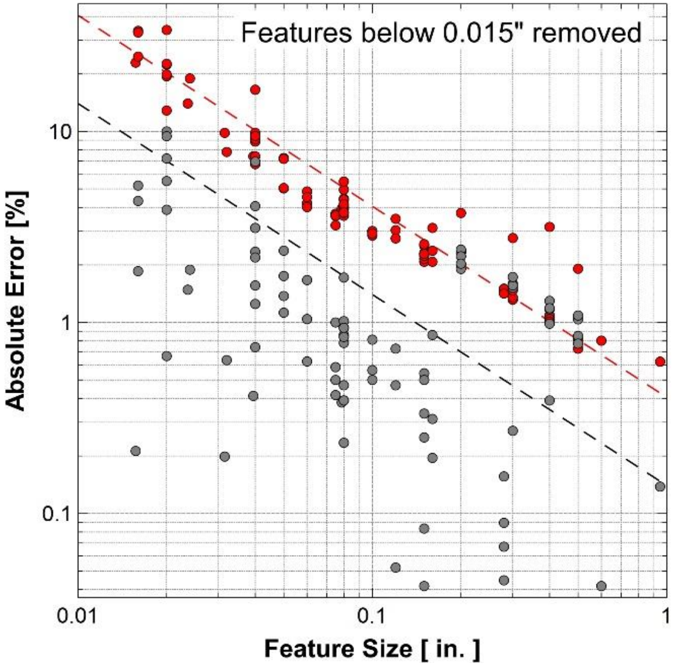




Study on L-PBF Reproducibility – Inconel 718



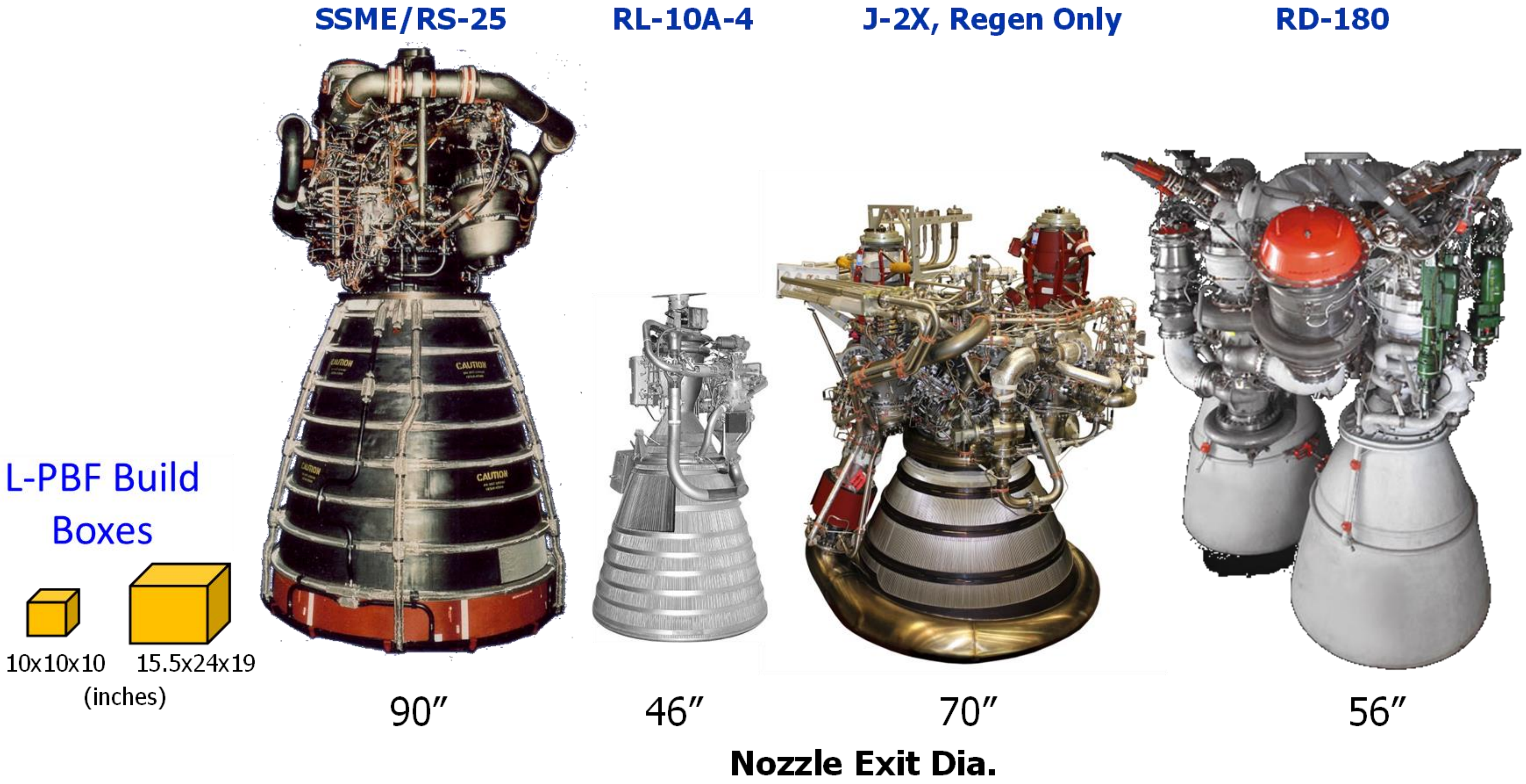




- A systematic mean tolerance across all features was 0.0014 inches (36 µm) with a 95% confidence interval (CI) of 0.0041 inches (104 µm). Therefore, relative error decreases inversely with feature size.
- Features sized at 0.004 inches (0.1 mm) failed to build for thin walls and slots
- Features sized at 0.008 inches (0.1 mm) failed to build for horizontal holes
- Features sized at 0.008 inches (0.02 mm) had high variability for thin walls, slots, and extruded cylinders

P.R. Gradl, D.C. Tinker, J. Ivester, S.W. Skinner, T. Teasley. (2021). *Geometric Feature Reproducibility for Laser Powder Bed Fusion (L-PBF) Additive Manufacturing with Inconel 718.* **In-Review Article.**

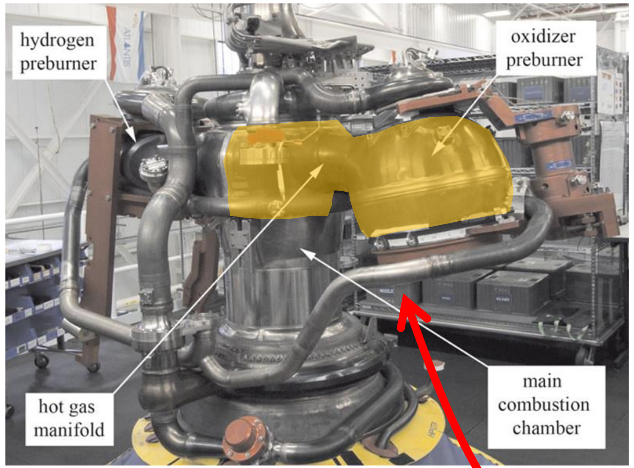
The need for large scale AM…



Case Study – RS25 Powerhead

Traditional Manufacturing

Forged => Machined

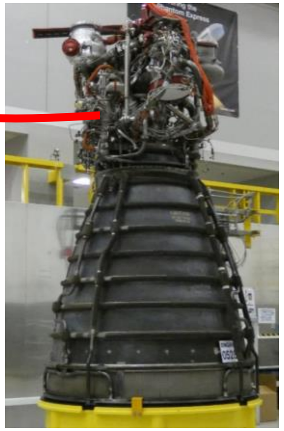


L-PBF Development

>90 days using L-PBF (Large Platform)

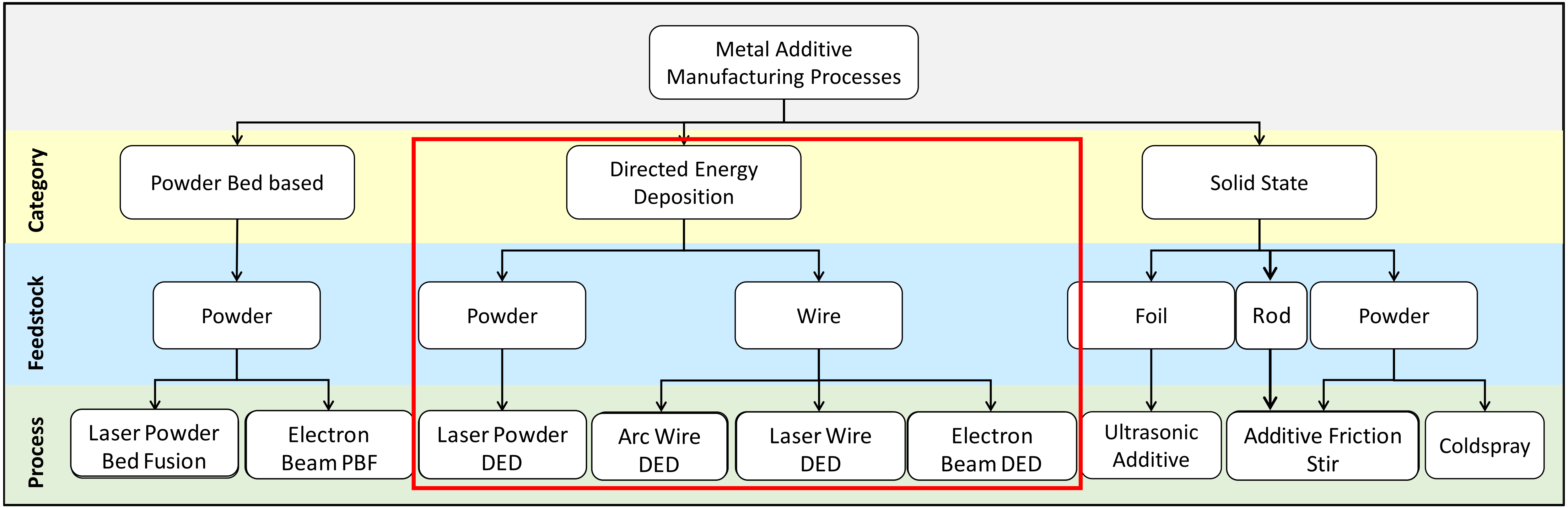
DED Development

<14 days deposition
using LP-DED



Sivolella D. (2014) Power to orbit: the main engines. In: To Orbit and Back Again. Springer Praxis Books. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-0983-0_3

Metal AM Technologies - Overview



*Does not include all metal AM processes

Based on Ref:

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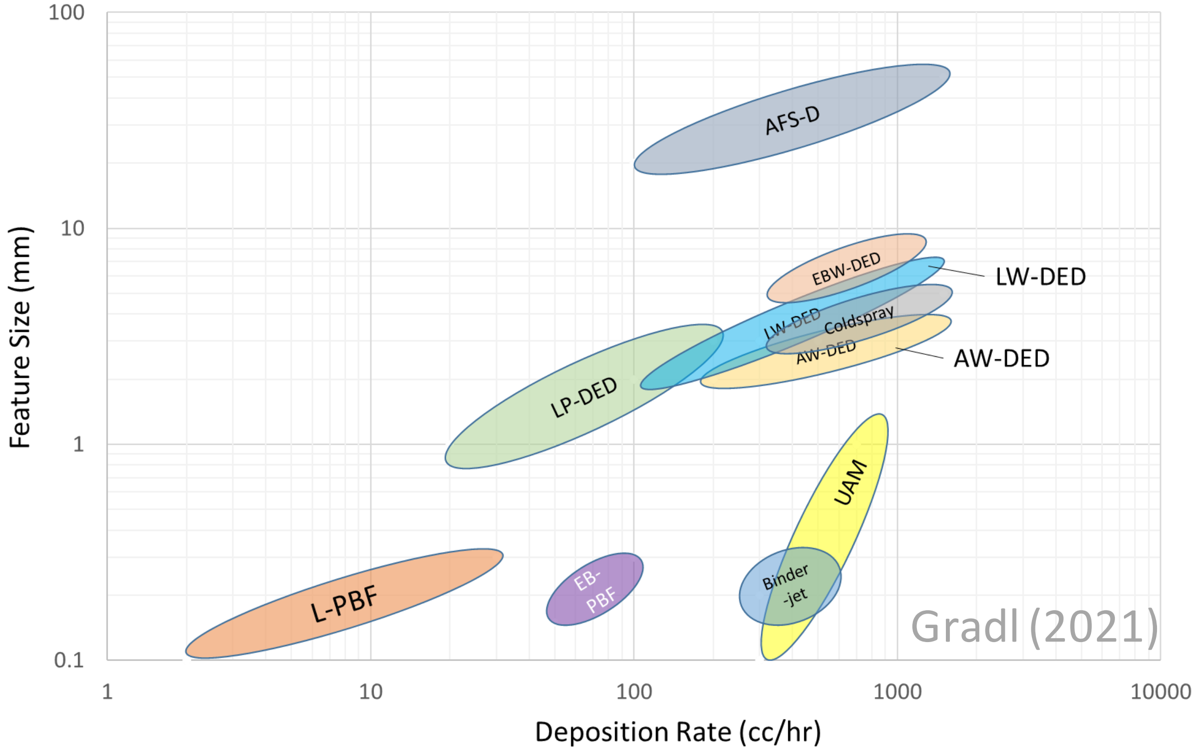
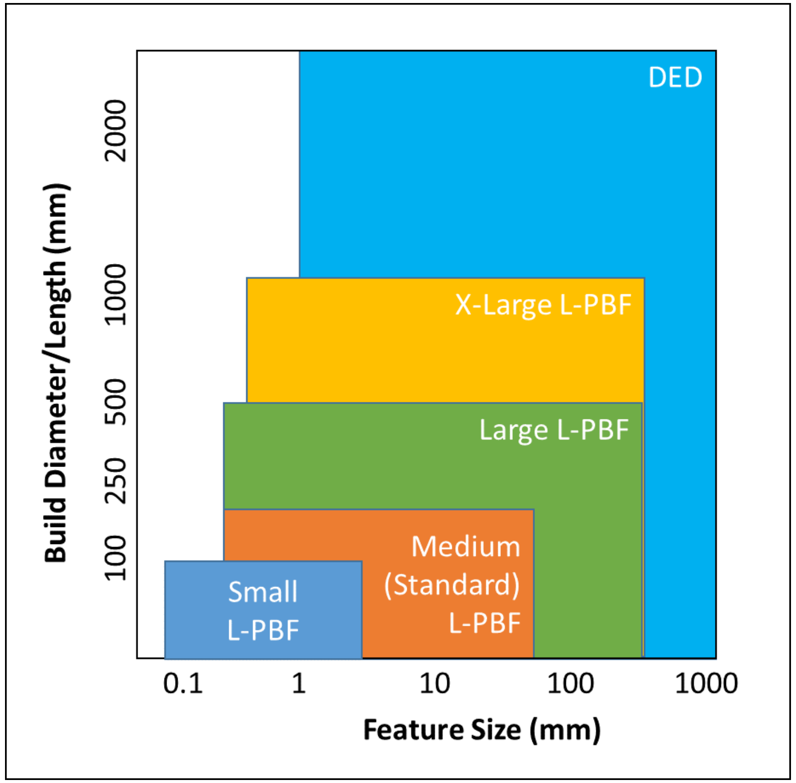
- Ek, K., “Additive Manufactured Metals,” Master of Science thesis, KTH Royal Institute of Technology (2014).

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:

- Kerstens, F., Cervone, A., & Gradl, P. (2021). End to end process evaluation for additively manufactured liquid rocket engine thrust chambers. *Acta Astronautica*, *182*, 454–465. https://doi.org/10.1016/j.actaastro.2021.02.034
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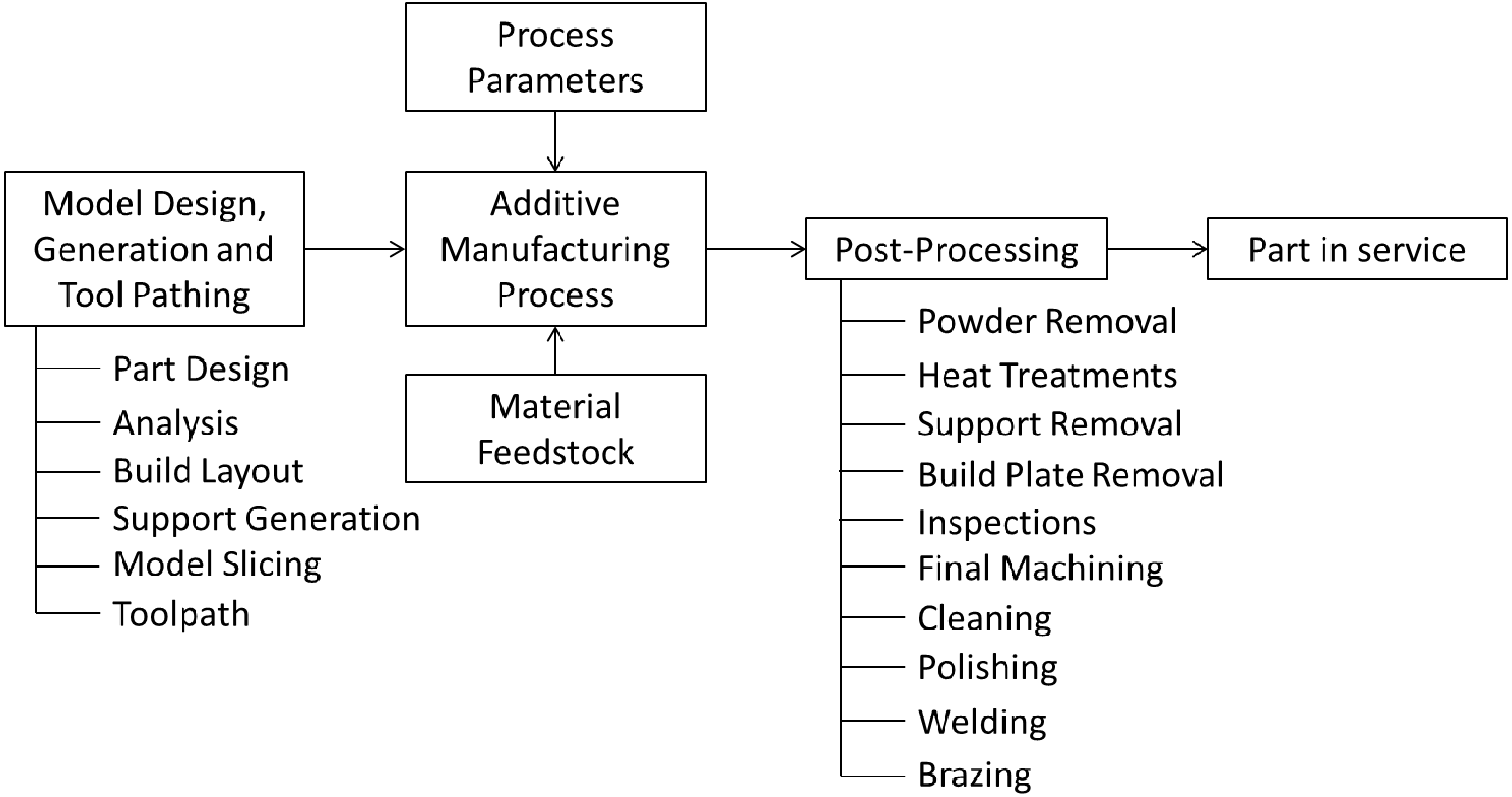
- Gradl, P.R., Mireles, O., Andrews, N. “Introduction to Additive Manufacturing for Propulsion Systems. 10.13140/RG.2.2.13113.93285

AM is often viewed as a serial process…



Process Parameters

Model Design, Generation and Tool Pathing

- Part Design
- Analysis
- Build Layout
- Support Generation
- Model Slicing
- Toolpath

Additive Manufacturing Process

Material Feedstock

Post-Processing

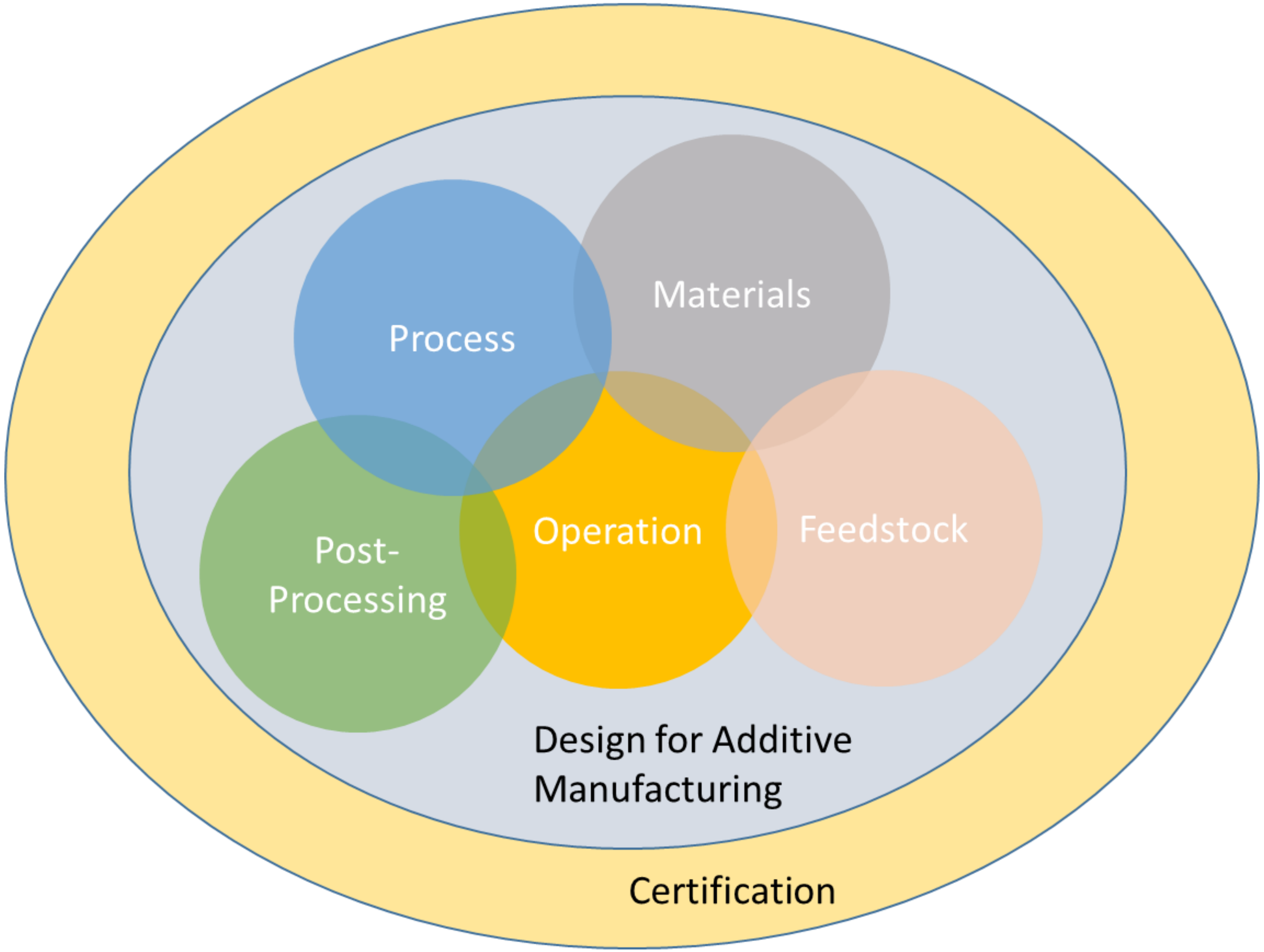
- Powder Removal
- Heat Treatments
- Support Removal
- Build Plate Removal
- Inspections
- Final Machining
- Cleaning
- Polishing
- Welding
- Brazing

Part in service

References:

- AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl, Protz, Mireles, Garcia (unreleased)

Successful AM Integrates the entire process

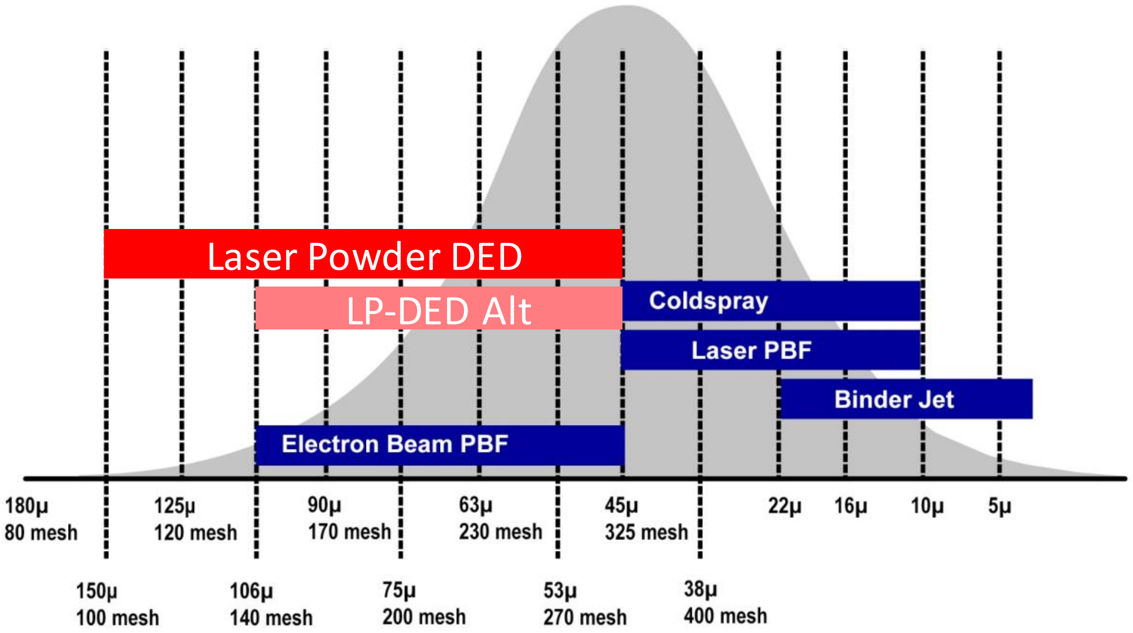


Feedstock Material for AM

Feedstock can be Powder or Wire

Process	Type of Feedstock	Typical Feedstock Size	Stock Lead Times
L-PBF	Powder	10-45 µm	Short
EB-PBF	Powder	45-105 µm	Short
LP-DED	Powder	45-105 µm	Short
AW-DED	Wire	1.14 – 2 mm dia	Short
LW-DED	Wire	0.76 – 1.52 mm dia	Short-Medium
LHW-DED	Wire	1.14 mm dia	Short
EB-DED	Wire	1.14 – 3.2 mm dia	Short
UAM	Sheet	Varies	Long
Friction Stir AM	Bar	Varies	Long
Coldspray	Powder	10-45 µm	Short
Binderjet	Powder w/ Binder	3-22 µm	Short

*UAM = Ultrasonic Additive Manufacturing



Material Availability for Metal AM (DED)

As available materials and processes continue to grow, so does complexity of characterization and standardization

Ni-Base

- Inconel 625
- Inconel 718
- Hastelloy-X
- Haynes 230
- Haynes 214
- Haynes 282
- Haynes 188
- Monel K-500
- C276
- Rene 80
- Waspalloy

Fe-Base

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

Cu-Base

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

Al-Base

- AlSi10mg
- A205
- F357
- 6061 / 4047

Refractory

- W
- W-25Re
- Mo
- Mo-41Re
- Mo-47.5Re
- C-103
- Ta

Ti-Base

- Ti6Al4V
- γ-TiAl
- Ti-6-2-4-2

Co-Base

- CoCr
- Stellite 6, 21, 31

Bimetallic

- GRCop-84/IN625
- C-18150/IN625

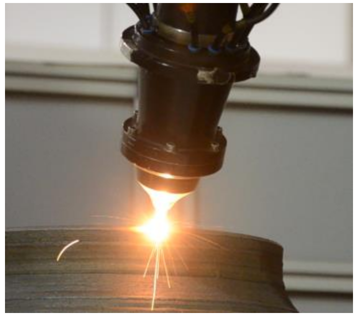
MMC

- Al-base
- Fe-base
- Ni-base

Industry Materials developed for L-PBF, E-PBF, and DED processes (*not fully inclusive*)

Comparison of L-PBF and DED

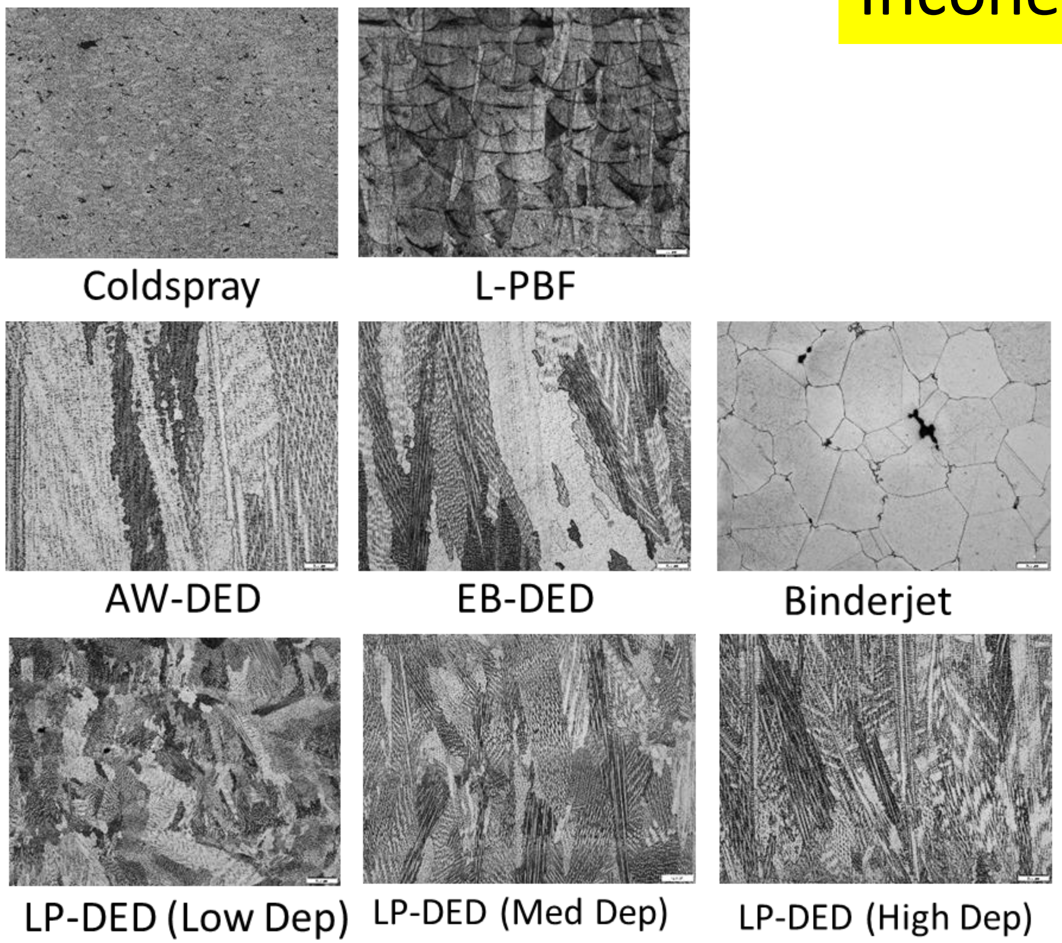
Different methods for different components!

	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 (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

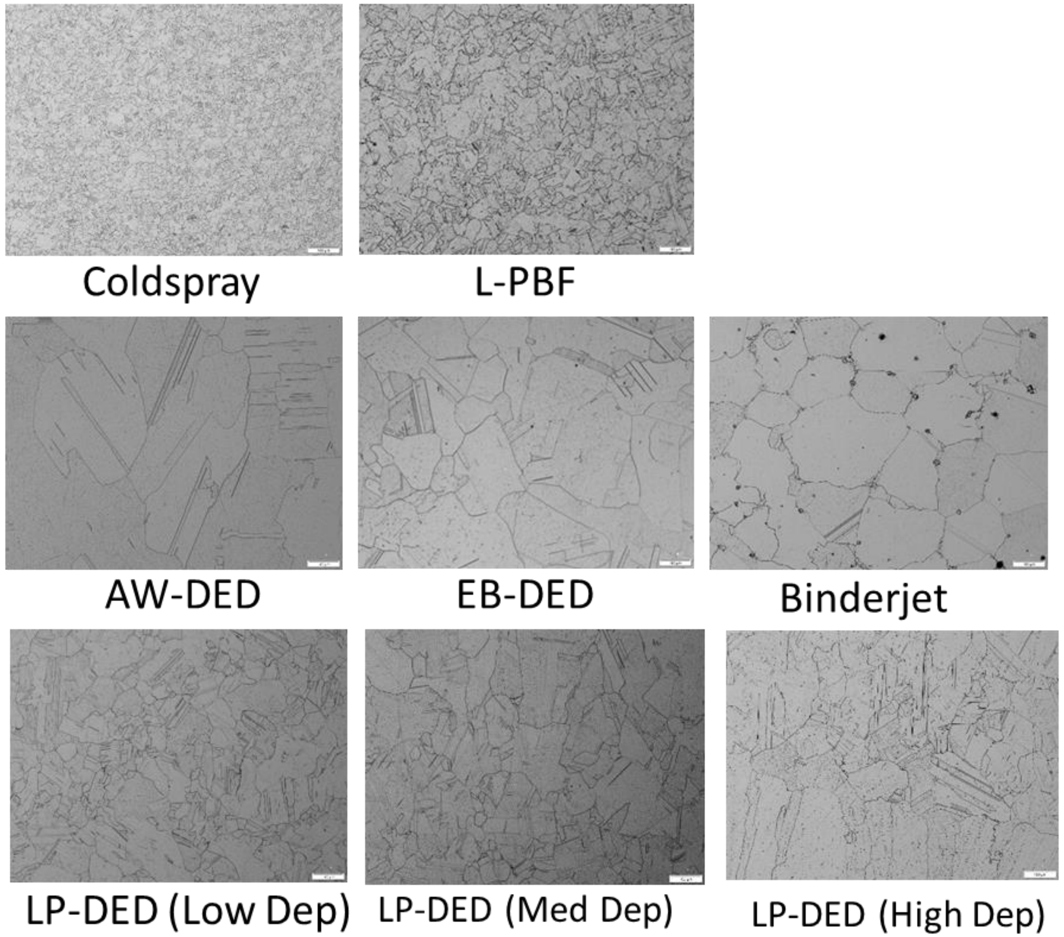
Each process results in different material characteristics

Inconel 625

As-Built


Coldspray
L-PBF
AW-DED
EB-DED
Binderjet
LP-DED (Low Dep)
LP-DED (Med Dep)
LP-DED (High Dep)

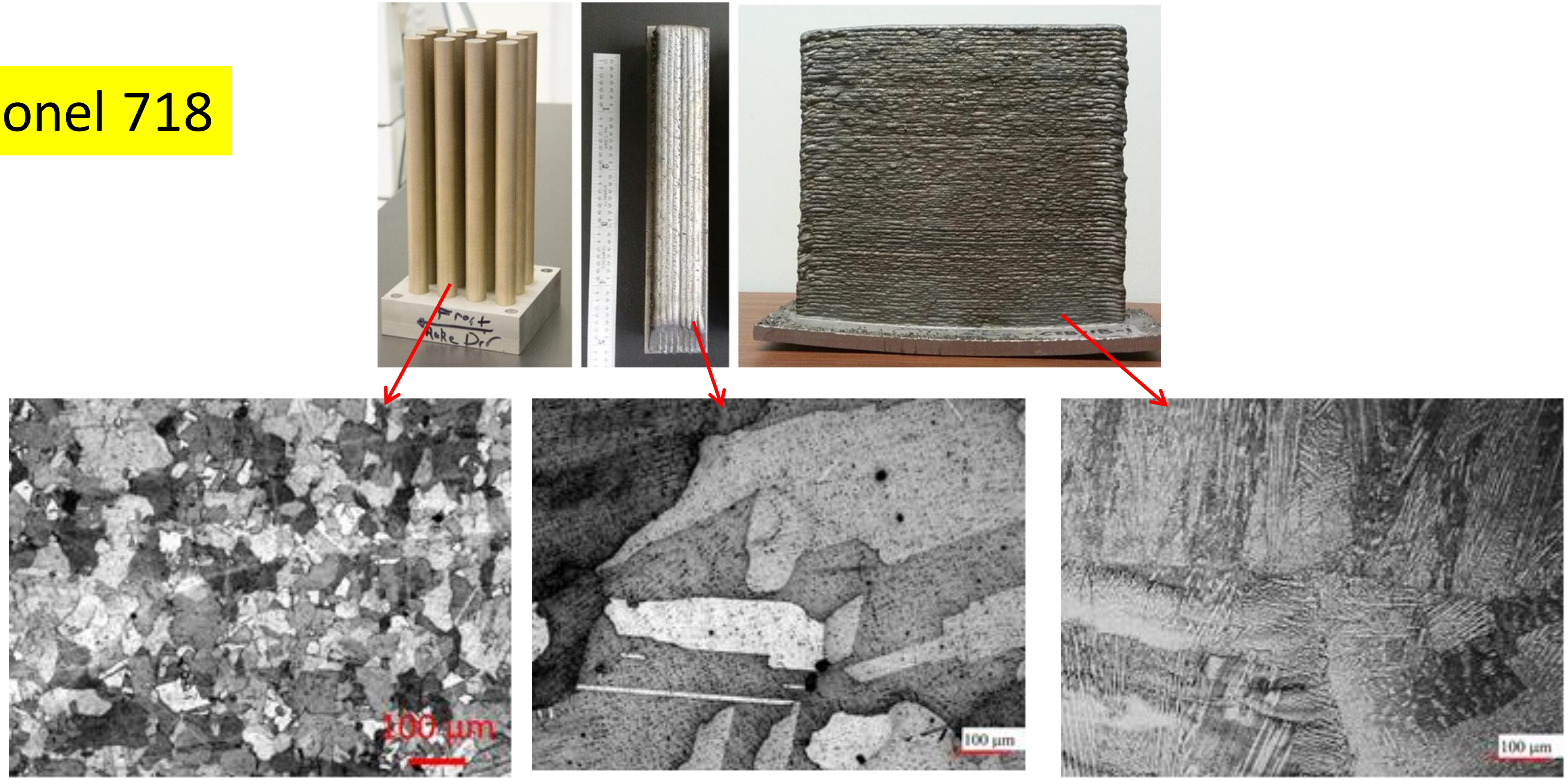
SR + HIP + Sol


Coldspray
L-PBF
AW-DED
EB-DED
Binderjet
LP-DED (Low Dep)
LP-DED (Med Dep)
LP-DED (High Dep)

Study Courtesy: UTEP and NASA MSFC

Microstructure – Different AM Processes

Inconel 718



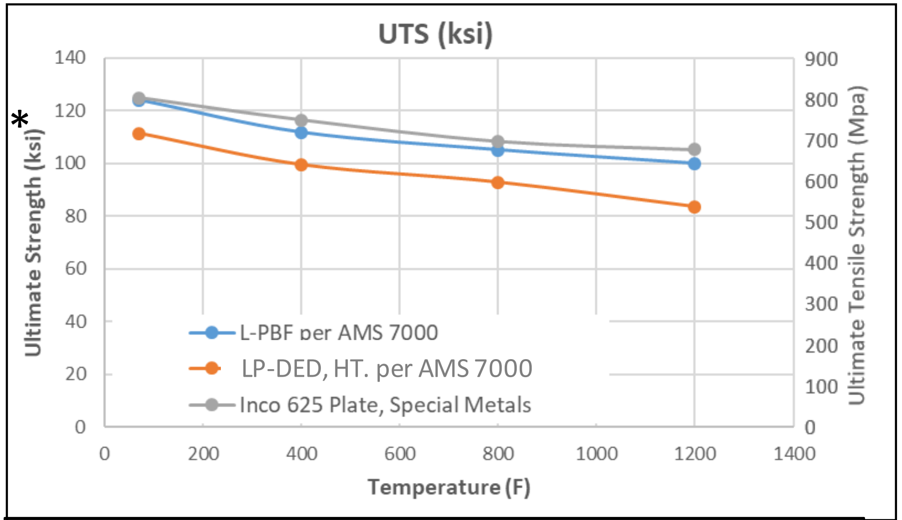
Laser Powder Bed Fusion (L-PBF) Laser Powder DED (LP-DED) Arc Wire DED (AW-DED)

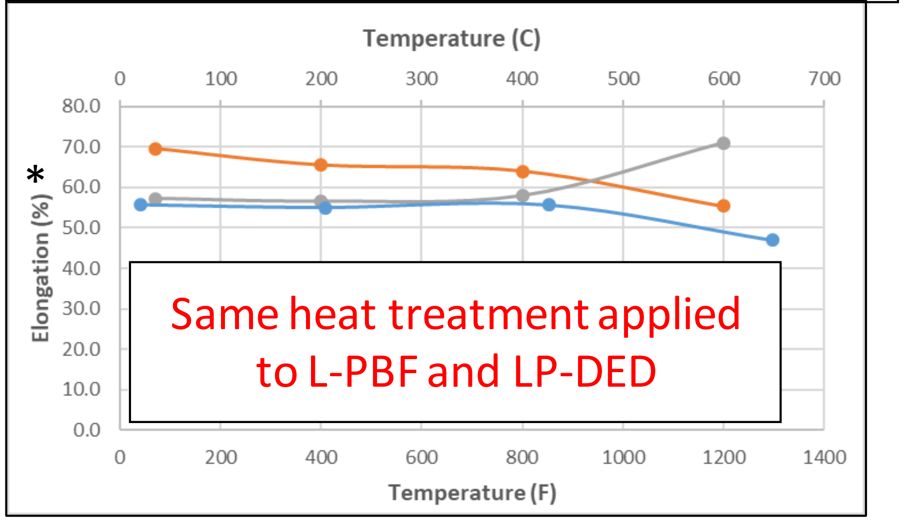
Schneider, J.A., "Comparison of microstructural response to heat treatment of Inconel 718 prepared by three different metal additive manufacturing processes," JOM, https://doi.org/10.1007/s11837-020-04021-x, vol. 72/3, pp. 1085-1091, 2020.

Material Properties for Metal

- In general, once AM processes are refined they can yield near wrought properties
- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Coldspray,….), 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 structures, which ultimately have an effect on properties
- Heat treatments should be developed based on the requirements and environment of the end component use
- Properties should be developed after AM process is stable and parameters confirmed

Example of Inconel 625, L-PBF and LP-DED (Typical)





Same heat treatment applied to L-PBF and LP-DED

*Not design data and provided as an example only

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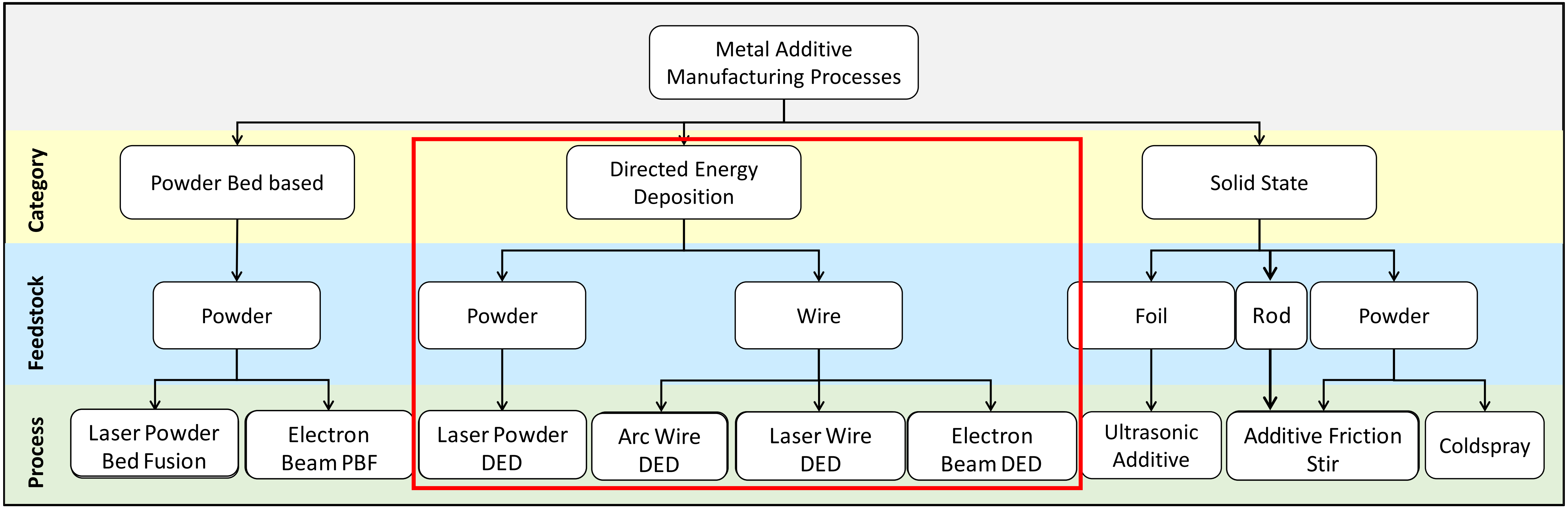

Category

Feedstock

Process

Metal Additive Manufacturing Processes
- Powder Bed based
  - Powder
    - Laser Powder Bed Fusion
    - Electron Beam PBF
- Directed Energy Deposition
  - Powder
    - Laser Powder DED
  - Wire
    - Arc Wire DED
    - Laser Wire DED
    - Electron Beam DED
- Solid State
  - Foil
    - Ultrasonic Additive
  - Rod
    - Additive Friction Stir
  - Powder
    - Additive Friction Stir
    - Coldspray

*Does not include all metal AM processes

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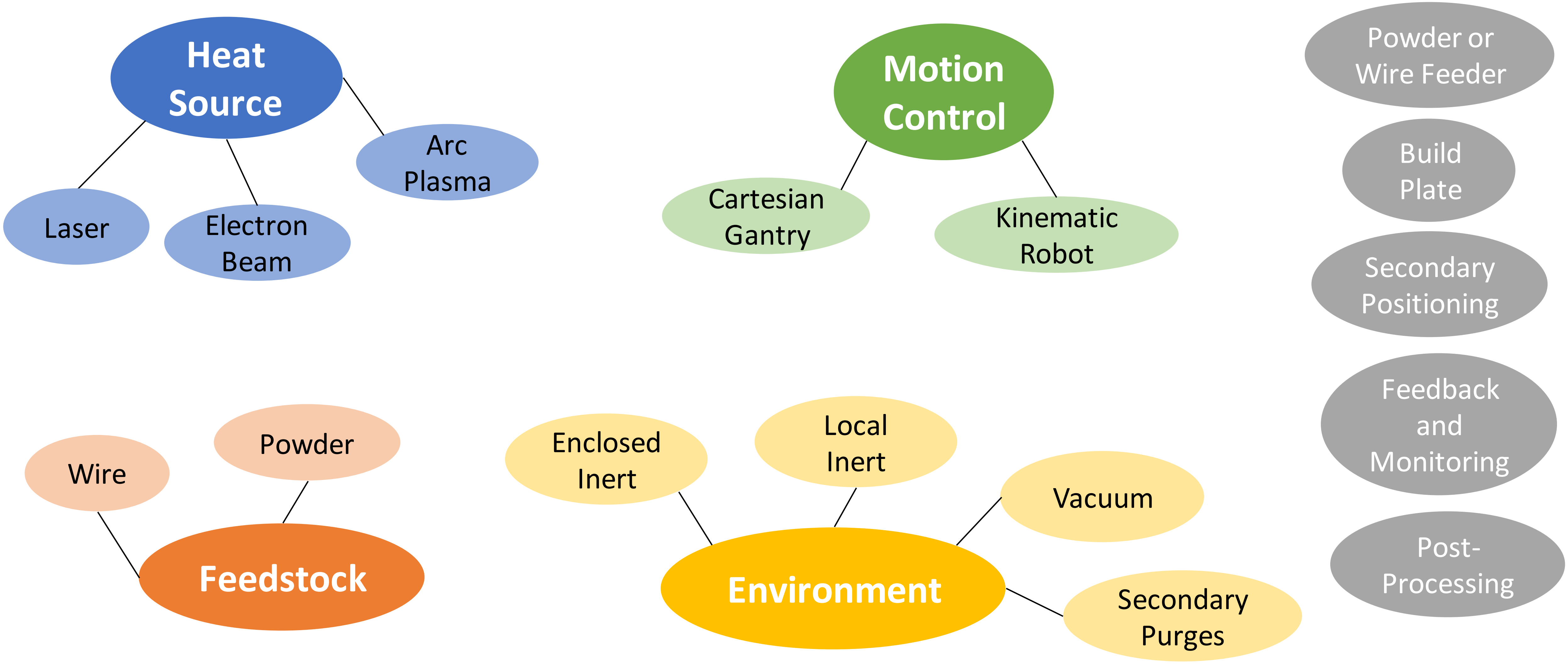
- Ek, K., "Additive Manufactured Metals," Master of Science thesis, KTH Royal Institute of Technology (2014).

Why DED?

- Each Metal AM technique provides advantages and disadvantages
- 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 roughness

Aspects of AM DED Systems



Various DED Technologies

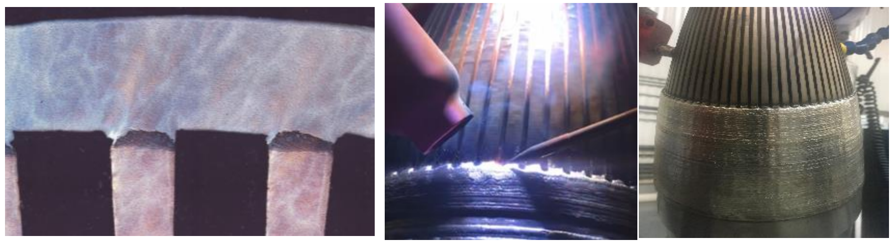
Freeform fabrication technique focused on near net shapes as a forging or casting replacement and also near-final geometry fabrication. Can be implemented using powder or wire as additive medium.

Laser Powder DED (LP-DED)

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

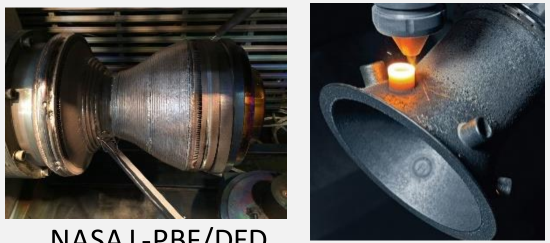
Laser Wire DED (LW-DED) / Hotwire

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 DED

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

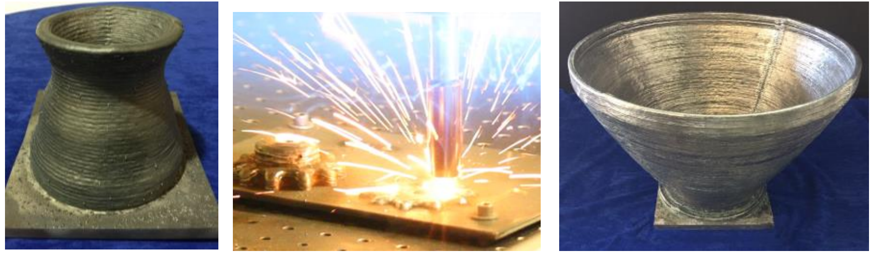


NASA L-PBF/DED

*Photos courtesy DMG Mori Seiki and DM3D

Arc Wire DED (AW-DED)

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

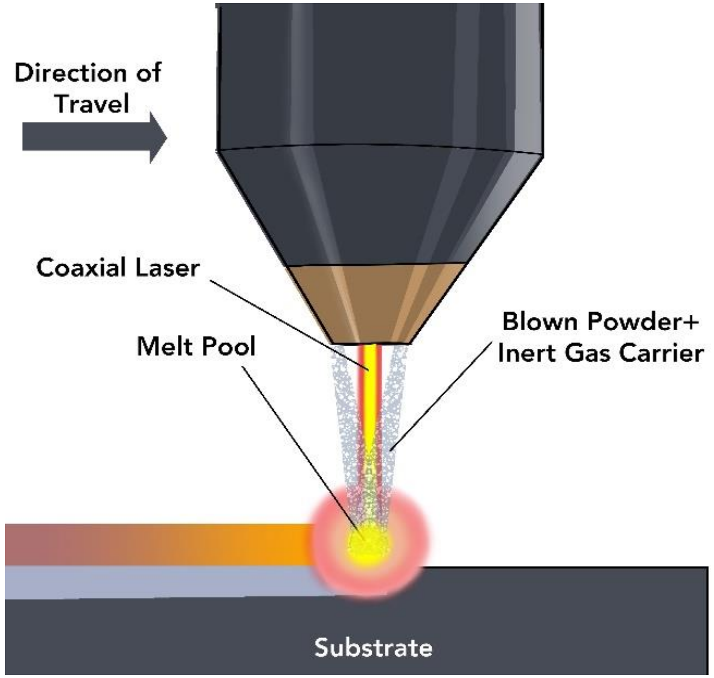


Electron Beam DED (EB-DED)

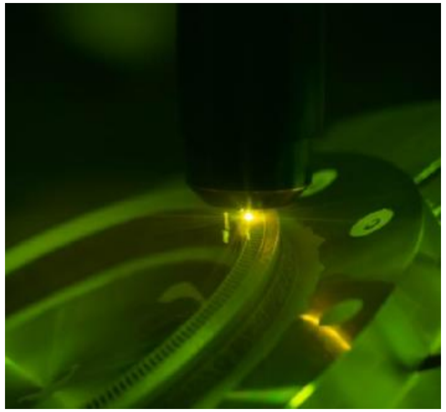
An off-axis wire-fed deposition technique using electron beam as energy source; completed in a vacuum.

Laser Powder DED

- 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 than L-PBF, higher heat input



DED NASA HR-1 Liner



Integrated Channel DED Nozzle

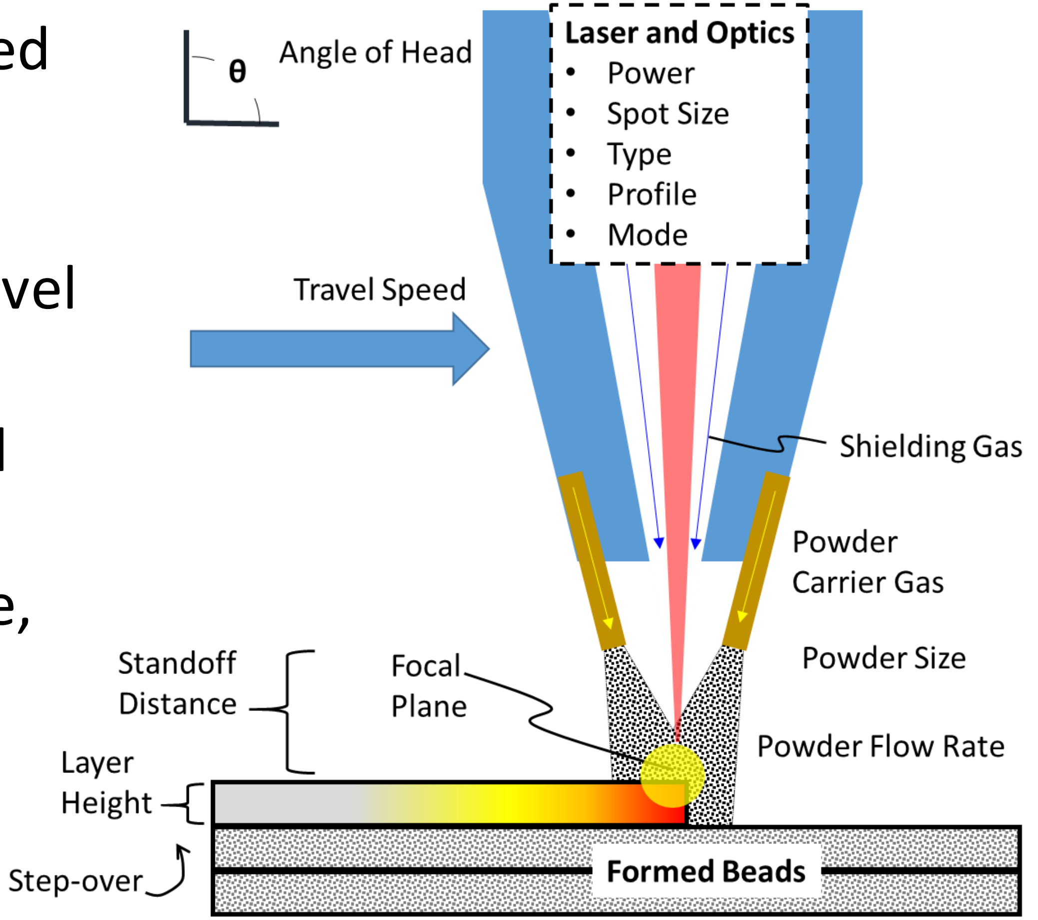
Inco 718, 1:4 Scale

JBK-75, IN625, NASA HR-1 Manifolds

JBK-75 Integrated Channel

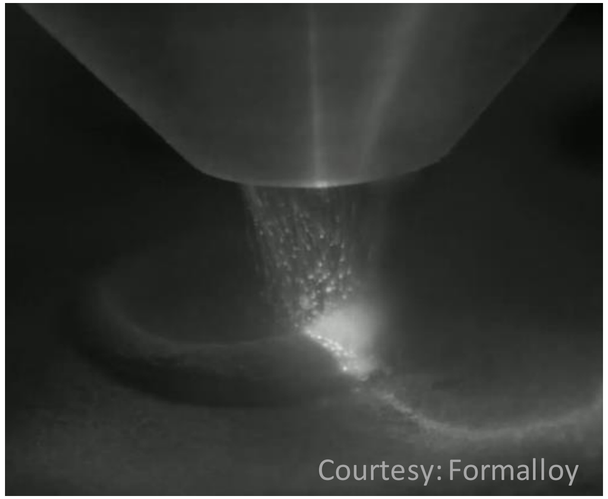
LP-DED Process Overview

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



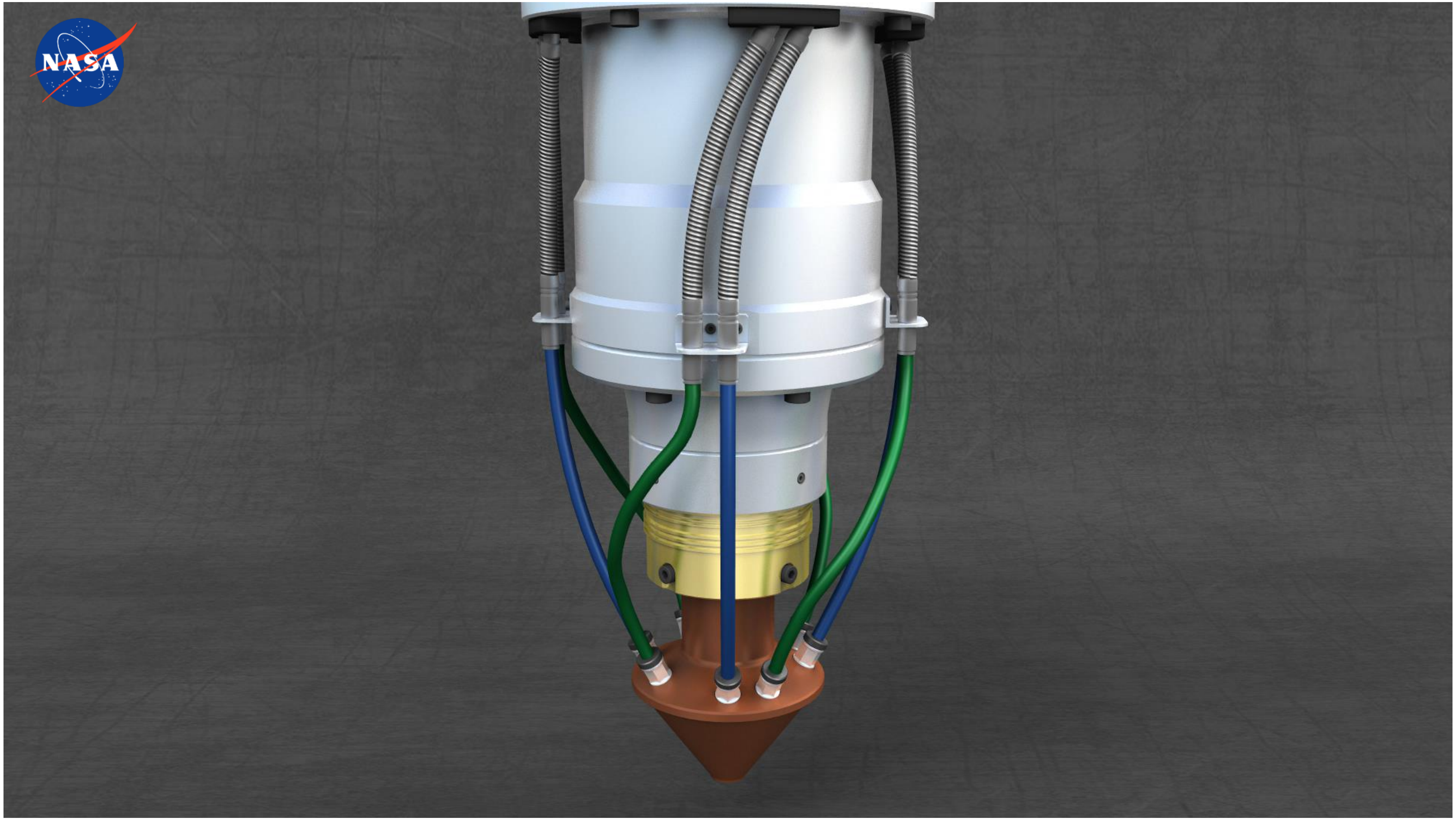
AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl , Protz, Mireles, Garcia (unreleased)


Courtesy: BeAM

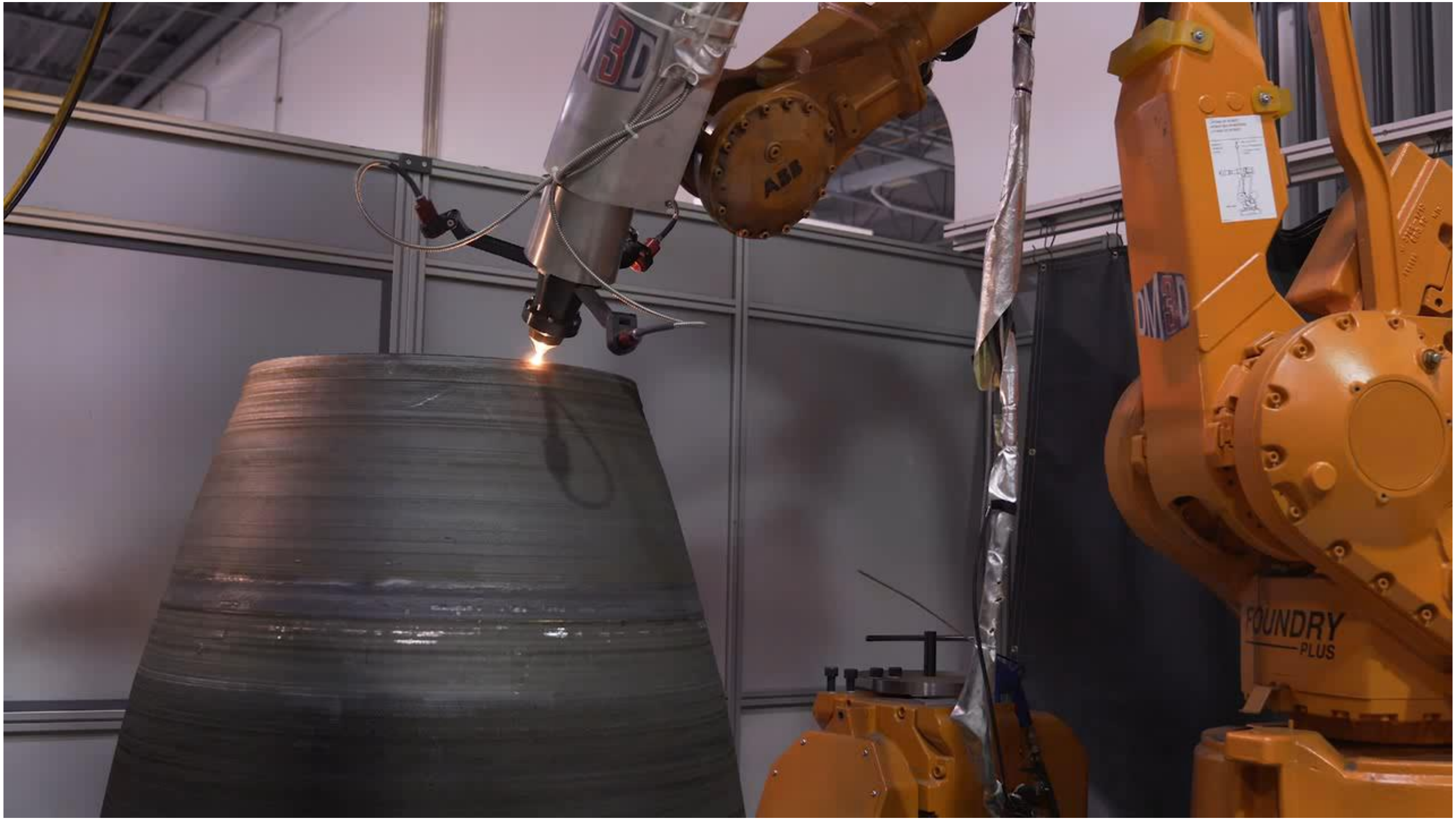

Courtesy: Formalloy

- 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 et al (unreleased)

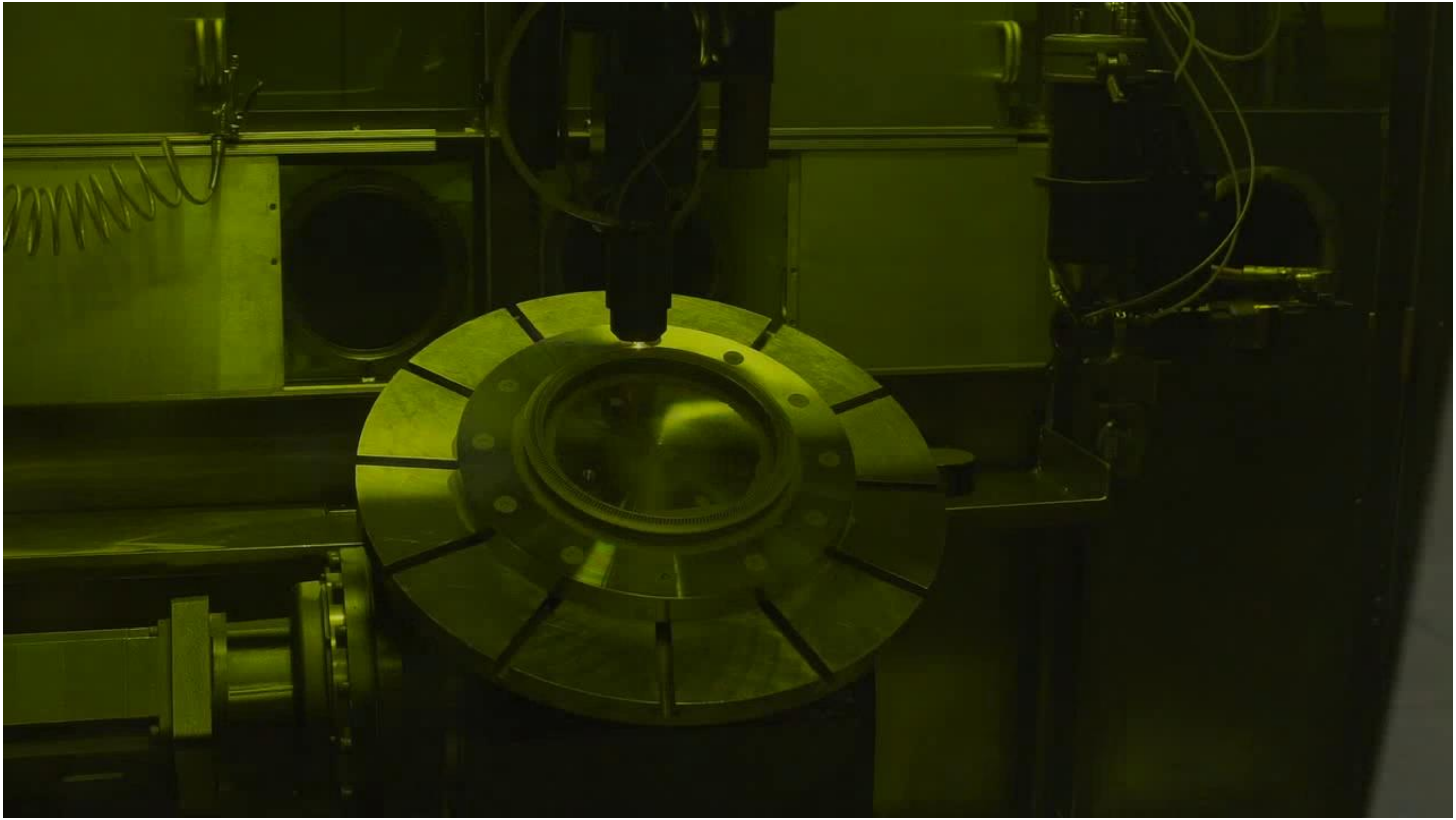
Animation of LP-DED Process



Example of LP-DED for large scale



Example of LP-DED with small features

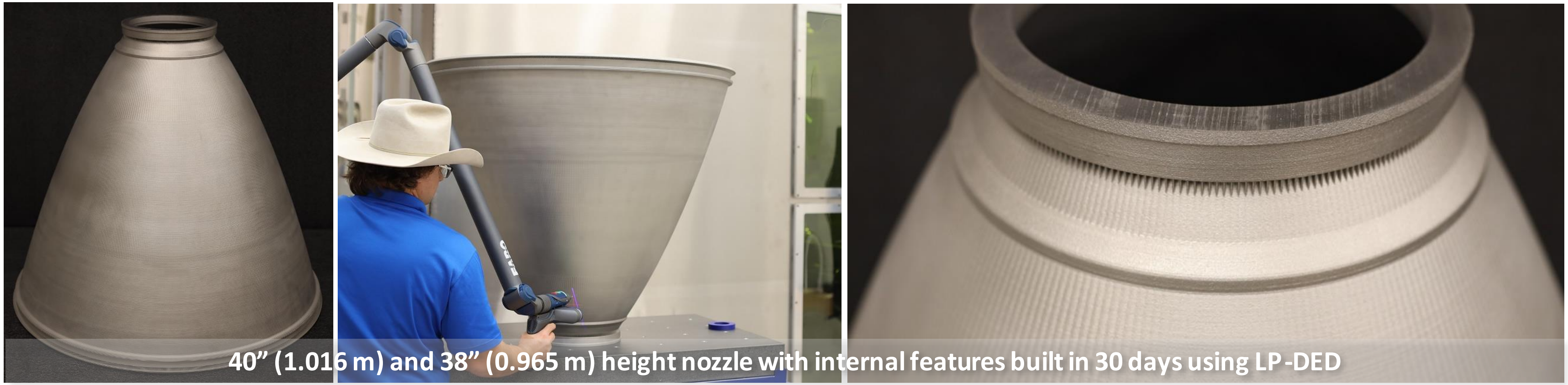


Differences in Deposition Rates for LP-DED

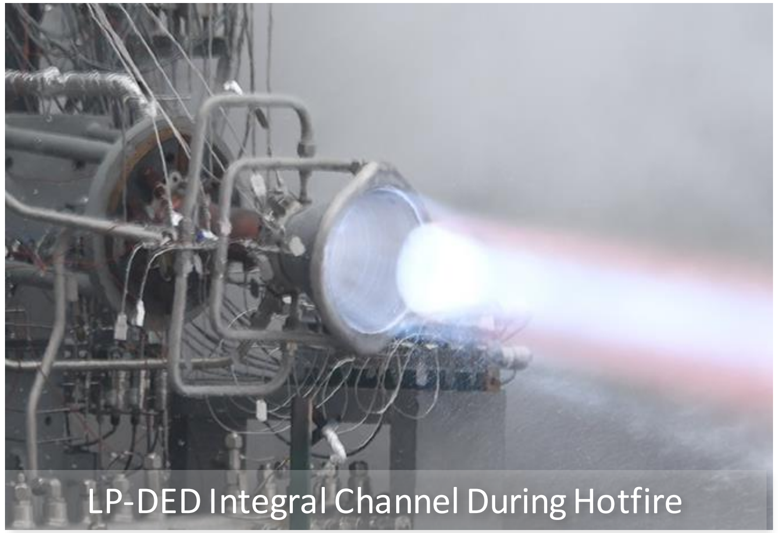
Laser Power: 1070 W	Laser Power: 2000 W	Laser Power: 2620 W
Dep. Rate: 1 in^3/hr (23 cc/hr)	Dep. Rate: 3 in^3/hr (49 cc/hr)	Dep. Rate: 5 in^3/hr (82 cc/hr)
Deposition Time: 24 hours	Deposition Time: 11 hours	Deposition Time: 6 hours

*Courtesy: RPM Innovations

Examples of Small Feature Large Scale LP-DED



40” (1.016 m) and 38” (0.965 m) height nozzle with internal features built in 30 days using LP-DED



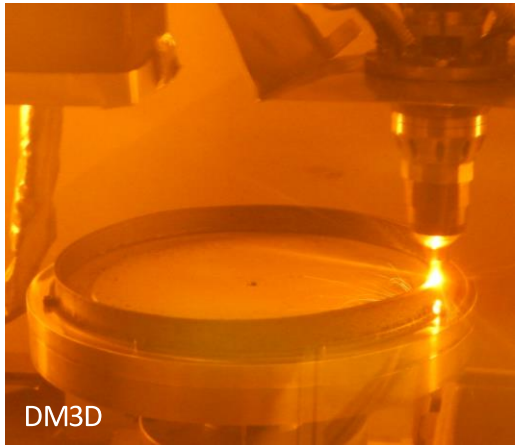
LP-DED Integral Channel During Hotfire

Courtesy: RPM Innovations (RPMI)

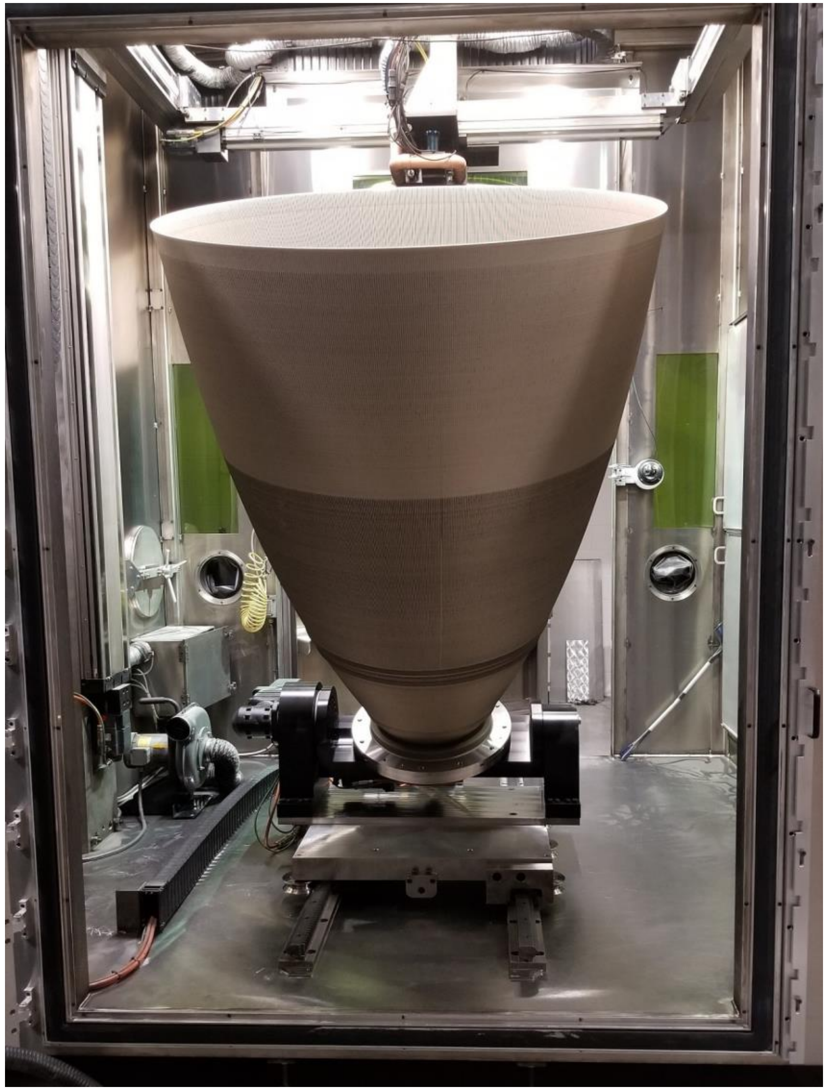
Component Applications using LP-DED

½ Scale RS25 Nozzle Liner

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



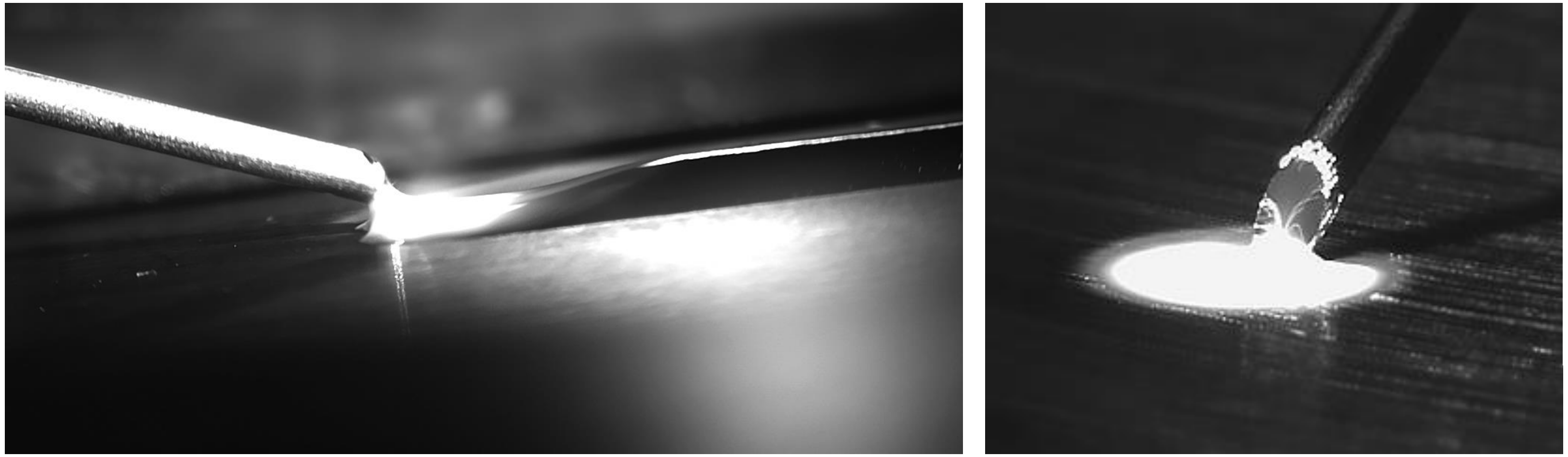
LP-DED Large Scale Nozzle with Fine Features

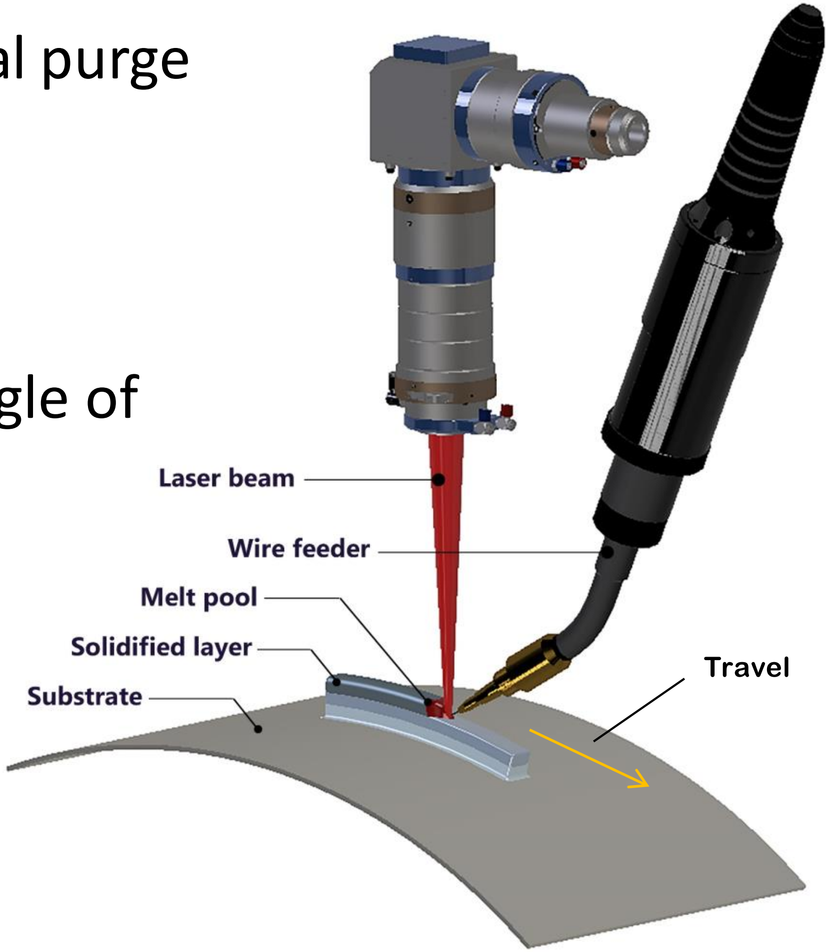


60” (1.52 m) diameter and 70” (1.78 m) height
90 day deposition

Laser Wire DED

- Uses a laser energy source with a off-axis wire feed and local purge
- 100% efficiency in material usage
- High deposition rates, but balances low heat input
- Can be used on complex surfaces
- Key parameters: Laser Power, Wire feedrate, Travel rate, Angle of Head, Shielding gas flowrate

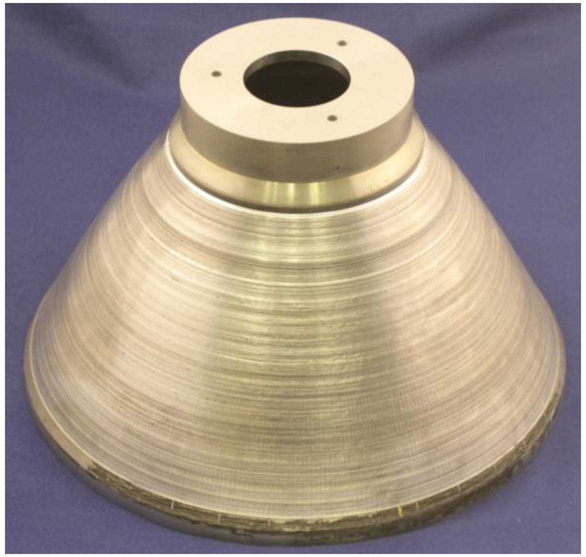


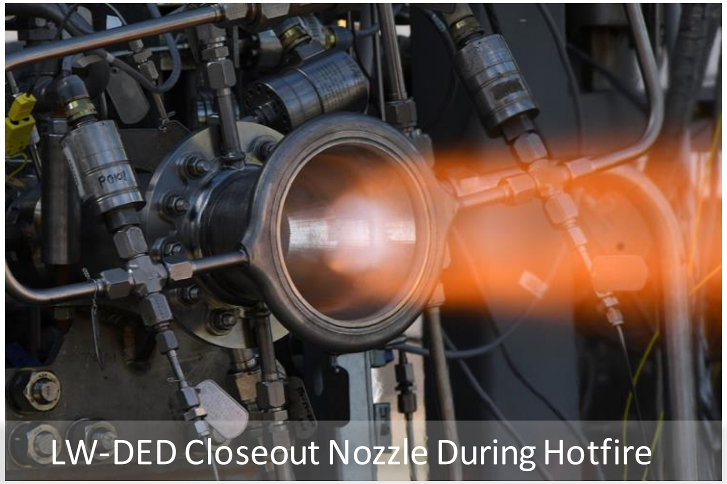


All Images Courtesy of Procada

LW-DED Component Examples

- Used on a variety of components including rocket nozzles
- Add secondary material “in-place” or freeform deposition
- Multi-alloys demonstrated



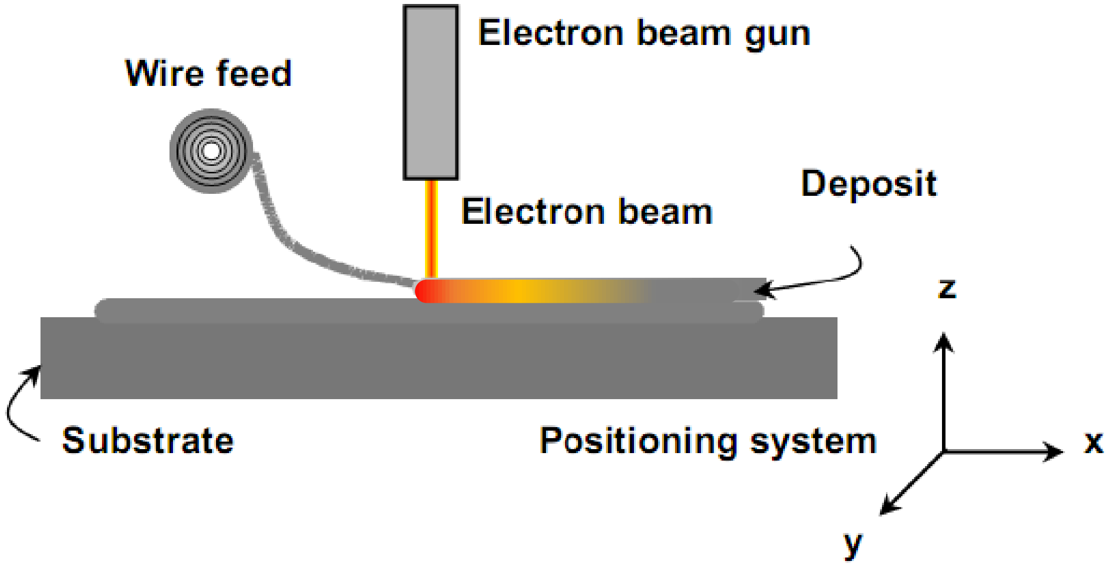


LW-DED Closeout Nozzle During Hotfire

LW-DED using multi-alloys

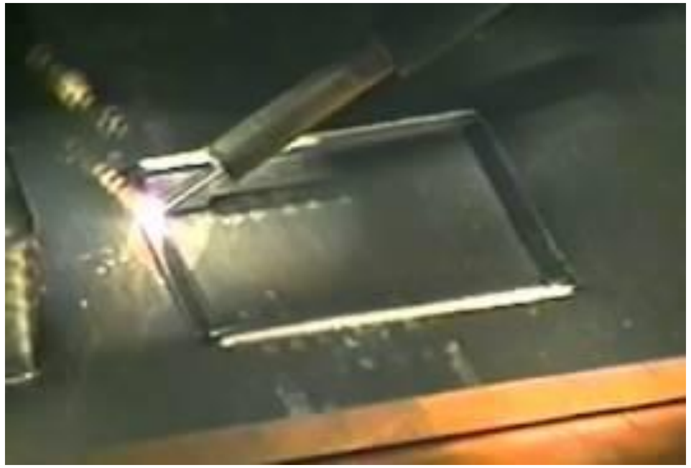
Electron Beam DED

- Uses electron beam energy source with a wire feed inside vacuum chamber
- 100% efficiency in material usage
- High deposition rates
- Key parameters: Beam current and acceleration voltage, Wire Feedrate, Travel Rate, Angle of Turntable



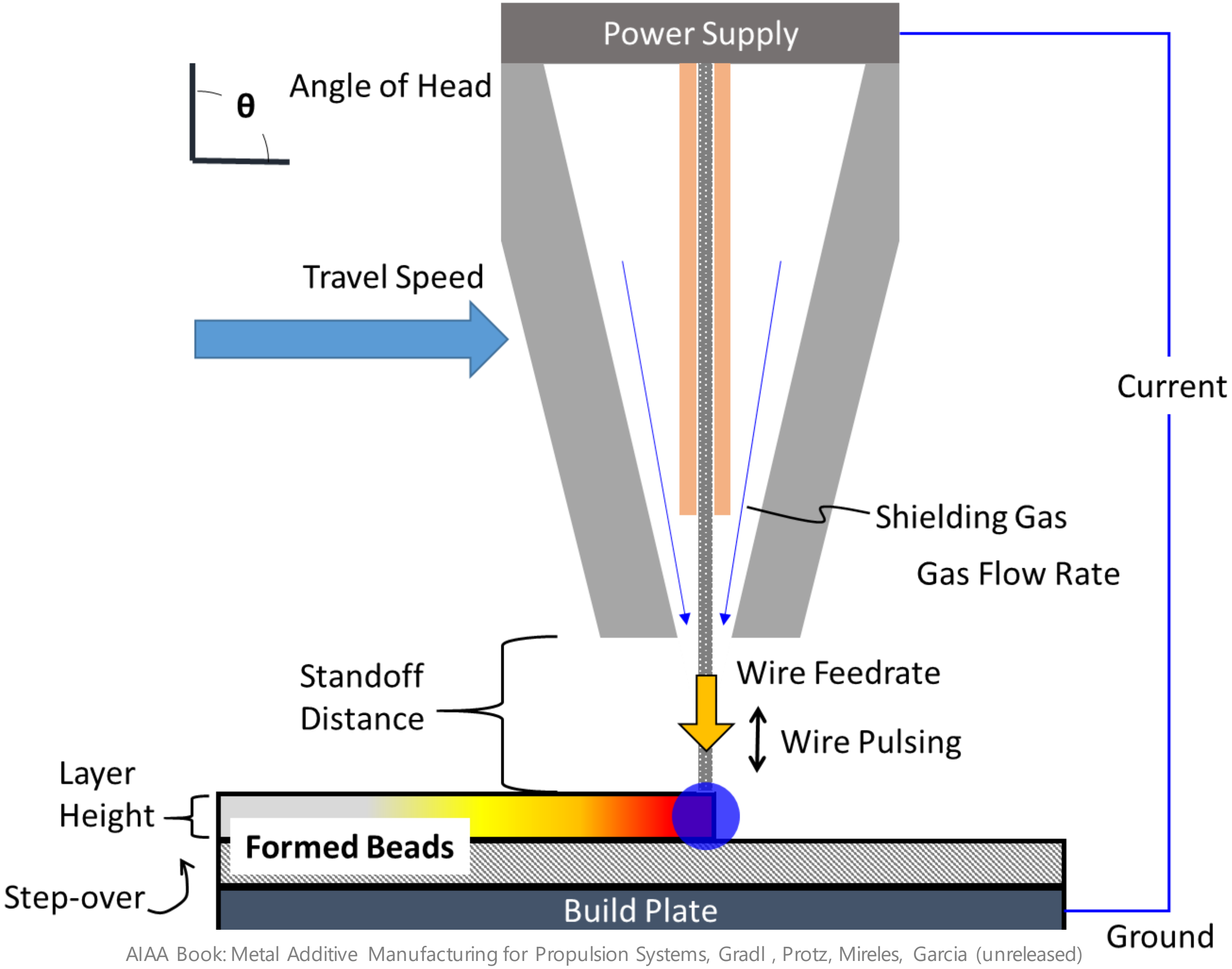
Monolithic EB-DED Freeform

EB-DED Inco 625 Jacket on L-PBF GRCop-84 Liner



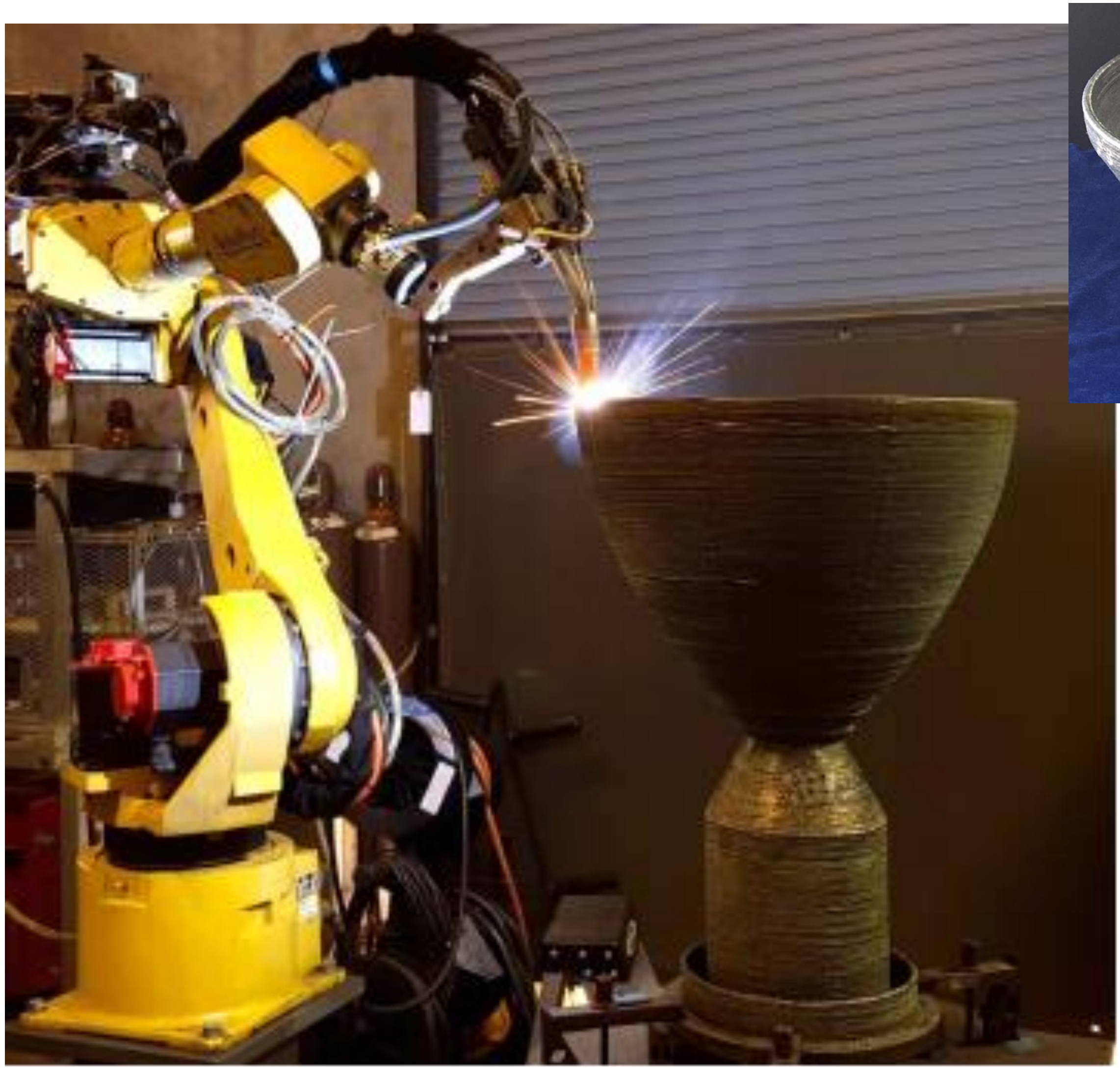
Arc Wire DED

- Electric energy source providing arc with co-axial wire feed and local purge
- Very high efficiency of material usage
- Low cost process
- Key parameters: Voltage, Current, Wire Pulse Rate, Wire Feedrate, Travel Rate, Angle of Head and Turntable, Shielding Gas flowrate



AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl , Protz, Mireles, Garcia (unreleased)

Arc Wire DED

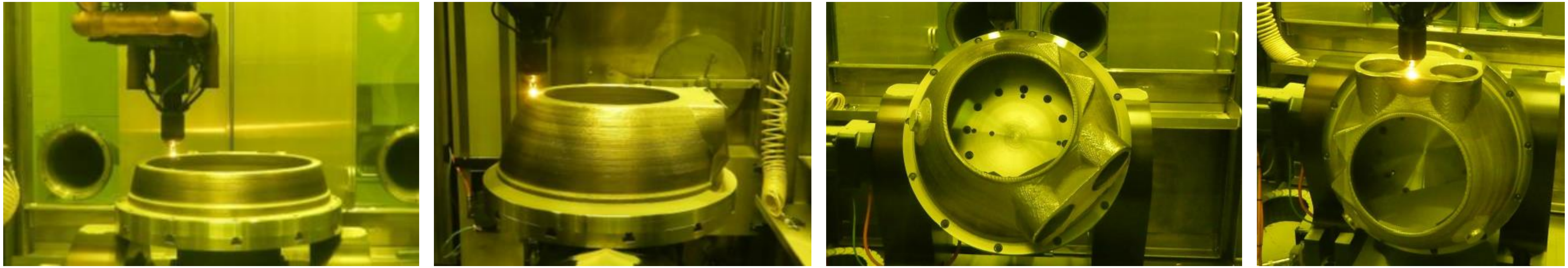


Courtesy: Keystone Synergistic

Courtesy: GEFERTEC

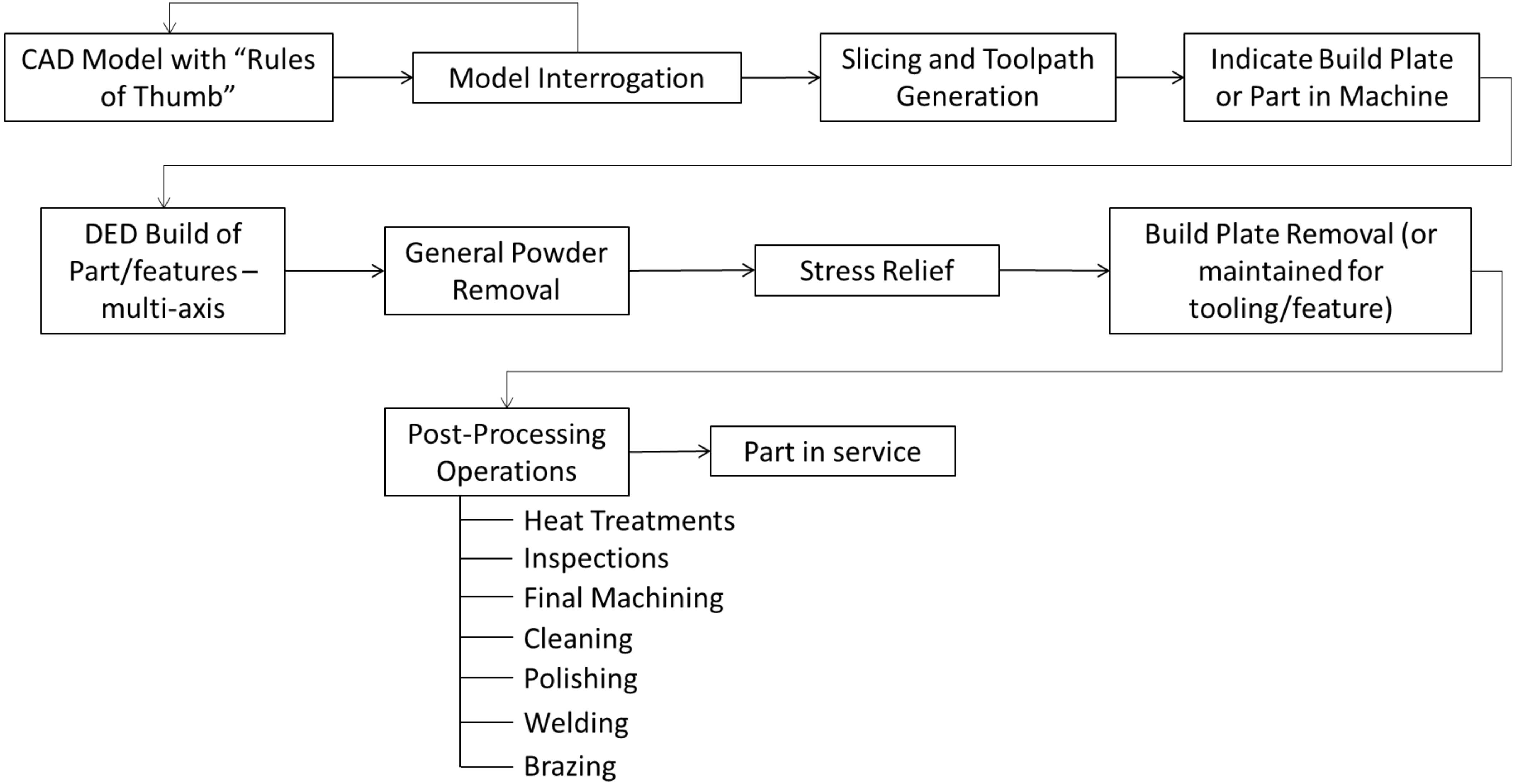
Freedom in DED design and deposition strategies

Ability to use multiple axes for complex features fabricated locally



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

Typical DED Process Flow



CAD Model with "Rules of Thumb"

Model Interrogation

Slicing and Toolpath Generation

Indicate Build Plate or Part in Machine

DED Build of Part/features – multi-axis

General Powder Removal

Stress Relief

Build Plate Removal (or maintained for tooling/feature)

Post-Processing Operations

Part in service

- Heat Treatments
- Inspections
- Final Machining
- Cleaning
- Polishing
- Welding
- Brazing

AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl , Protz, Mireles, Garcia (unreleased)

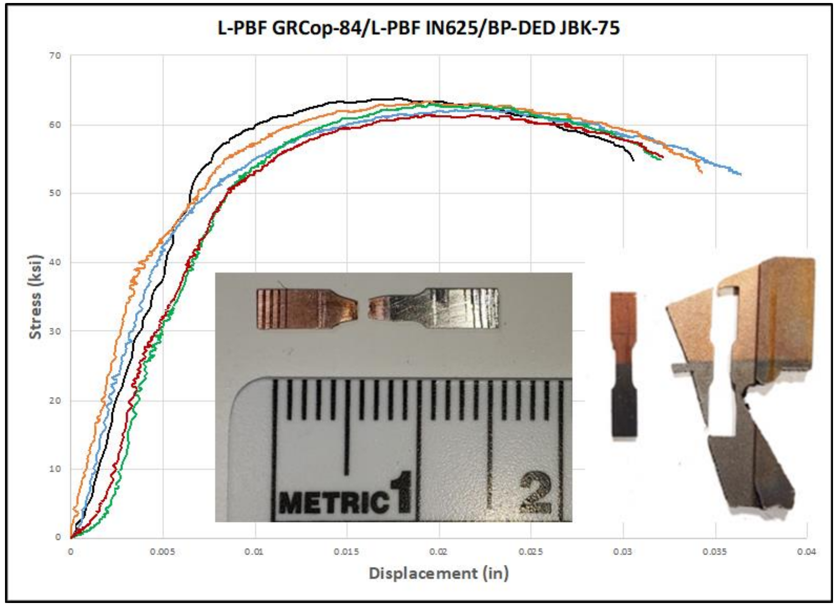
Bimetallic and Multi-metallic Additive Manufacturing for Components

- Bimetallic and multi-metallic joints may be necessary in some designs to minimize weight by using high strength-to-weight materials locally based on component load requirements
  - Locations include for joining manifolds on the chamber and axial joint between chamber and nozzle
- Evaluation of various processes including Cold Spray, Laser Hot Wire, and Laser Powder DED
- Demonstrating fundamental materials characterization and large scale hardware


Coldspray Chamber Demo


Cold Spray

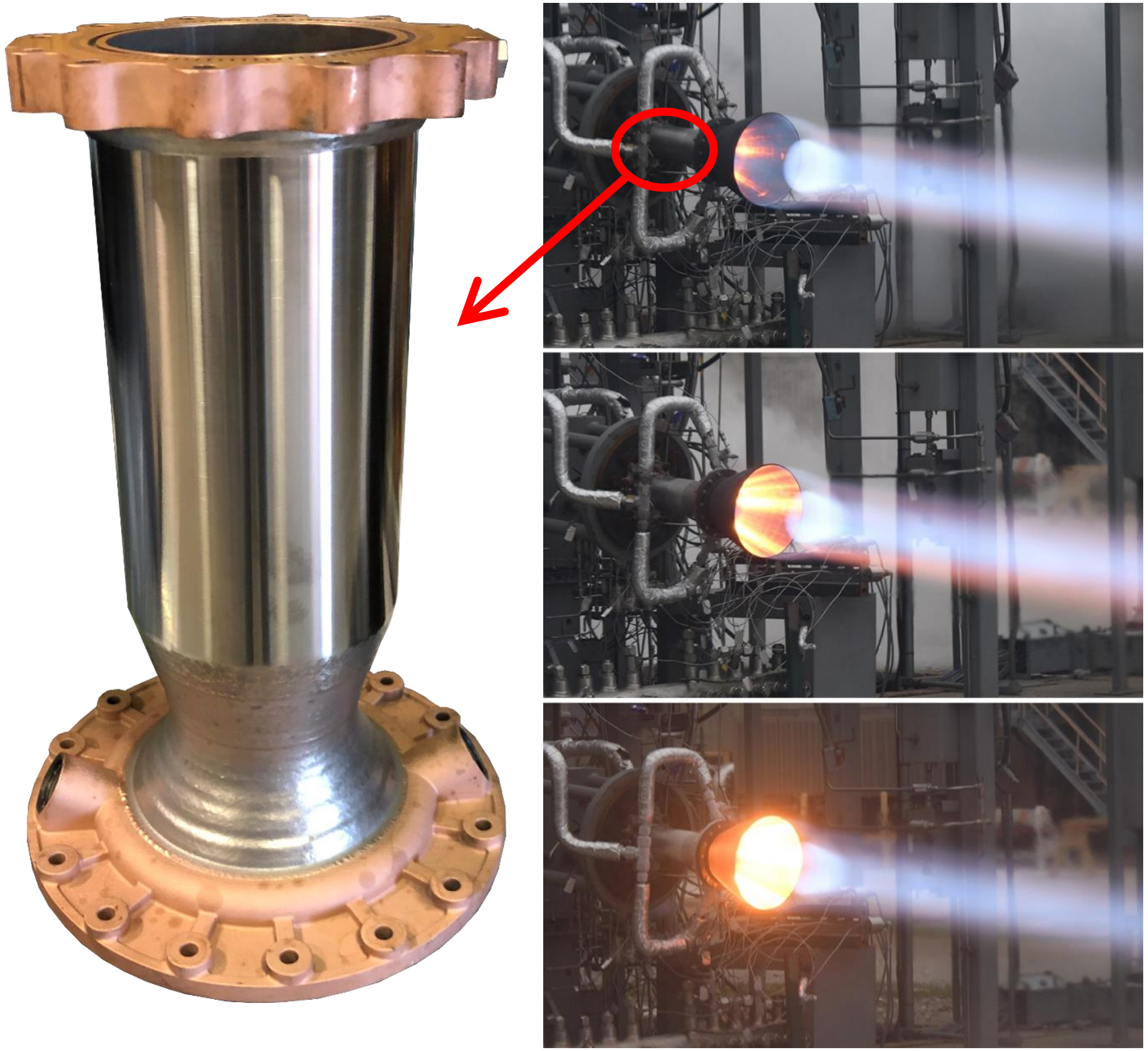

Laser Hot Wire



Microtensile testing of Bimetallic/Multi-metallic Joints


2k-lb$_f$ Blow Powder DED Coupled Bimetallic Chamber

Bimetallic and Multimetallic AM

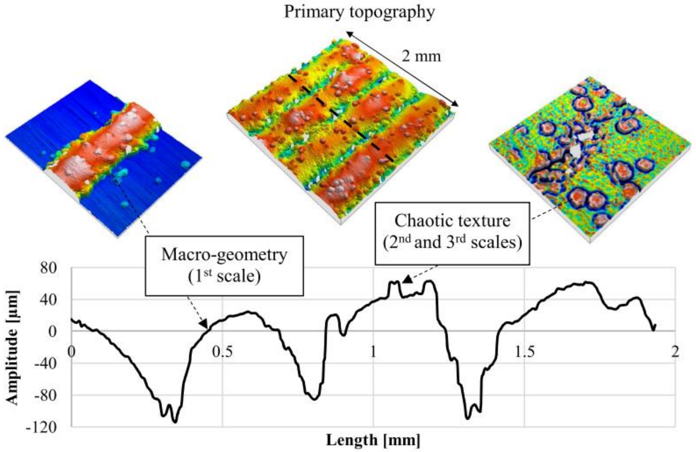


Coldspray

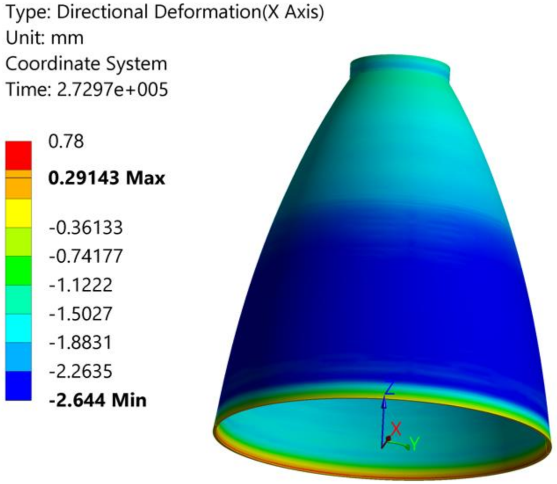
Laser Powder DED

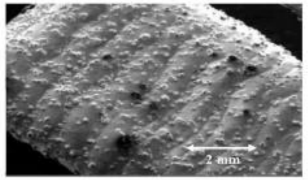
Challenges with DED

- Machining
- Programming / Tooling
- Pre-heating (some processes)
- Surface Roughness
- Smaller supply chain
- Residual Stresses and distortion
- Joining (can differ than wrought)
- Weld/deposition failures:
  - Melt pool instabilities
  - Lack of fusion
  - Oxidation
  - Deposition overrun/under
  - Delamination
  - Elemental segregations
  - Cracking

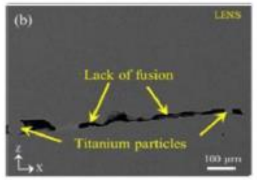


Surface Roughness

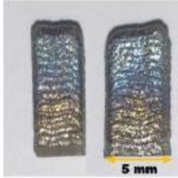




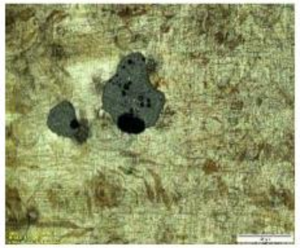
Unmelted Powder



Lack of Fusion



Oxidation



Pores

Delamination

Distortion

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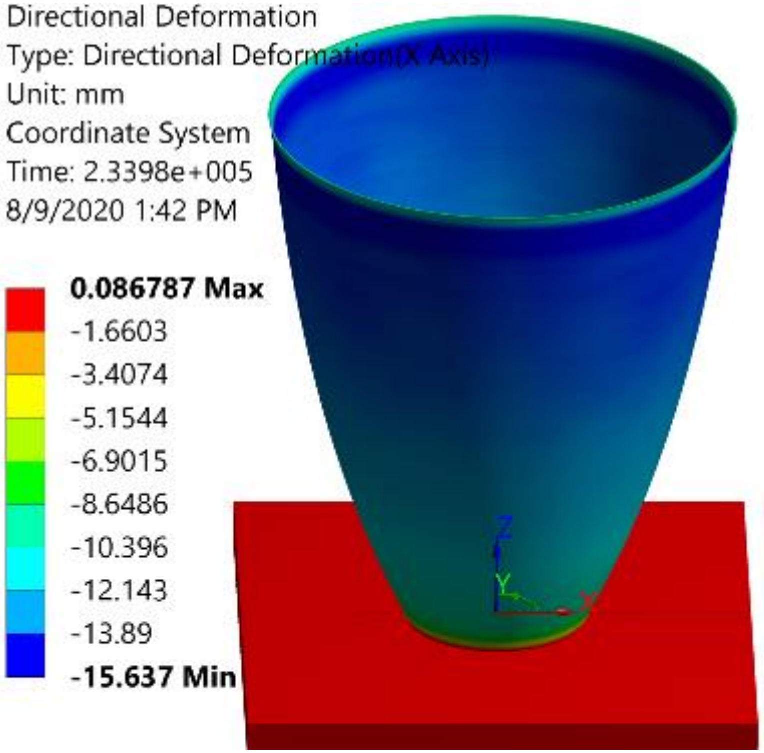
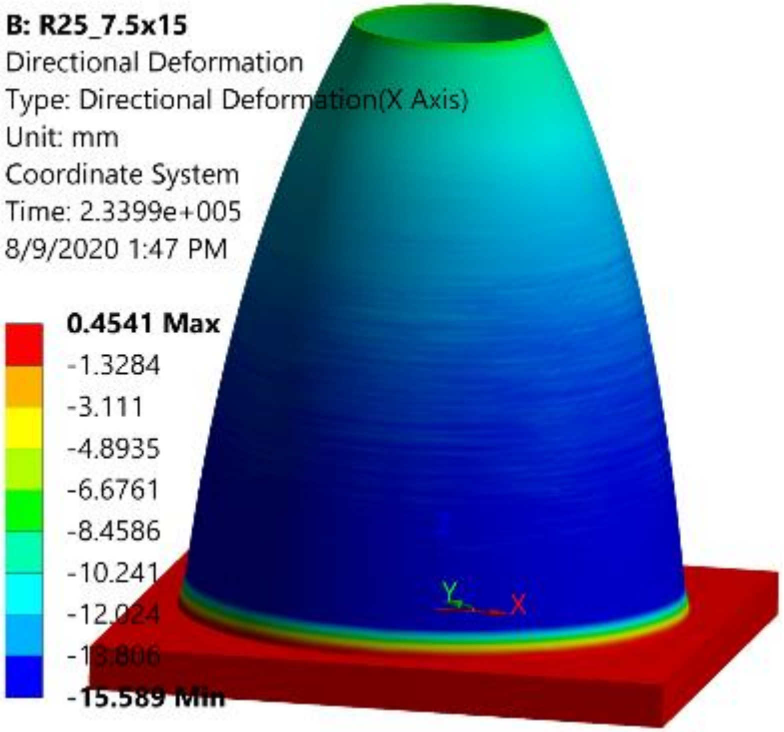
Challenges in Large Scale AM

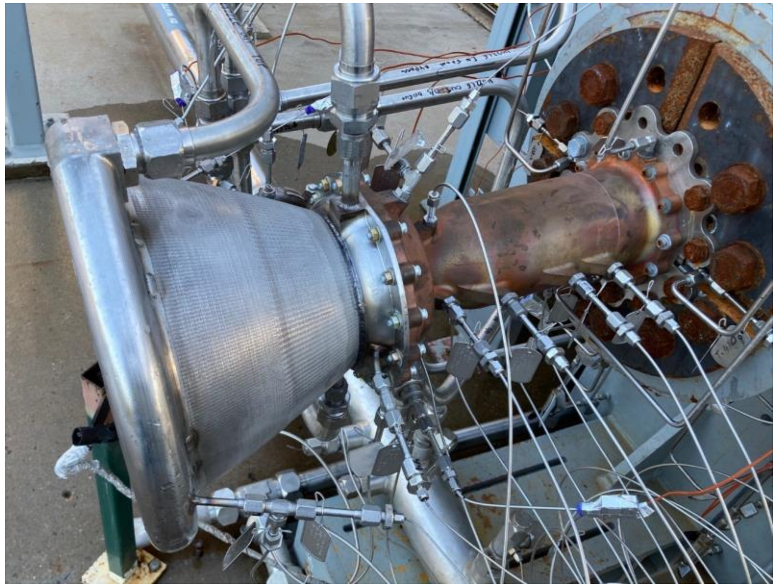
- Build durations are significantly increased with large scale AM due to amount of material being deposited
- Stops and starts will be more prevalent and re-starts may not be feasible
- Distortion is a concern with all AM processes, particularly at large scale

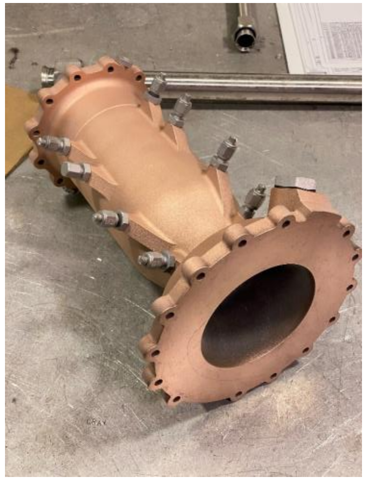




Ref: Kevin Wheeler / NASA Ames

Hot-fire Testing of Metal AM Parts





L-PBF GRCop-42 Combustion Chamber, NASA HR-1 LP-DED Nozzle, Inconel 625 L-PBF Injector

General Summary

- It's *all* welding, so same physics apply
- Additive manufacturing is not a solve-all; consider trading with other manufacturing technologies and use only when it makes sense
- Complete understanding of design process, build-process, and post-processing critical to take full advantage of AM
- DED offers a lot of flexibility for large scale and multiple material with the same build for near net shape or final shape applications
- Additive manufacturing takes practice!
- Standards and certification of the processes in-work
- AM is evolving and there is a lot of work ahead

EXPLORE MOON to MARS

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ATI
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Brad Bullard
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Ivan Locci
Jim Lydon
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AME
Westmoreland Mechanical Testing
David Myers
Ron Beshears
James Walker
Steve Wofford
Jessica Wood
Robert Hickman
Johnny Heflin
Mike Shadoan
Keegan Jackson
Many others in Industry, commercial space and others

Standards for DED Techniques

Published

- ASTM F3187-16: Standard Guide for Directed Energy Deposition of Metals

Standards under development

- ISO/ASTM PWI 52943-1
  Additive manufacturing — Process characteristics and performance — Part 1: Standard specification for directed energy deposition using wire and beam in aerospace applications
- ISO/ASTM PWI 52943-2
  Additive manufacturing — Process characteristics and performance — Part 2: Standard specification for directed energy deposition using wire and arc in aerospace applications
- ISO/ASTM PWI 52943-3
  Additive manufacturing — Process characteristics and performance — Part 3: Standard specification for directed energy deposition using laser blown powder in aerospace applications

**(PWI: Preliminary Work Item)*

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Case Studies of Additive Manufacture Research & Development at MSFC

Omar Mireles / Paul Gradl
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May 25, 2021

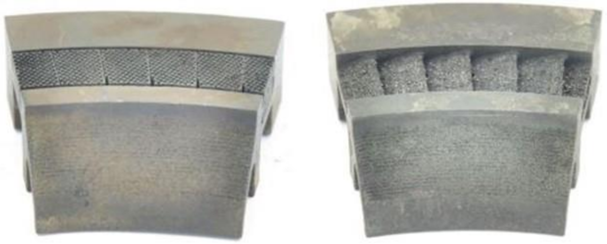
Dissolving AM IN718 Support Structures

- Process
  - Sensitizing agent applied to AM part.
  - During stress relief heat treatment the sensitizing agent diffuses 100-200 µm into the part altering surface chemical composition.
  - Sensitized region dissolved in an electrochemical process.
  - Supports and surface material <100 µm is removed.

- Objectives
  - Demonstrate viability to dissolve AM IN718 support structures.
  - L-PBF AM specimens produced and heat treated (MSFC).
  - Sensitization agent and acid development to remove supports (CSM).
  - Microstructural characterization and mechanical tests (MSFC).

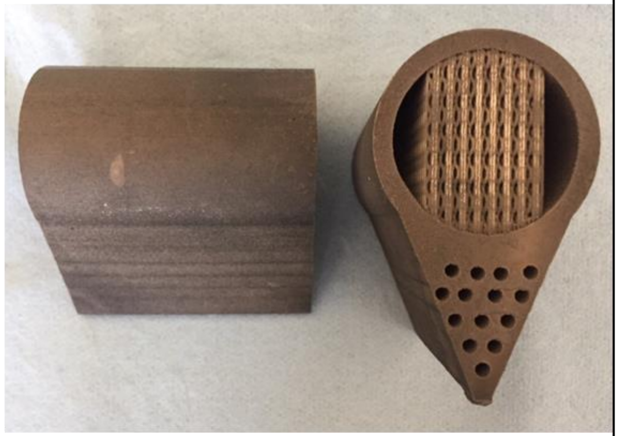
AM IN718 Concept feasibility and specimen array build layout.

- Results
  - Electrochemical dissolution of AM IN718 shown feasible.
  - Self-terminating reaction allows for support removal with minimal part impact.
  - No statistically significant impact on microstructure or mechanical properties.
  - Process should be limited to geometries that cannot be optimized for AM such as aerodynamic surfaces, thin features, and inaccessible passages.



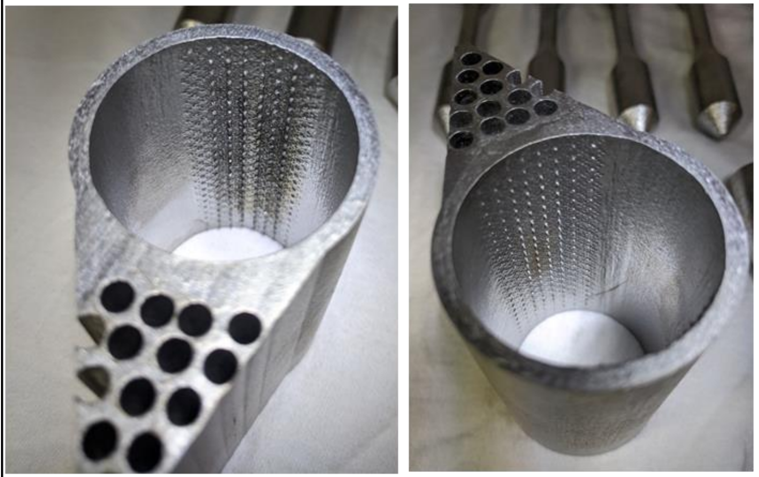
IN718 stator segments pre-etch (left) and post-etch (right). Supports dissolved sufficiently to remove via grit blasting.

Evaluation of Various Techniques for Support Removal

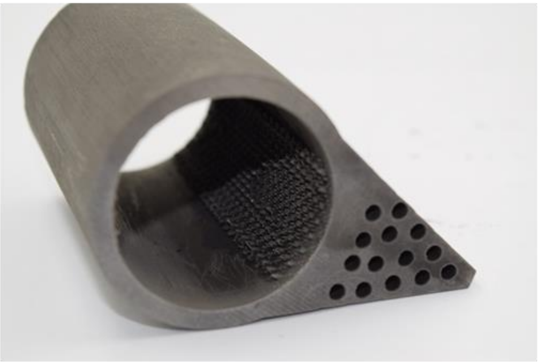


As-built Supports

Chemical Mechanical Polishing



Chemical Milling



Sensitization and Etched

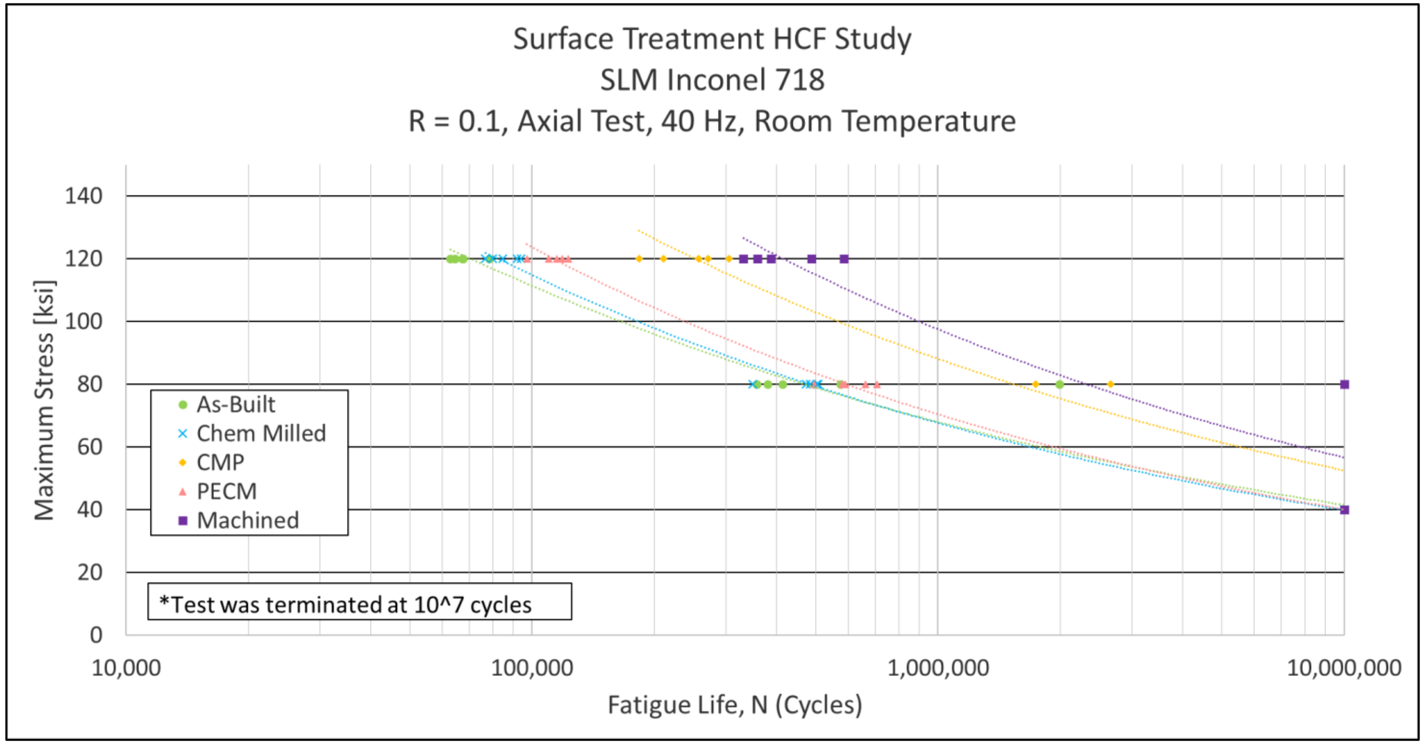
Inconel 718 L-PBF built on EOS M400 with standard parameters

- Completed Stress Relief + HIP + Solution + Aging
- Objective was to evaluate support removal of internal surfaces
- Varying levels of material removal and residual support structure
- Implementation requires proper design

Feasibility Study on Post-Processing High Cycle Fatigue

1. As-built (tensile bar)
2. Chemical Milling [CM]
3. Pulsed Electrochemical Machining [PECM]
4. Chemical Mechanical Polishing [CMP]
5. Not shown: Machined

(75) tests conducted per ASTM E4666-16 at room temperature, run-out at 10,000,000 cycles

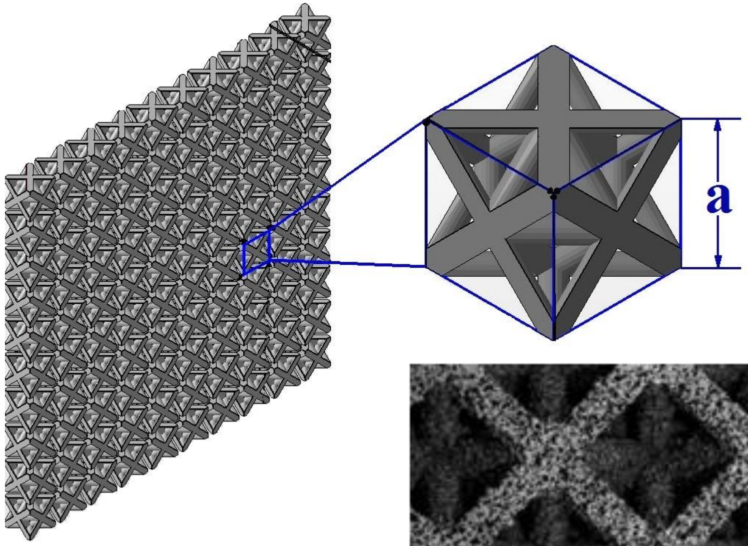


Extensive data being generated under future NASA projects on various alloys for internal and external surfaces

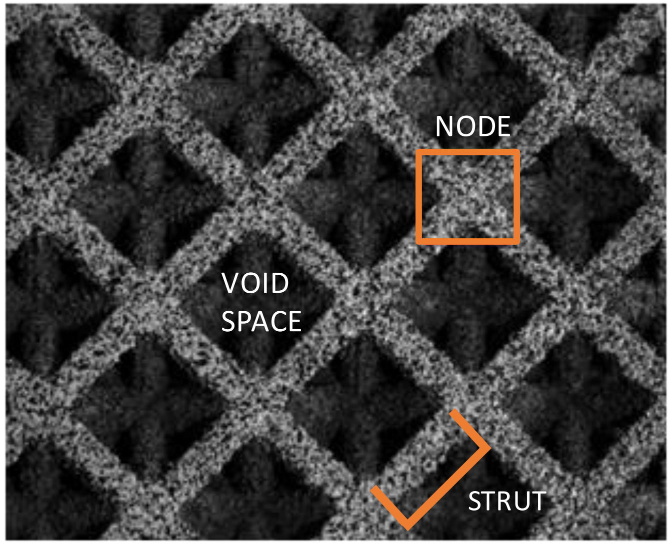
Lattice Structure Development & Application

- Applications
    - Reduce weight, retain stiffness.
    - Variable relative density & surface area.
    - Permeable solid: porous foam replacement.
    - Metal matrix composite (back infiltration).
    - Custom properties: mimic properties of different materials in the same part using the same material in adjacent regions.
- Limitations
    - Computationally expensive.
    - Inadequate property data.
- Terminology
    - Topology (lattice shape)
    - Unit cell (a)
    - Strut thickness (t)
    - Relative Density (ρ_{rel})

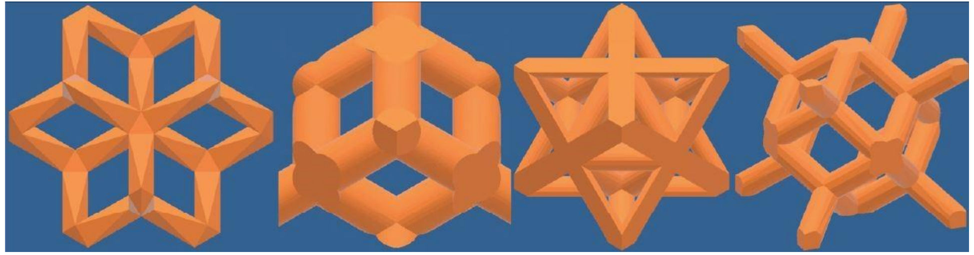
$$\rho_{rel} = \frac{V_{solid}}{V_{solid}+V_{void}} \text{ x 100 (\%RD)}$$



Lattice structure: repeating topology of unit cell (a).



Optical micrograph of Octet-Truss (30 %RD) lattice with 4 mm unit cell from AM IN718.

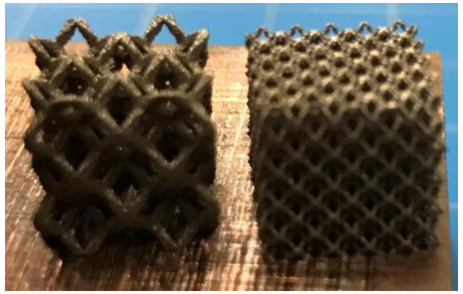


Dode Medium-13%RD

Diamond-20%RD

Octet Truss-30%RD

Rhombic Dodecahedron -20%RD

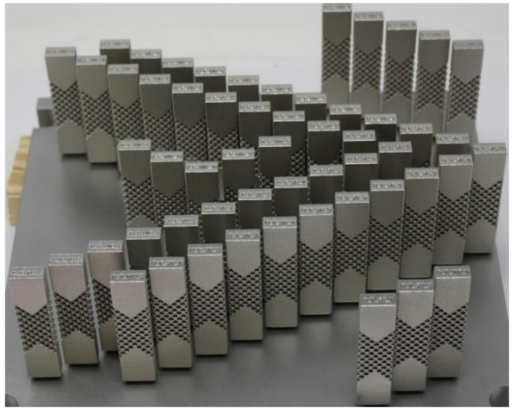


GRCop84 trial cubes (L) a = 5 mm, (R) a = 2 mm.

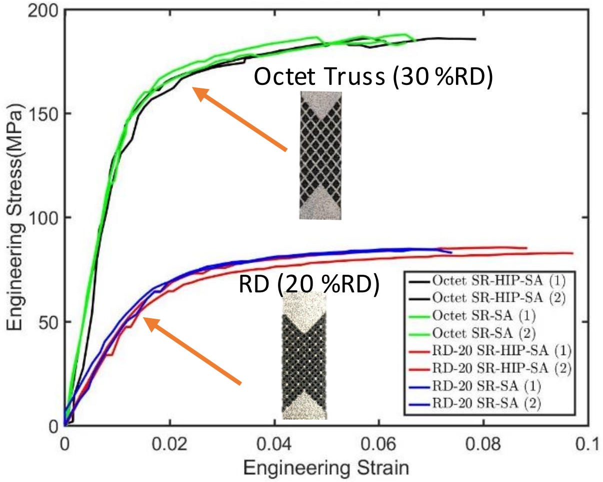
Lattice Mechanical Properties

- L-PBF IN718 vs. heat treatment at quasi-static strain rates.
- Lattice-to-solid transitions (discrete vs. gradient).
- Conditions: As-Built (AB), Stress-Relieved (SR), SR+Hot Isostatic Press (HIP), SR + HIP + Solution/Age (SA), SR+SA.

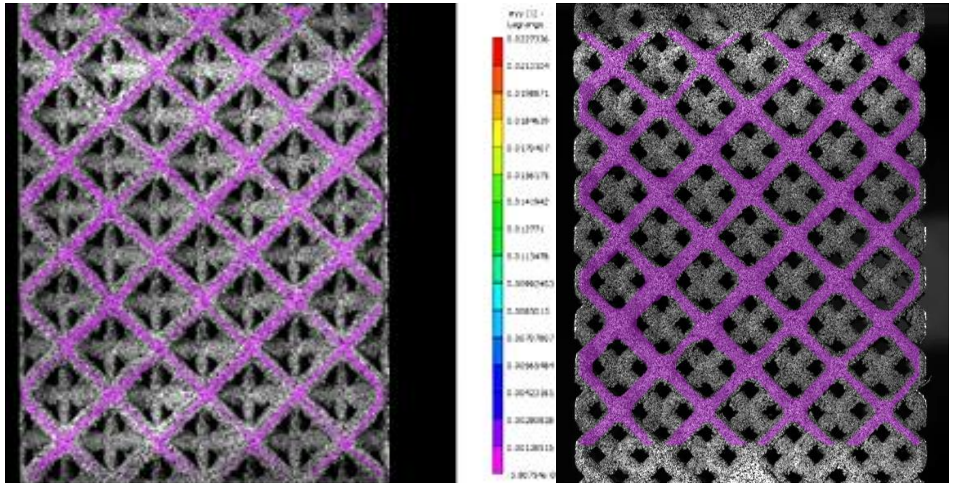
Discrete transition burn-out (IN718).



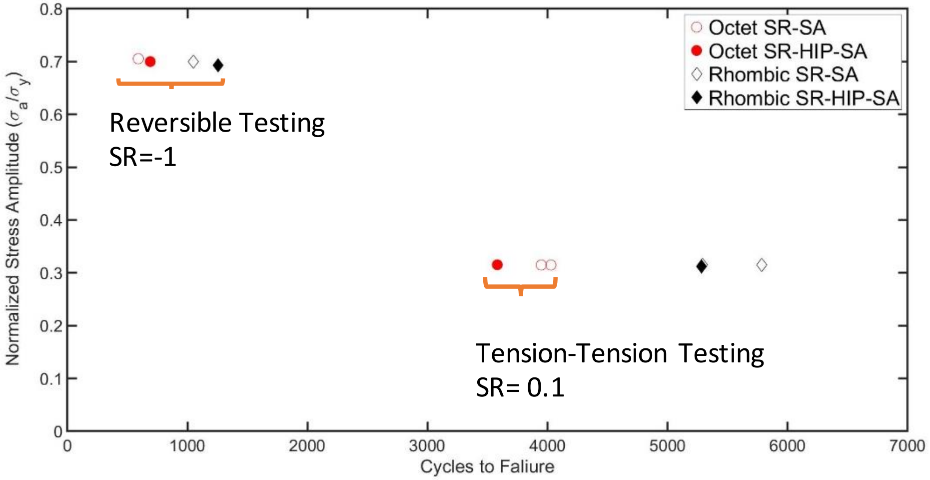
Gradient transition optimized specimens (IN718).



Stress-Strain curve of Octet-Truss (30 %RD) and Rhombic Dodecahedron (20 %RD), *a* = 4 mm, IN718.



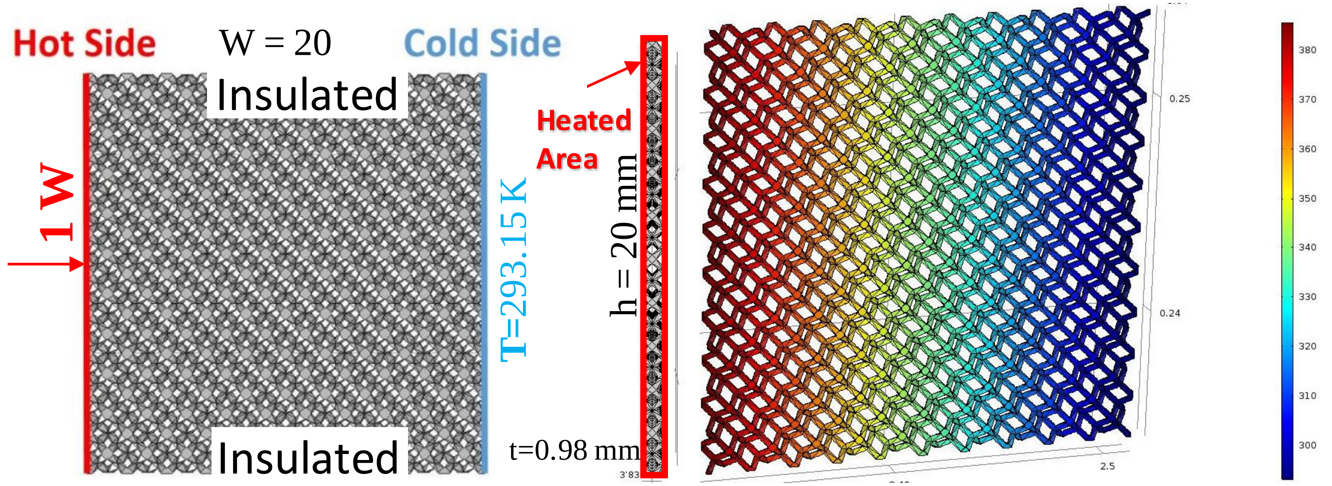
Node strain localization of Octet-Truss-30%RD (left) and **Strut** strain localization of Rhombic Dodecahedron (20 %RD), *a* = 4 mm, IN718 in SR+HIP+SA condition.



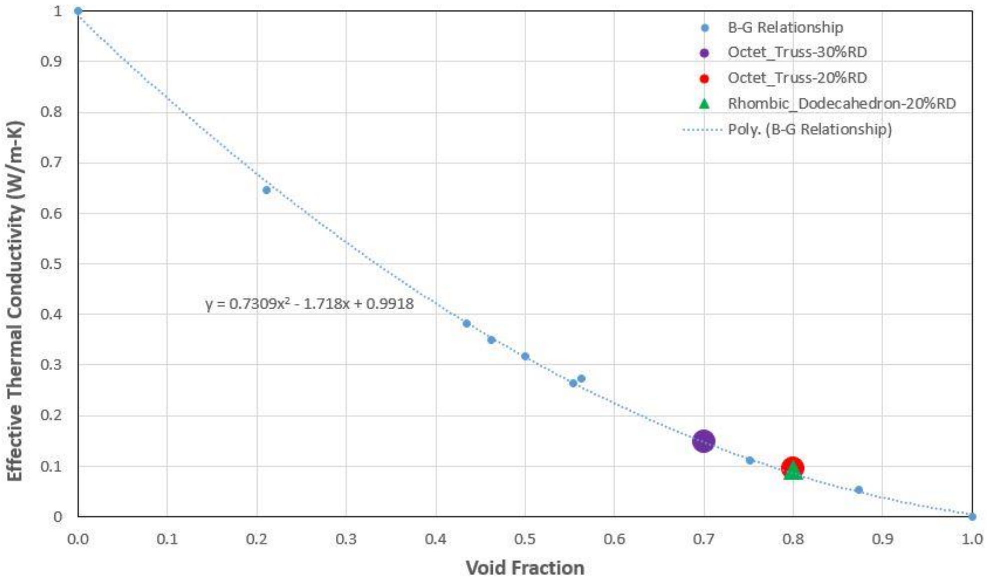
S-N curve of Octet-Truss (30 %RD) & Rhombic Dodecahedron (20 %RD), *a* = 4 mm, IN718, as-built surface finish.

Mechanical properties influenced by ρ_{rel}, then lattice topology, then unit cell size (thicker struts = stronger lattices).
Node or strut failure mode is topology dependent, not necessarily microstructure.
Lattice structures are stress concentrators and utilization in fatigue environments should be limited.
HIP does add cycle life before failure in either topology.

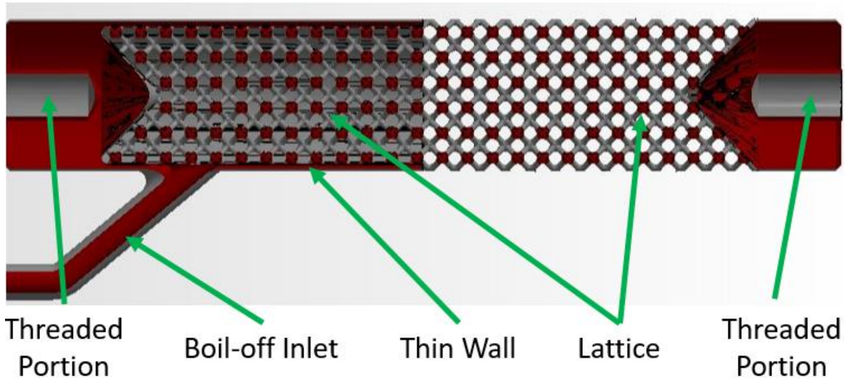
Lattice Thermal Simulation



Dode-Medium (13 %RD) lattice thermal conduction model.



Lattice effective thermal conductivity vs. topology void fraction.

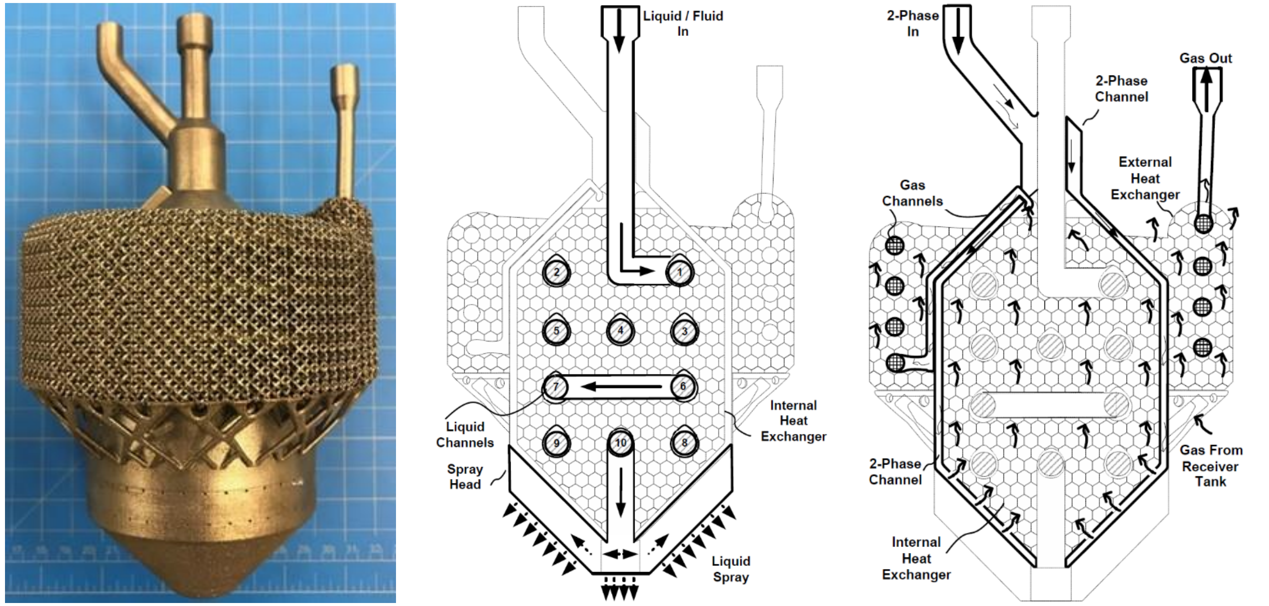


Cryogenic Strut CIF: reduce mass 30-40%, reduce thermal conductivity to 10% of fully dense material.

Effective thermal conductivity proportional to %RD (solid volume dominated).
Dependent more on *a* and *t* not necessarily topology.

CFM TVS Augmented Injector

- Design: 3 functions in 1 part
  - Liquid to gas heat exchanger
  - Liquid spray injector head
  - External condenser heat exchanger
- Function
  - Fluid spray promotes tank ullage condensation, drops pressure, and maintains fill flow.
  - Tank vent closed early in fill process (before fluid introduced). In some cases vent may not be opened.
  - Long-term storage pressure control: if fluid pumped back through the injector to reduce pressure or connected to a closed loop cryo-cooler circuit.



TVS Augmented Injector V4 (IN718), liquid circuit, 2-phase/gas circuit. Inner & outer lattice Dode-Medium (13 %RD)

Flow distributor lattice structure (Octet-Truss 30%RD) to improve radial flow spatial distribution.

TVS Augmented Injector V4 (AlSi10Mg) water flow test and LN_2 tests.

High Strength Aluminum Maturation

- High strength AM aluminum alloy needs:
  - NTP turbopump housings
  - CFM components
  - Lightweight structures
- Limited AM alloy options (AlSi10Mg, F357, A205)
  - AlSi10Mg properties well below wrought 6061-T6.
  - HIP+solutionize/age of AlSi10Mg add 4 weeks to schedule.
- High strength Al-alloys of critical importance to propulsion, structures, etc.
- Candidate Alloys
  - HRL 7A77
  - E3D Al6061-RAM2
  - APWorks Scalmalloy

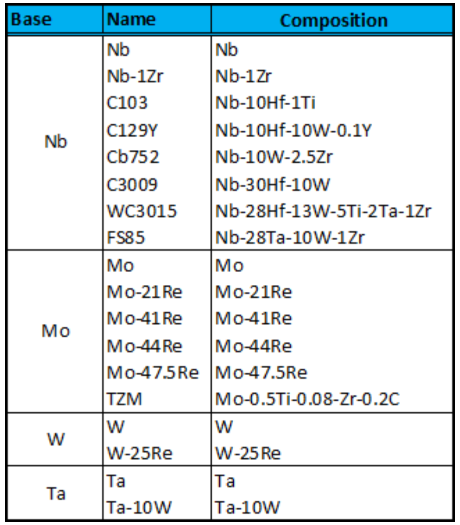
Alloy	ρ (g/cm^3)	YS (MPa)	UTS (MPa)	ε (%)	K (W/m-K)
AlSi10Mg (baseline)	2.67	252.35	315.78	11.4	173
F357 (AlSi7Mg0.6)	2.67	256.48	324.74	10.9-18.2	150
A6061-RAM2 (Al0.4Cr0.2Cu0.7Fe0.8Mg 0.2Mn0.6Si0.2Ti0.2Zn)	2.73	285	315	13	119
Scalmalloy (Al4.5Mg0.66Sc0.4Zr)	2.67	470	520	13	105

Comparison of common AM Al-alloy properties.

Topology Optimized AM Scalmalloy antenna struts currently on-orbit. Courtesy Begoc, 2019*.

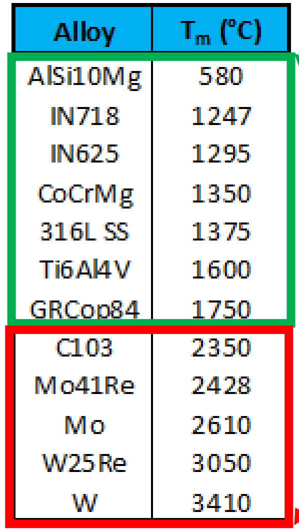
Refractory Metal Additive Manufacture Development
Background

- Problem
  - High temperature refractory alloys needed for numerous applications.
  - Traditional refractory alloy manufacture is difficult and expensive.
  - High buy-to-fly ratios (20:1) and limited supply chain.
  - Refractory alloys designed for forging/machining and use expensive additives (Re $3.5k/kg).



Base	Name	Composition
Nb	Nb Nb-1Zr C103 C129Y Cb752 C3009 WC3015 FS85	Nb Nb-1Zr Nb-10Hf-1Ti Nb-10Hf-10W-0.1Y Nb-10W-2.5Zr Nb-30Hf-10W Nb-28Hf-13W-5Ti-2Ta-1Zr Nb-28Ta-10W-1Zr
Mo	Mo Mo-21Re Mo-41Re Mo-44Re Mo-47.5Re TZM	Mo Mo-21Re Mo-41Re Mo-44Re Mo-47.5Re Mo-0.5Ti-0.08-Zr-0.2C
W	W W-25Re	W W-25Re
Ta	Ta Ta-10W	Ta Ta-10W

Traditional Refractory Alloys



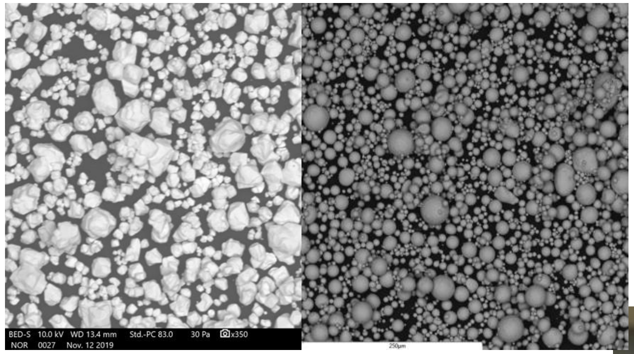
Alloy	T_m (°C)
AlSi10Mg	580
IN718	1247
IN625	1295
CoCrMg	1350
316L SS	1375
Ti6Al4V	1600
GRCop84	1750
C103	2350
Mo41Re	2428
Mo	2610
W25Re	3050
W	3410

AM SOA

Industry Need

AM Alloy Melt Temp

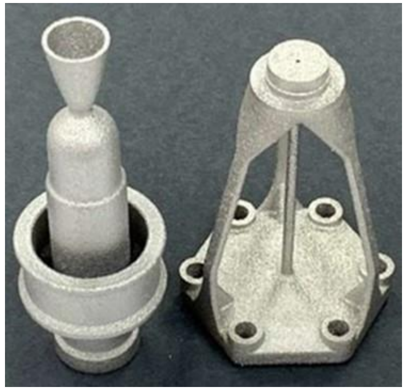
- Additive Manufacture (AM) State of the Art
  - Limited refractory alloy powder supply/use.
  - Refractory powder angular and mixed.
  - AM C103, Mo, and W at TRL 3-5.



Angular W & spherical C103 powders comparison.

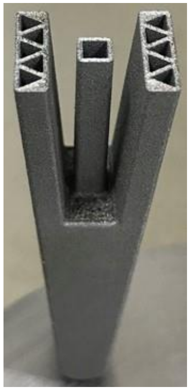
- Past & Current Refractory Experience
  - Traditional forming and AM of W and Mo for NTP fuel clads.
  - AM W of Green Propulsion Thrusters.
  - CAN: AM C103 with ATI & Castheon demonstrated order of magnitude cost reduction, design flexibility, 20% higher YS compared to traditional.
  - CAN: AM W Ultra-Fine Lattices with EOS for propulsion catalyst.
  - SBIR: AM TZM with VTS/UTEP identified powder supply inadequacies.

AM W Thruster



AM C103 Green Propulsion Thruster and Stand-Off.

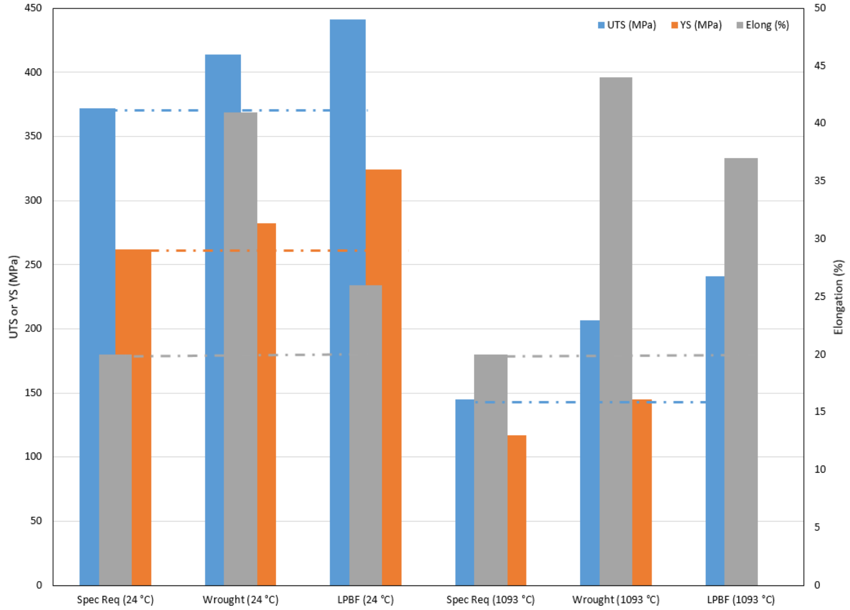
AM W NTP Fuel Clad.



AM W Wing Leading Edge.

AM of C103 (Nb10Hf1Ti)

- Traditional Manufacture Constraints
  - C103 bar stock $Ø_{max}$ = 102 mm (4 in), if larger fails ASTM B655.
  - Significantly limits design options.
  - Wrought min order of 45 kg (100 lb) with variation in $/mass.
  - 20:1-50:1 buy-to-fly = few $k for part and several $10k waste.
- Objectives
  - Investigate C103 AM to improve design flexibility, cost, & availability.
  - Produce, characterize, and supply C103 powder (ATI).
  - L-PBF parameters, post-processing, characterization (Castheon & MSFC).
- Results
  - AM powder is ~33% more expensive than wrought feedstock.
  - AM waste ~10% (1.1:1) = Few $k for part and few $0.1k waste.
  - *<u>Order of magnitude cost reduction.</u>*
  - Improved mechanical properties over wrought.
  - AM minimizes machining to interface surfaces (C103 is difficult to machine).
  - Surface finishing available via chemical etch, Micro-Tek, and electro-polish.
  - RCS thruster, in-space propulsion, and hypersonics now leverage AM C103.



C103 mechanical property comparison. Possible that fine distributed oxides from the L-PBF acts as a strengthener and stabilizer.

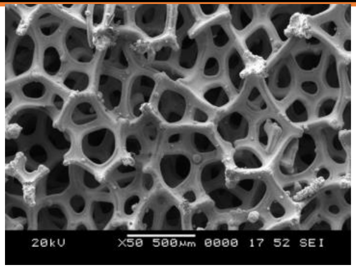
AM C103 MSFC Green Propulsion Thruster and Stand-off.

Ultra-Fine Lattice Structures of Green Prop Catalyst

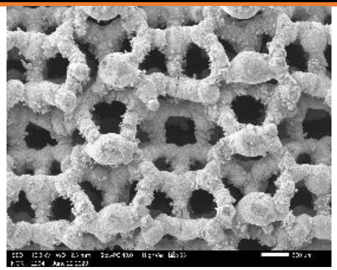
- Reticulated Vitreous Carbon (RVC) or ceramic (SiC) foams coated with platinum group metal (PGM).
  - Anisotropic (stochastic) properties.
  - High cost and long lead times.

- Objectives
  - Replace foams with AM ultra-fine lattices.
  - High spatial symmetry, repeatable (non-stochastic) and custom properties.
  - Reduce cost/schedule.
  - Increase commercial availability.

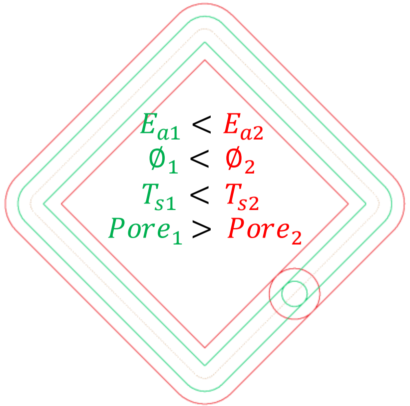
- Tasks
  - Identify lattice designs (MSFC).
  - Parameter development (EOS).
  - Metallography (MSFC).
  - µ-CT (3D Engineering Solutions).
  - Compressive strength (MSFC).
  - ΔP characterization (UTEP).



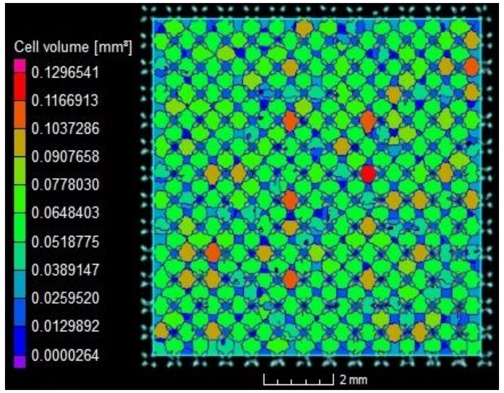
SEM micrograph of carbon foam with 400 µm median cell.



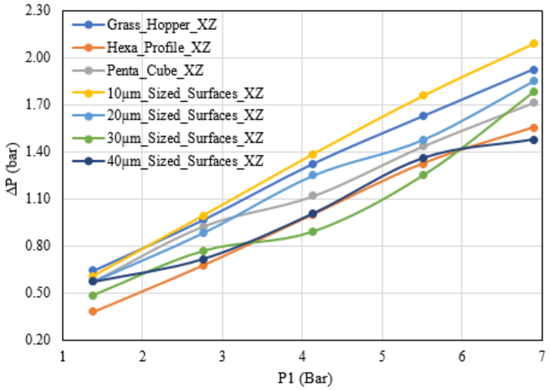
SEM micrograph of Hexa Profile AM W ultra-fine lattice.



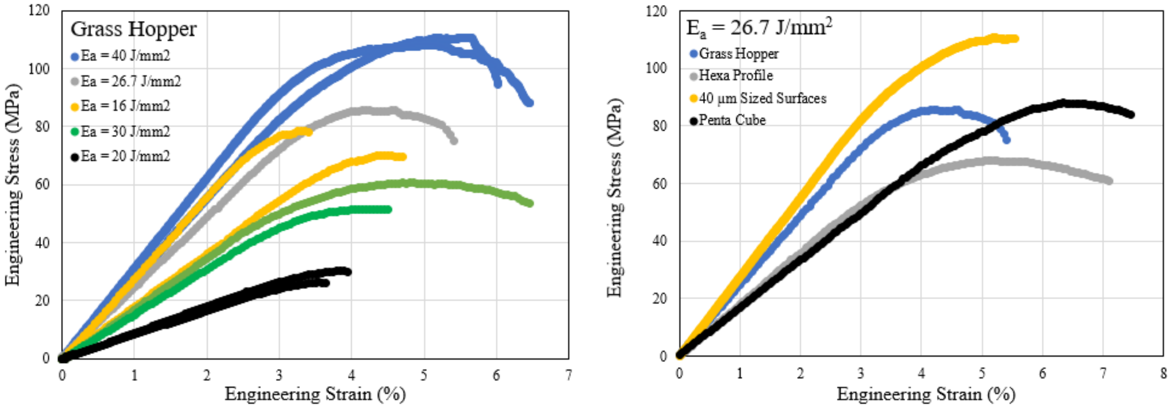
Scan path, E_a, melt pool diameter, strut thickness, & pore size.



µ-CT image of Ti6Al4V Hexa specimen cell volume.



ΔP for GN_2 of Ti64Al4V specimens in XZ plane.

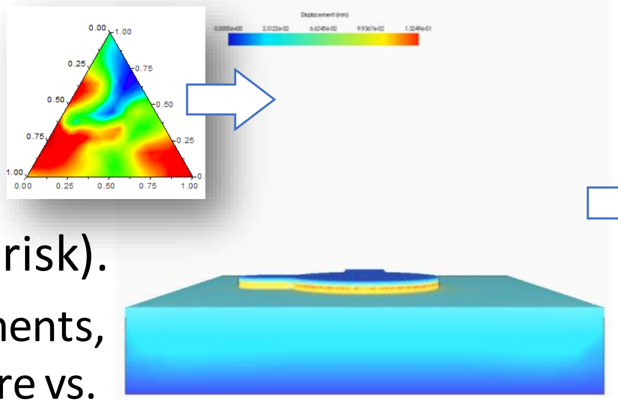


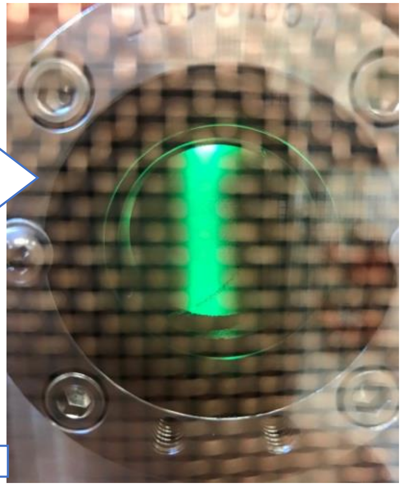
Compressive stress-strain diagrams of as-built AM W DOE 6 lattice structures.

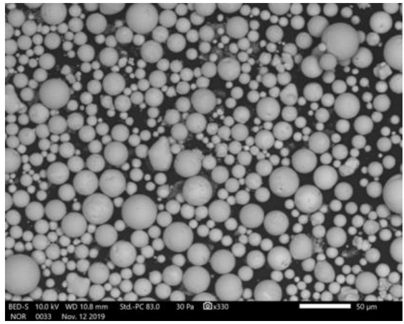
Refractory Metal Additive Manufacture Development

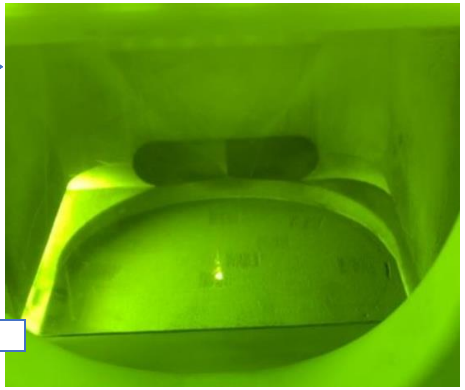
Enabling Technology Advances & Challenges

- Completed feasibility projects built confidence in the approach, scope of work, and risk posture.
  - Infuses AM to overcome traditional manufacture limitations.
- Simulation/modeling AM-optimized refractory alloy design (low risk).
  - Melt/solidification transformation and dynamics, design of experiments, build simulation, and property prediction using commercial software vs. traditional "cook and look".
- New alloy formulation pilot-scale powder production with industry (moderate/high risk). Multiple partners and methods to produce powder.
  - Gas atomization (plasma torch, electrode-induction).
  - Rotating electrode atomization (SPS for ingot consolidation).
  - Wire or strip atomization.
  - Angular/mixed powder spherodization.
- AM parameter development (low risk).
- Optimize heat treatments for properties (low risk).
- Small component test (low risk).

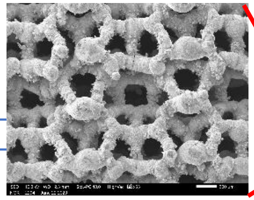

L-PBF AM build simulation.

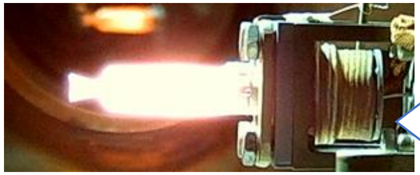

MSFC Tekna Tek15 plasma spherodization of W powder.


SEM micrograph of spherodized W powder.


MSFC EOS M100 printing W.


AM W Thruster.


AM Ir ultra-fine lattice catalyst.


Thruster hot-fire test.

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- The opinions expressed in this presentation are those of the authors and do not necessary reflect the views of NASA or any NASA Project.