Introduction to Metal Additive Manufacturing for Space Applications

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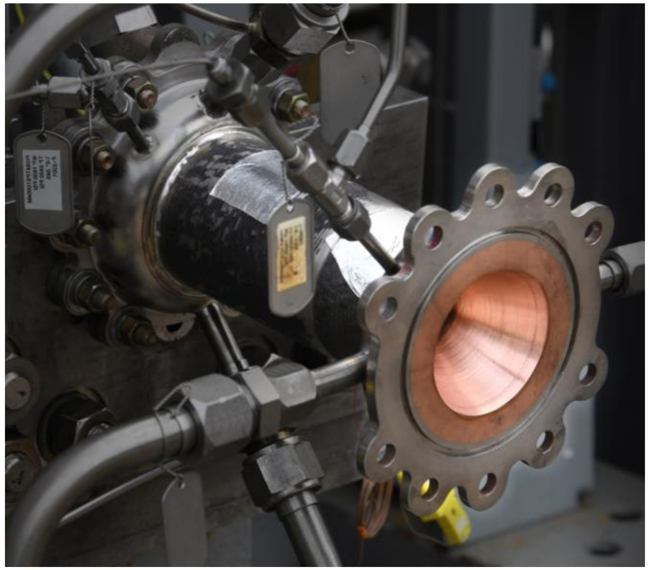
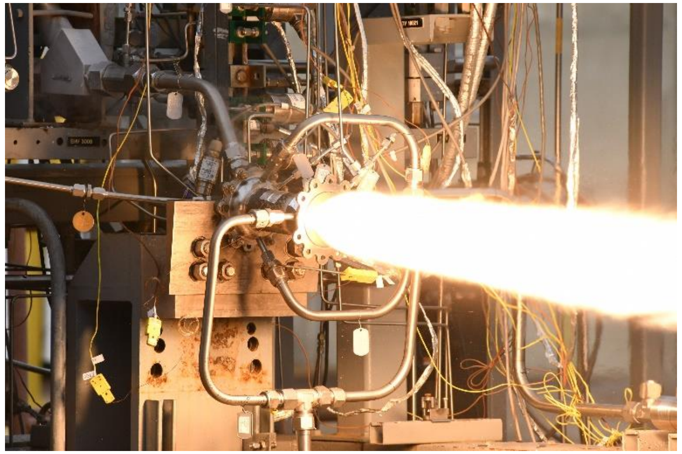
Agenda

- Why additive manufacturing?
- Various metal AM processes
- How to select an AM process
- Laser Powder Bed Fusion
- Directed Energy Deposition Processes
- Examples and Conclusions



Bimetallic AM Chamber Testing
L-PBF and LP-DED
Courtesy: NASA and Virgin Orbit



Terminology

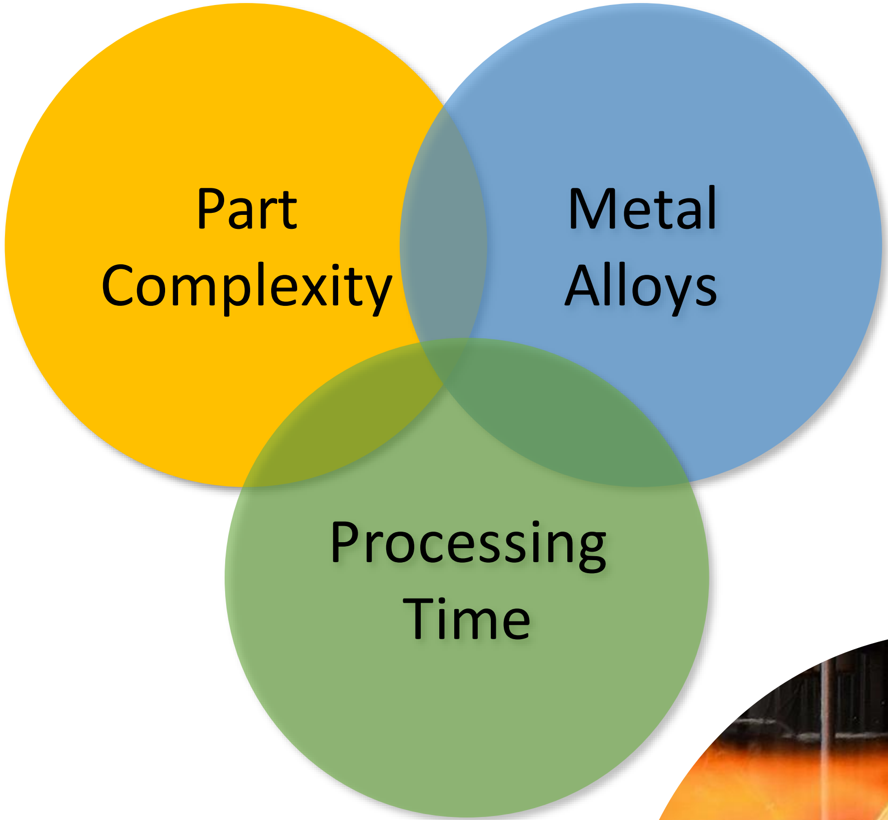
Course will focus exclusively on metal additive manufacturing

- AM = Additive Manufacturing
- DED = Directed Energy Deposition
- LP-DED = Laser Powder DED
- LW-DED = Laser Wire DED
- AW-DED = Arc Wire DED
- EBW-DED = Electron Beam Wire DED
- L-PBF = Laser Powder Bed Fusion
- UAM = Ultrasonic Additive Manufacturing
- AFS-D = Additive Friction Stir Deposition
- Cold spray

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

The Case for Additive Manufacturing in Propulsion

- Metal Additive Manufacturing (AM) 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



Part Complexity

Metal Alloys

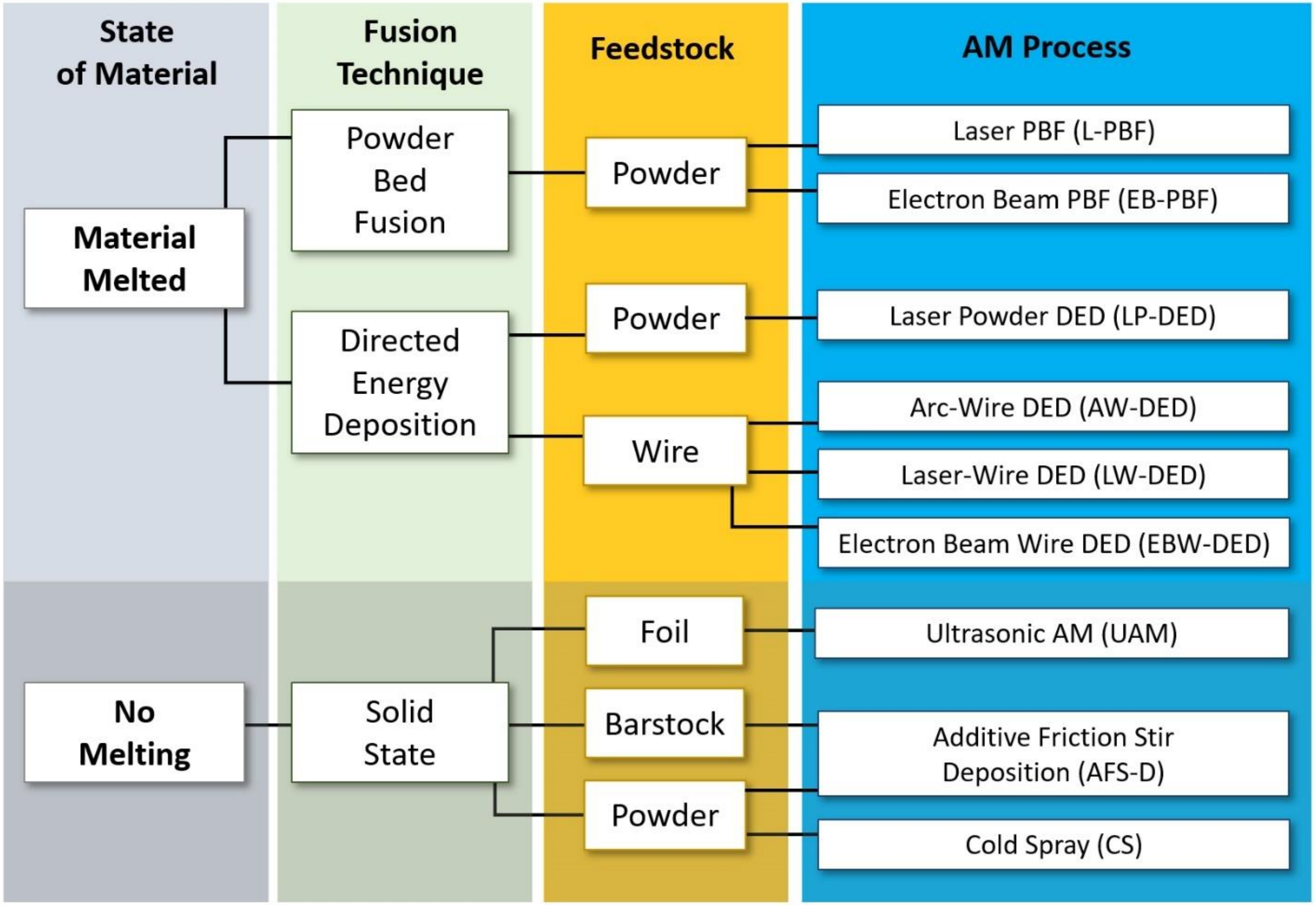
Processing Time

Case Study for AM

			
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)	$310k	$200k (35%)	$125k (60%)

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

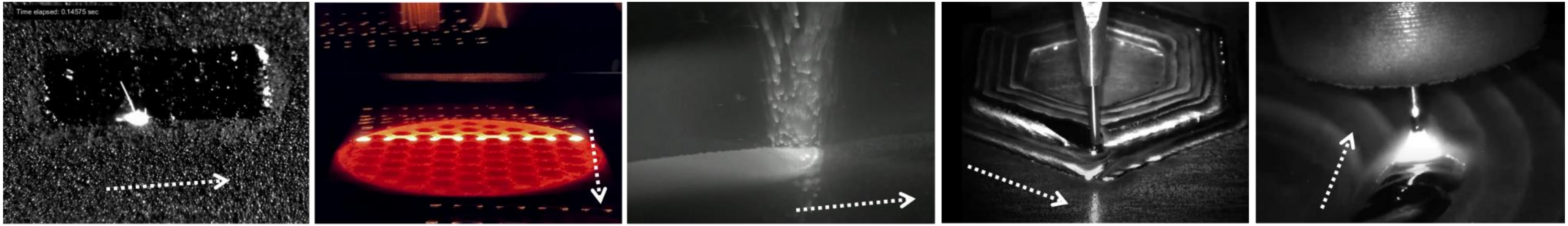
Various Metal AM Processes



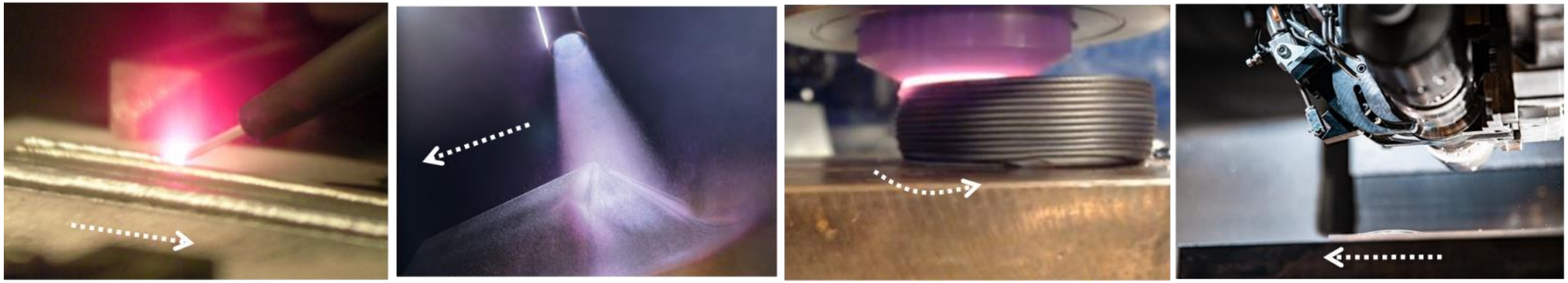
Terminology defined by ISO / ASTM52900-15

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].*

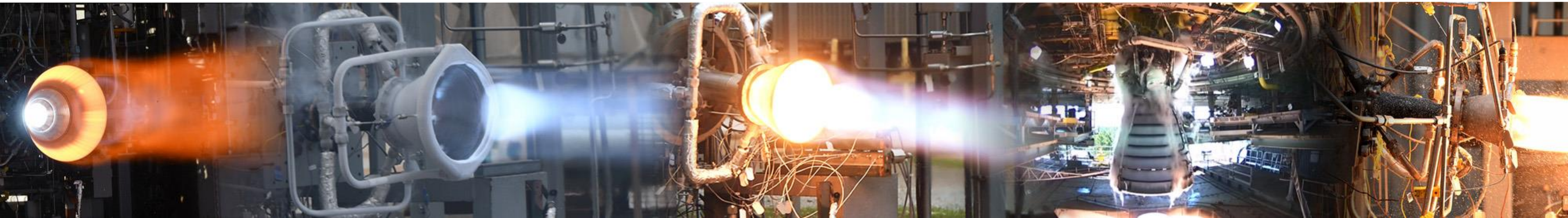
Reference: Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). “Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components”. (Journal Article In Review)

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

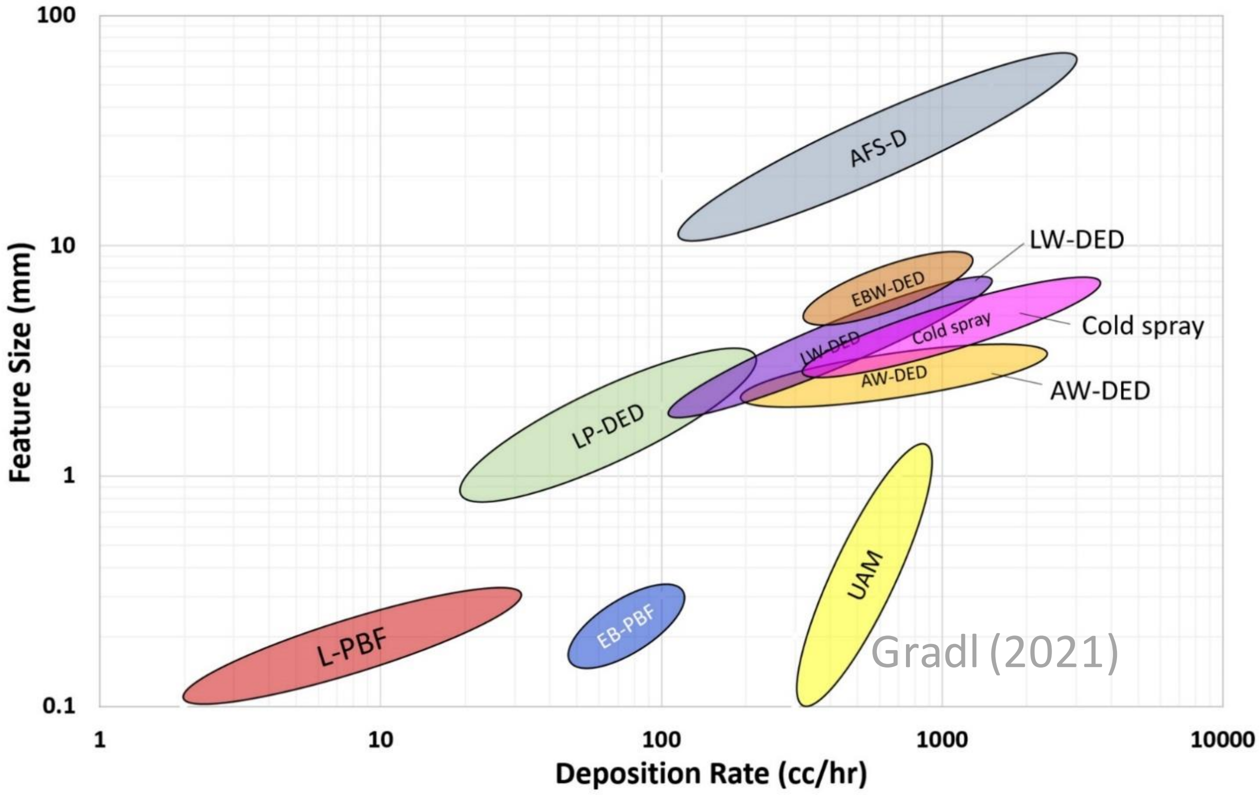
Laser Powder Bed Fusion (L-PBF) Copper Alloys combined with other AM processes to provide bimetallic

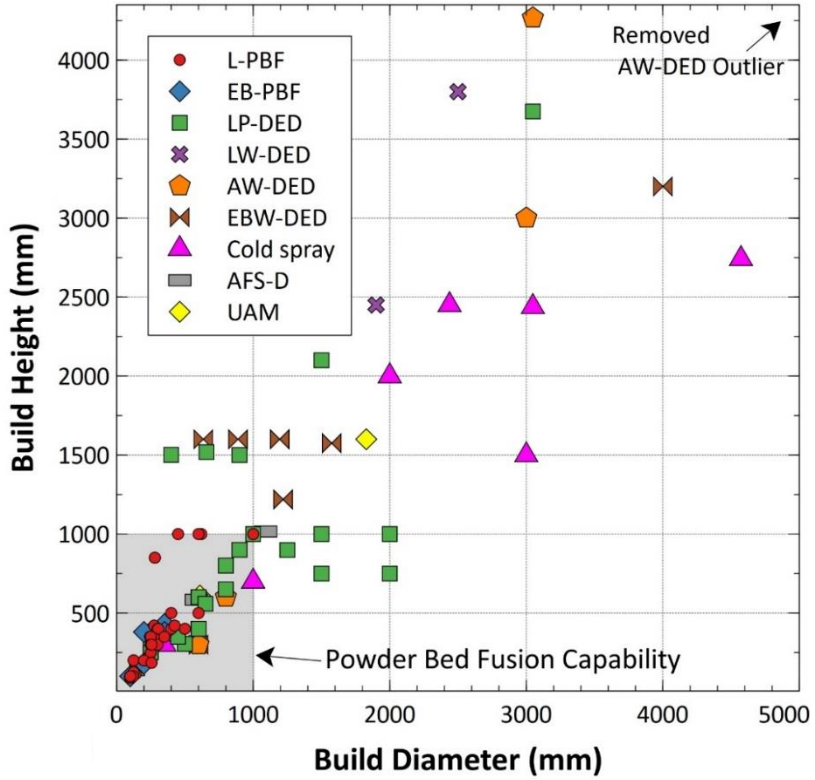
Directed Energy Deposition

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



Various criteria for selecting AM techniques





Complexity of Features

Scale of Hardware

Material Physics

Cost

Material Efficiency

Speed of Process

Material Properties

Internal Geometry

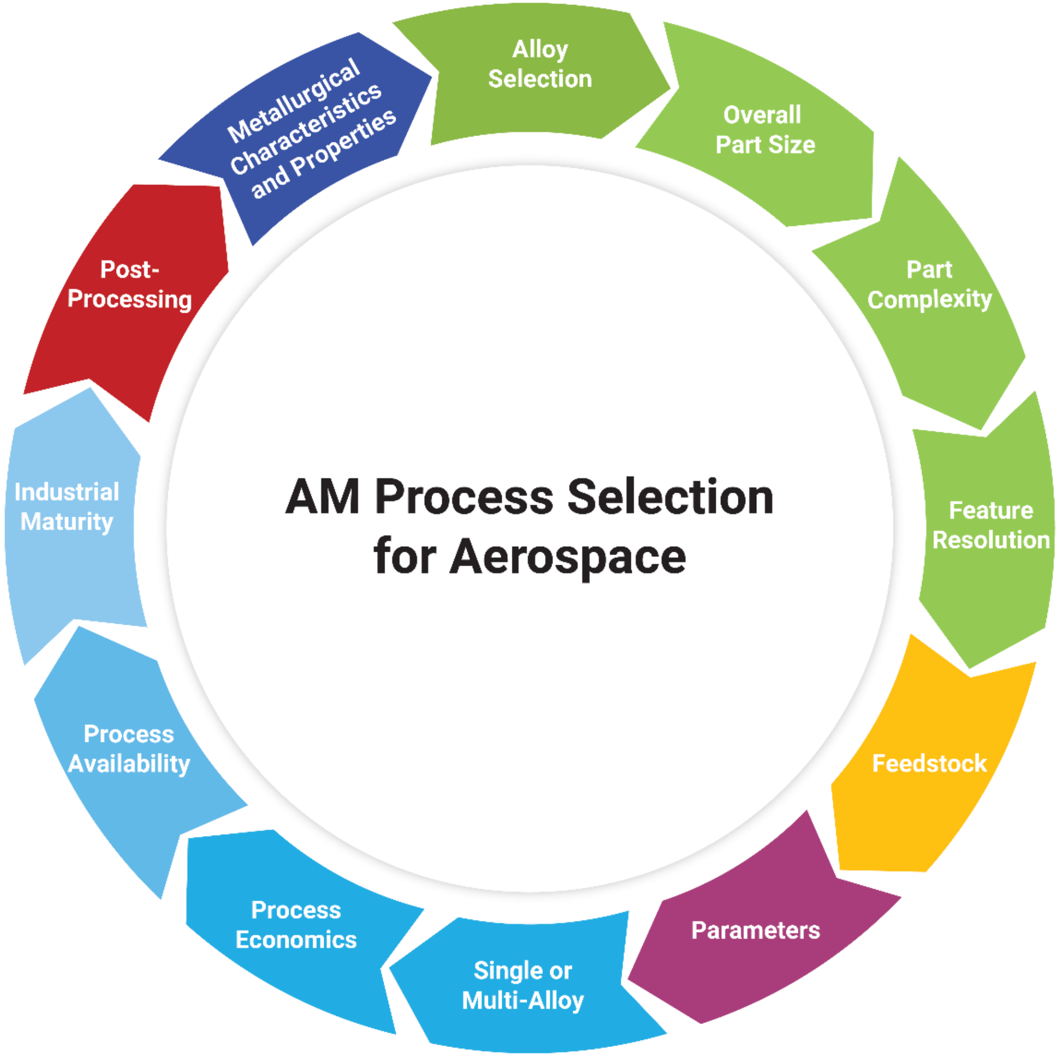
Availability

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
- AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl, Protz, Mireles, Garcia (unreleased)
- Gradl, P.R., Mireles, O., Andrews, N. "Introduction to Additive Manufacturing for Propulsion Systems. 10.13140/RG.2.2.13113.93285
- Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Review)

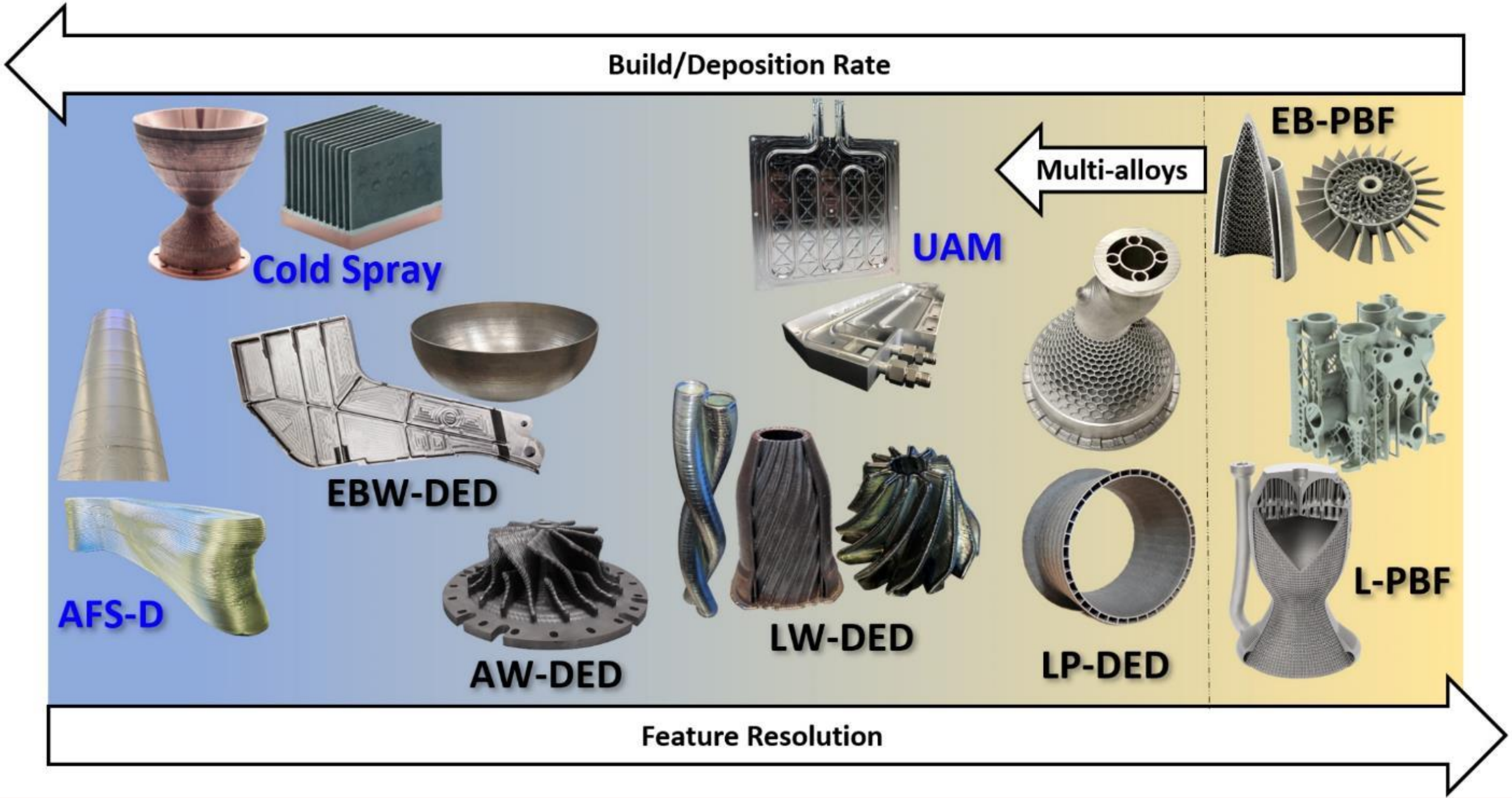
Methodical AM Process Selection



- 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, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). “Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components”. (Journal Article In Review)

Criteria for AM Process Selection



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 Cell Core GmbH/Sol Solutions Group AG, EB-PBF image credits to Wayland and GE Additive/Arcam.

Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Review)

Common Alloys used in Additive Manufacturing

Ni-Base

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-Base

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

Co-Base

CoCr/CoCrMo
Haynes 188
Stellite 6, 21, 31

Cu-Base

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

Ti-Base

Ti6Al4V
γ-TiAl
Ti-6-2-4-2

Platinum Group

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

Refractory

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

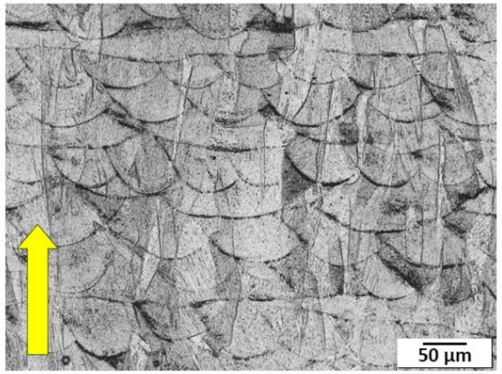
Al-Base

AlSi10Mg
A205
F357
1000
6061
2024
7075
7050
Scalmalloy
7A77

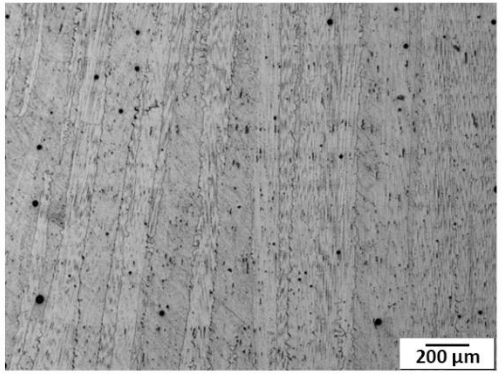
*Not a fully inclusive list of all AM alloys available

Microstructure of Various AM Processes
Inconel 625

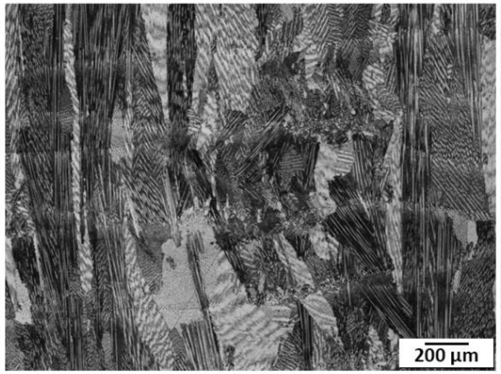
As-built microstructure of Inconel 625 => Requires proper post-processing heat treatments



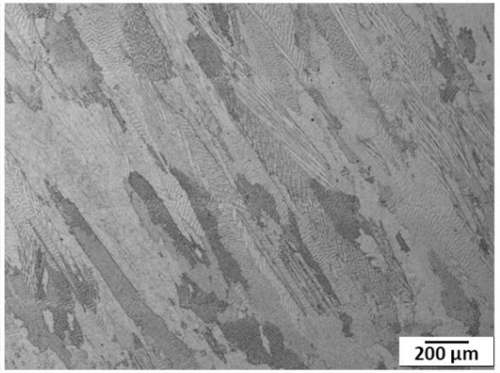
A) Laser Powder Bed Fusion



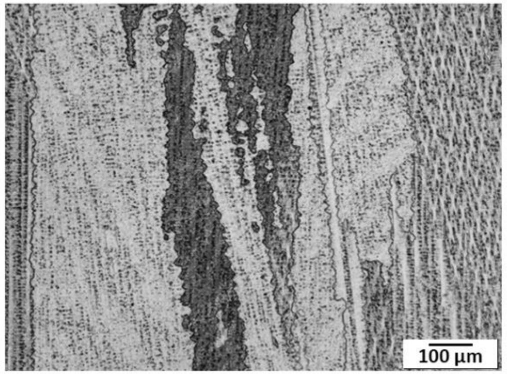
B) Electron Beam Powder Bed Fusion



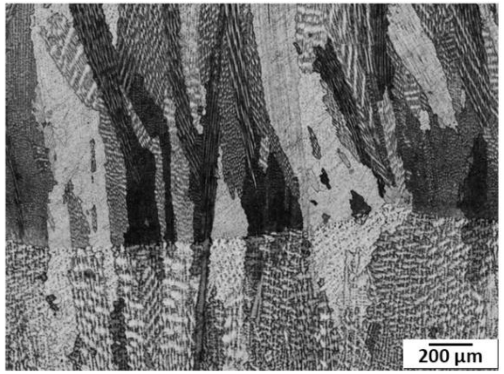
C) Laser Powder DED (1070 W)



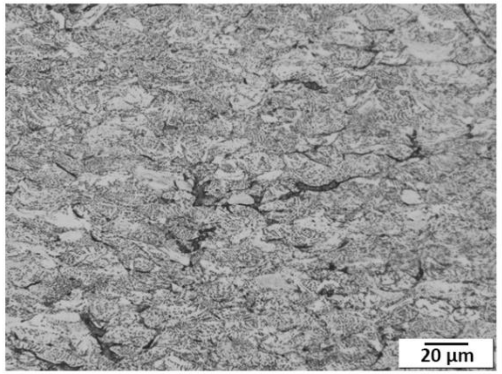
D) Laser Wire DED



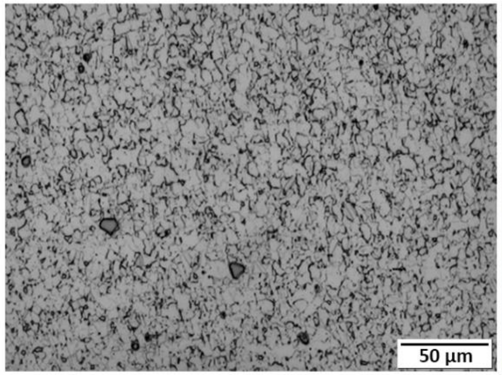
E) Arc Wire DED



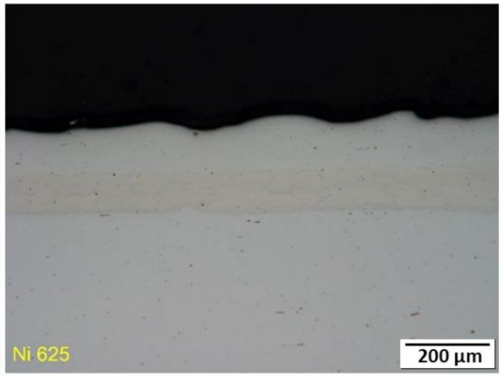
F) Electron Beam Wire DED



G) Cold Spray



H) Additive Friction Stir Deposition



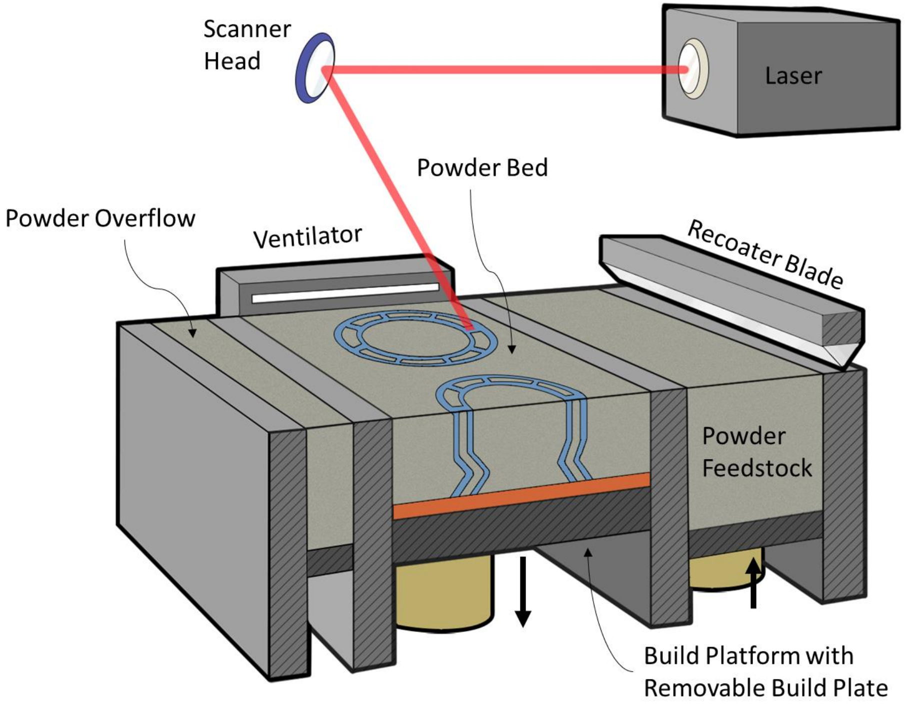
I) Ultrasonic Additive Manufacturing

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

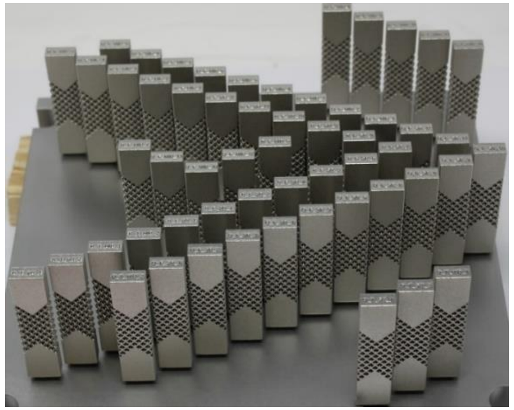
- Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). “Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components”. (Journal Article In Review)
- Rivera, O. G., Allison, P. G., Jordon, J. B., Rodriguez, O. L., Brewer, L. N., 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.

Laser Powder Bed Fusion (L-PBF)

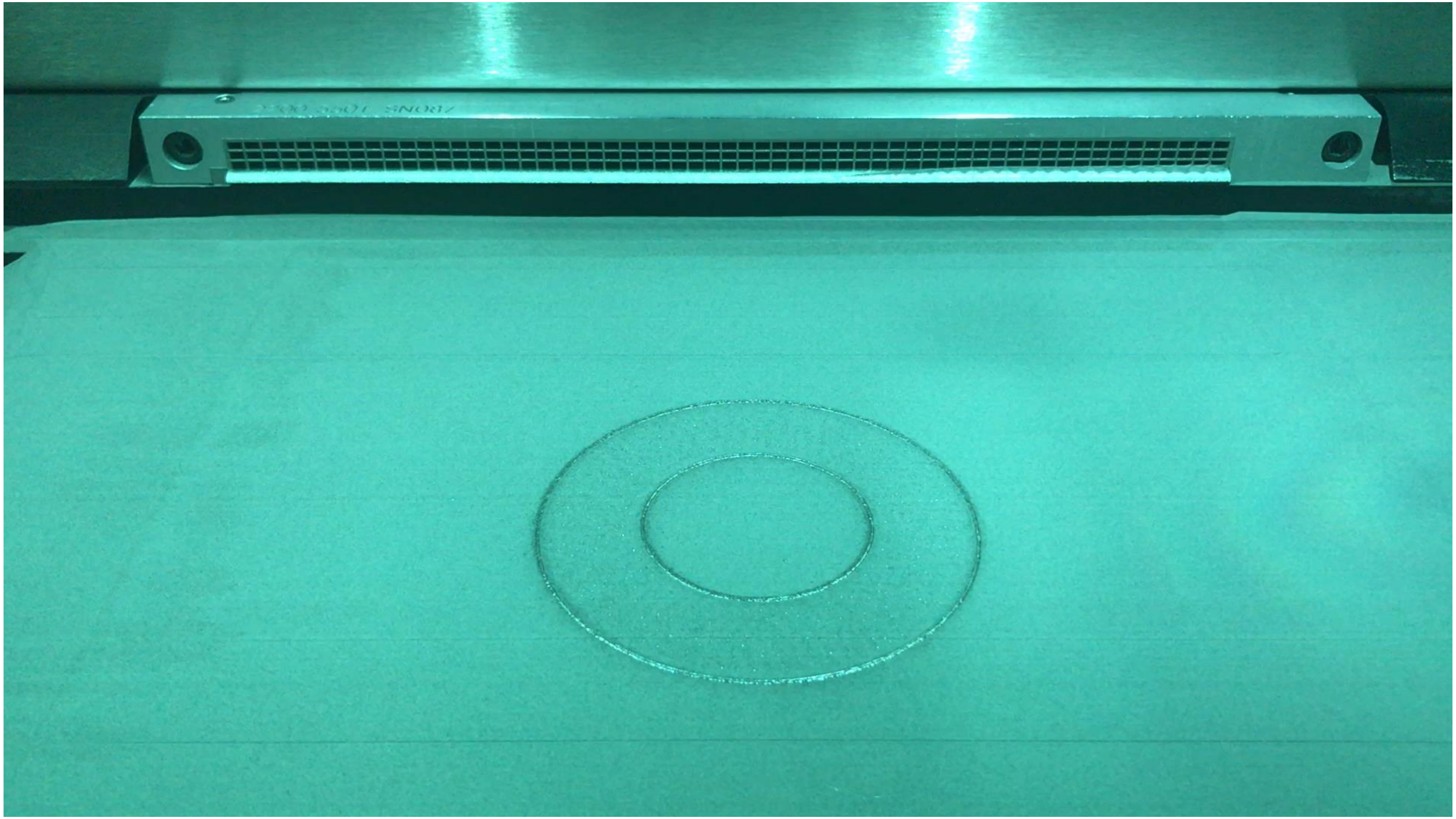
- **Laser Powder Bed Fusion (L-PBF)**
  - Basic Process: Layer-by-layer powder-bed approach where desired features are melted using a laser and solidify.
  - Advantages: High feature resolution, complex internal designs such as cooling channels.
  - Disadvantages: Scale limited and does not provide a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

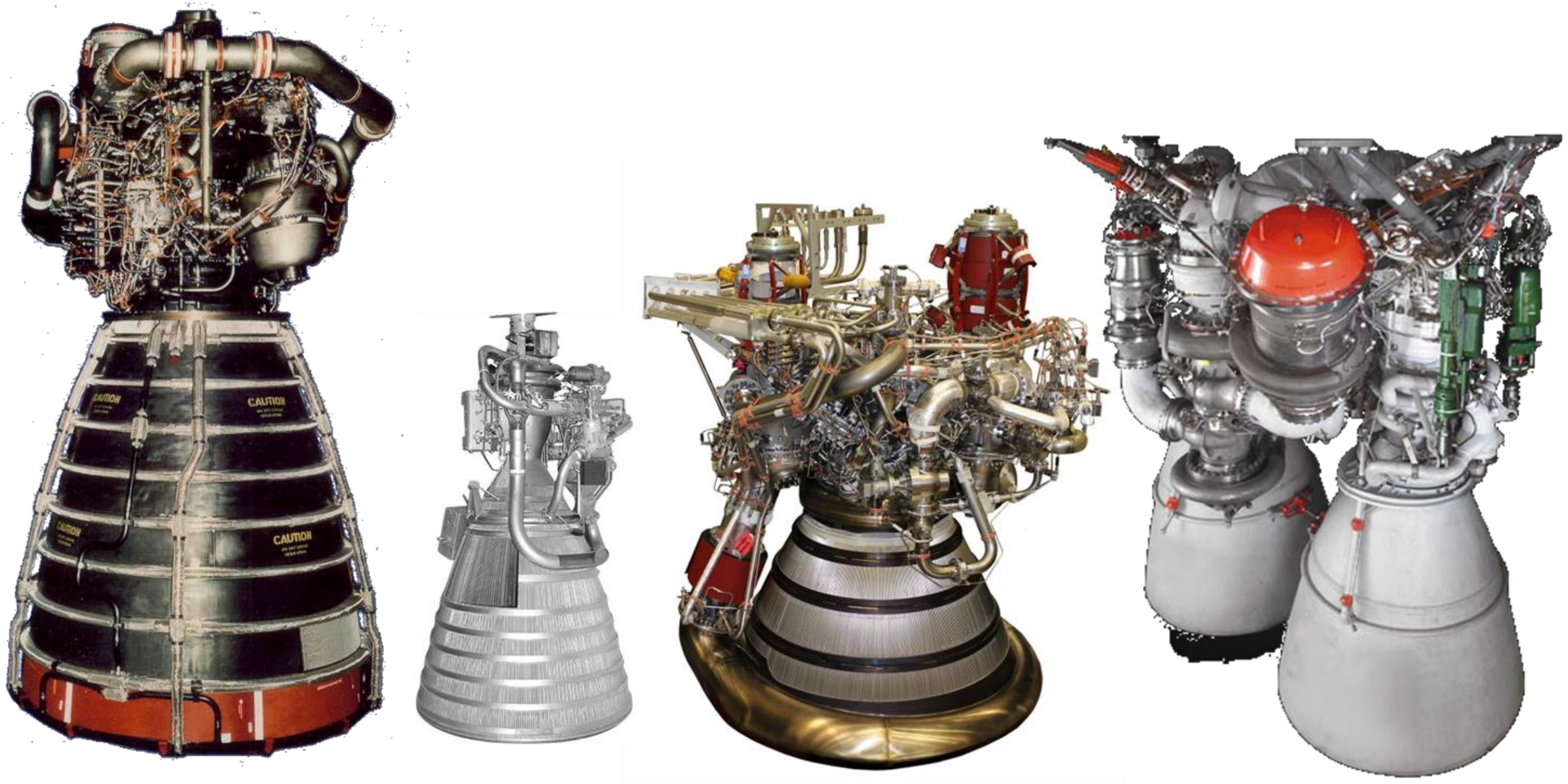


Laser Powder Bed Fusion (L-PBF)



The need for large scale AM…

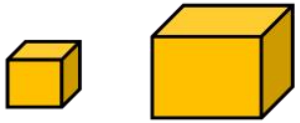
SSME/RS-25 **RL-10A-4** **J-2X, Regen Only** **RD-180**



90″ 46″ 70″ 56″

Nozzle Exit Dia.

L-PBF Build Boxes

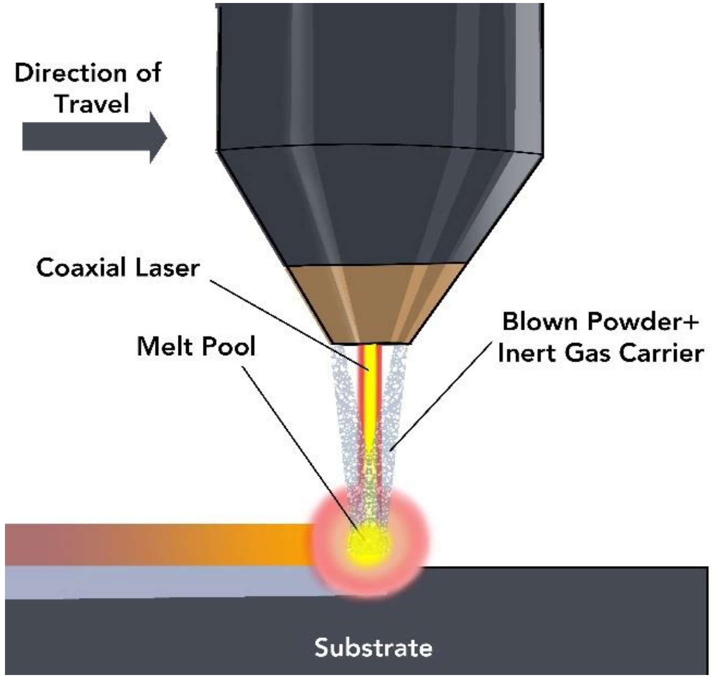


10x10x10 15.5x24x19

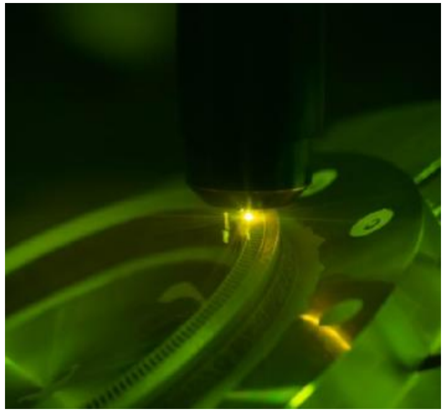
(inches)

Laser Powder Directed Energy Deposition (LP-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

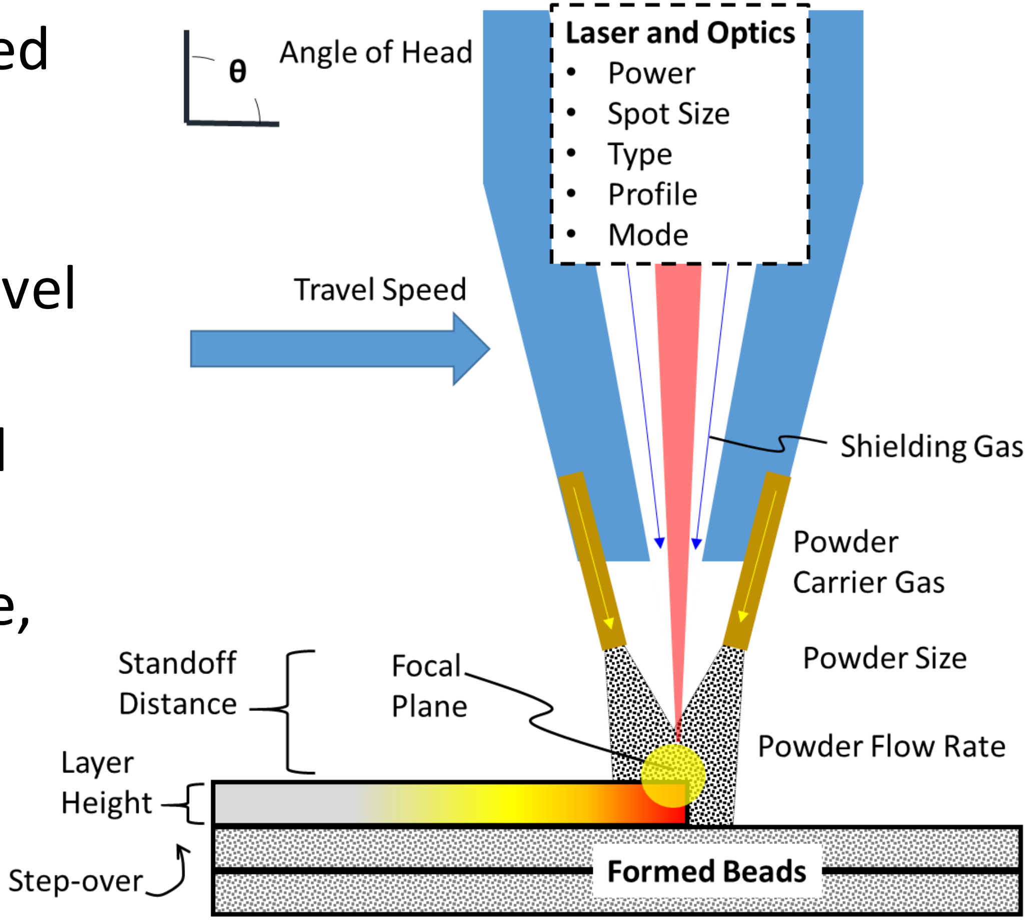

Inco 718, 1:4 Scale


JBK-75, IN625, NASA HR-1 Manifolds


JBK-75 Integrated Channel

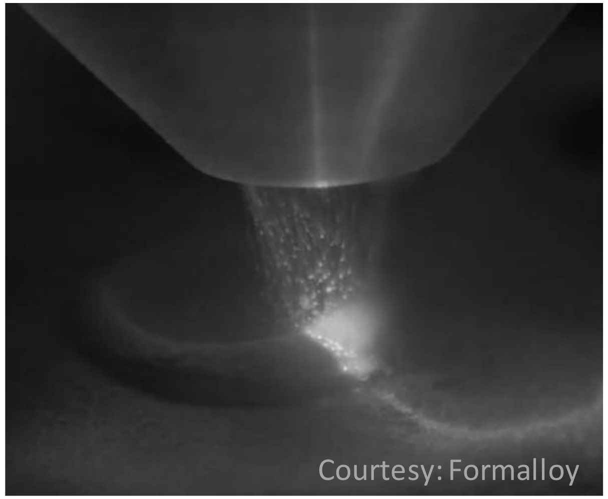
LP-DED Process Overview

- 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



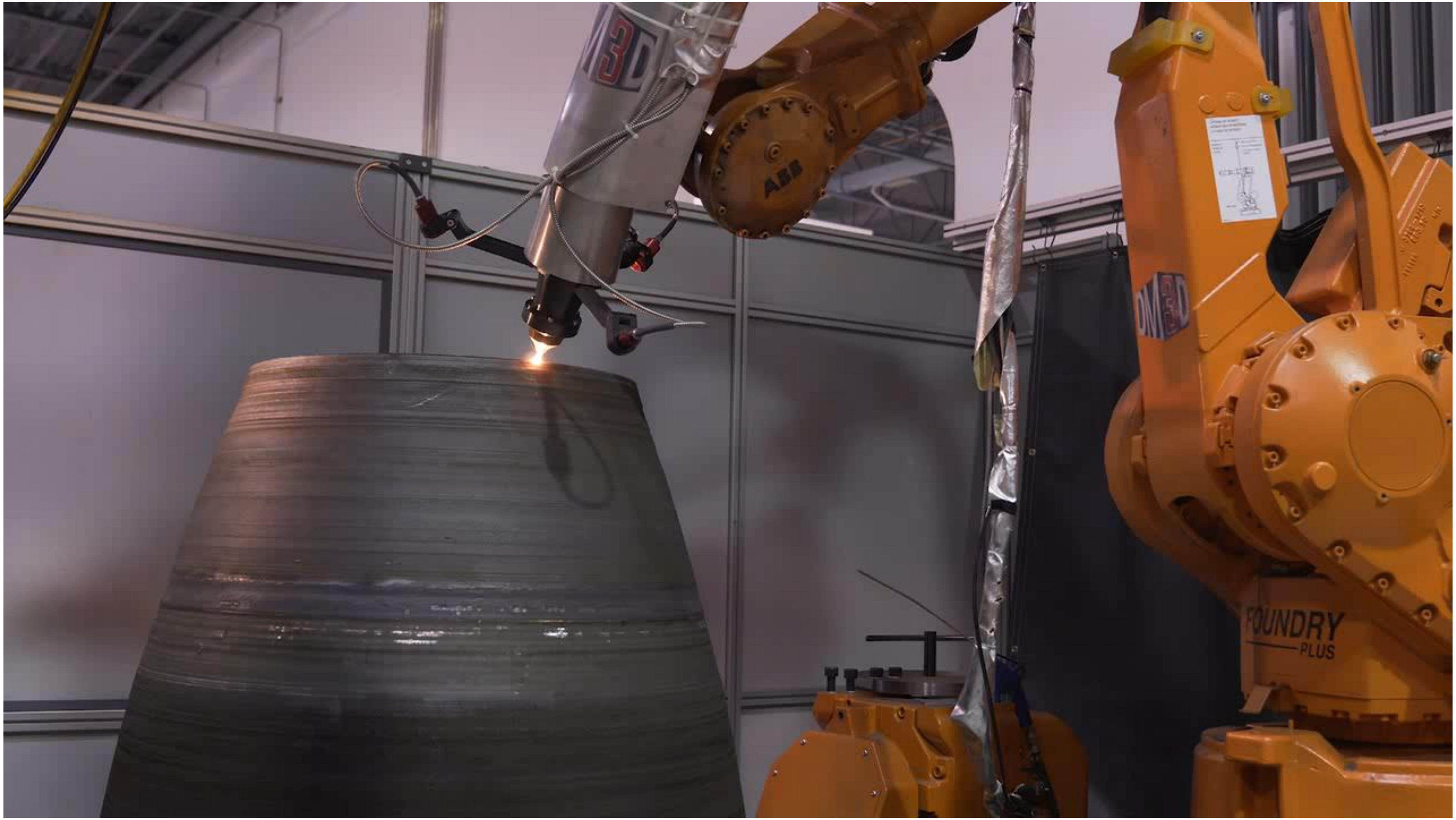
AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl , Protz, Mireles, Garcia (unreleased)


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)

Example of LP-DED for large scale



Laser Powder Directed Energy Deposition (LP-DED) Large Scale Nozzles

60" (1.52 m) diameter and 70" (1.78 m) height with integral channels

90 day deposition

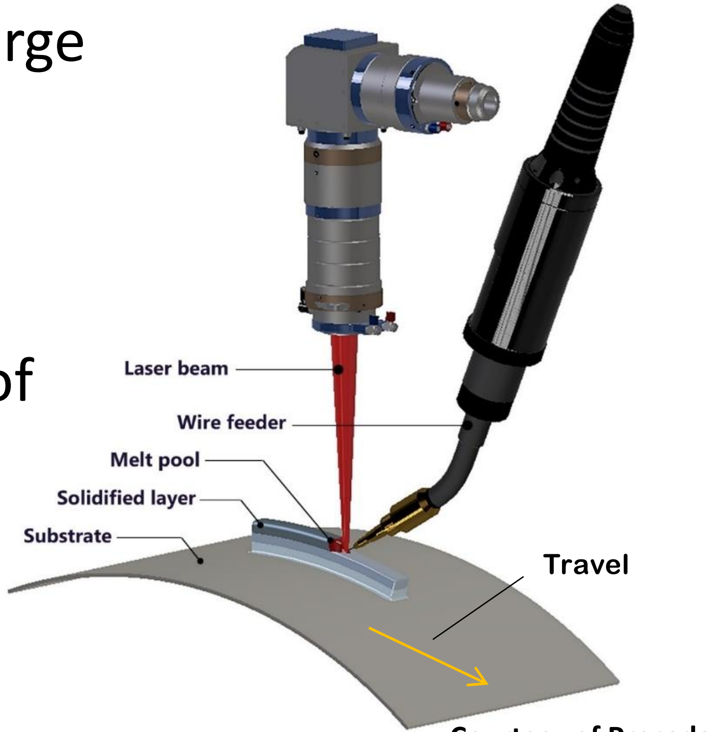
95" (2.41 m) dia and 111" (2.82 m) height

Near Net Shape Forging Replacement

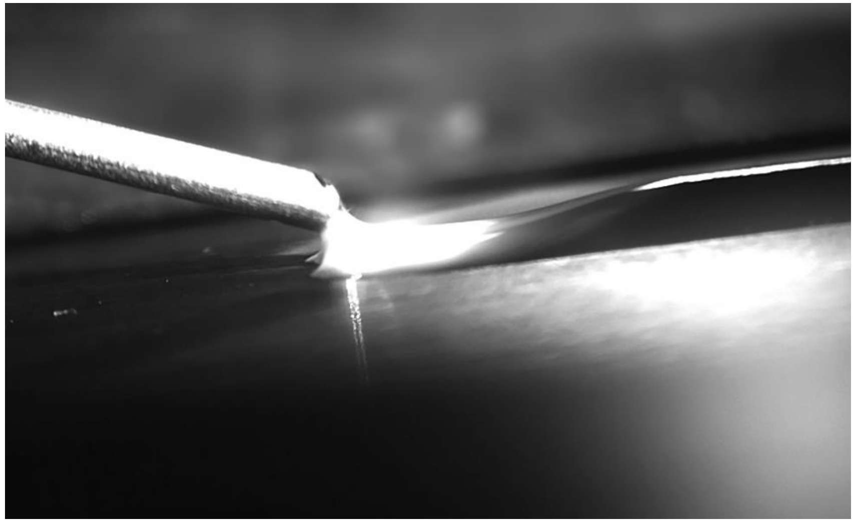
Reference: Gradl, P. R., Teasley, T. W., Protz, C. S., Garcia, M. B., Ellis, D., & Kantzos, C. (2021). Advancing GRCop-based Bimetallic Additive Manufacturing to Optimize Component Design and Applications for Liquid Rocket Engines. *AIAA Propulsion and Energy 2021*, 1–28. https://doi.org/10.2514/6.2021-3231

Laser Wire DED (LW-DED)

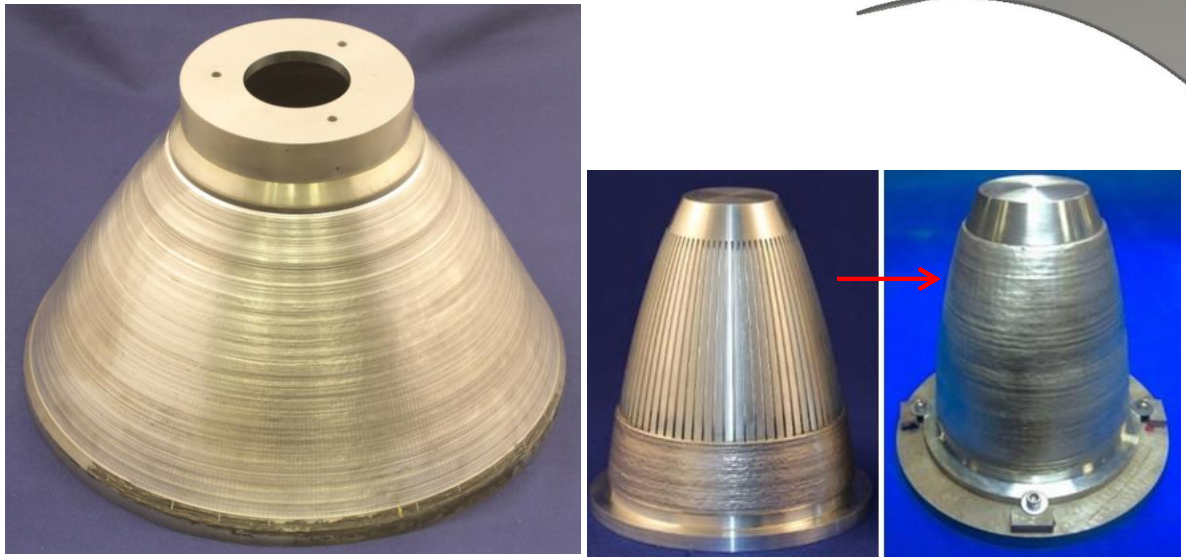
- Uses a laser energy source with a off-axis wire feed and local purge
- 100% efficiency in material usage
- High deposition rates, but balances low heat input
- Can be used on complex surfaces
- Key parameters: Laser Power, Wire feedrate, Travel rate, Angle of Head, Shielding gas flowrate



Courtesy of Procada

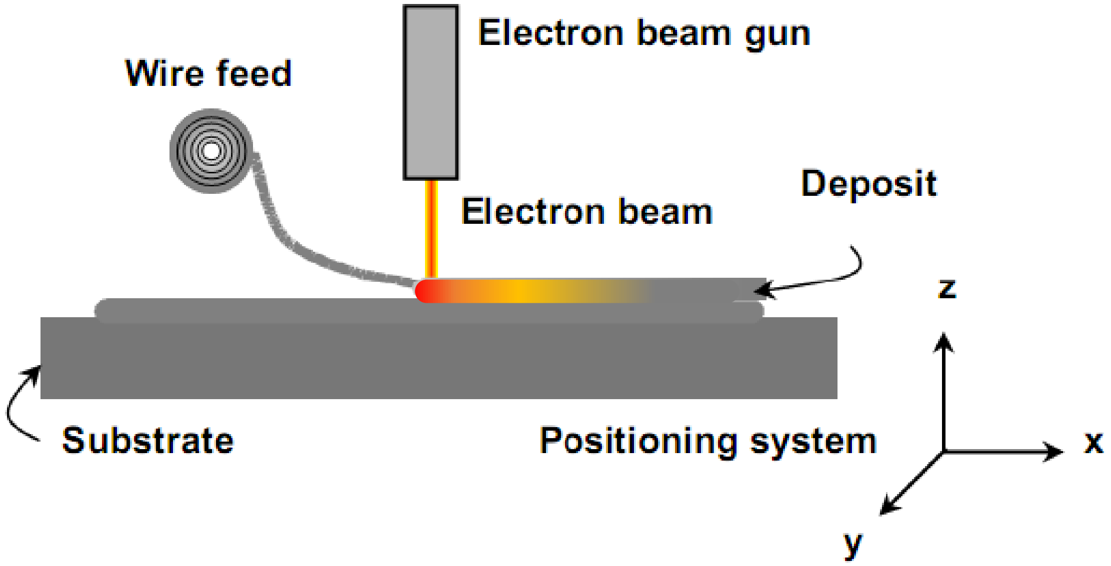


Courtesy of Procada



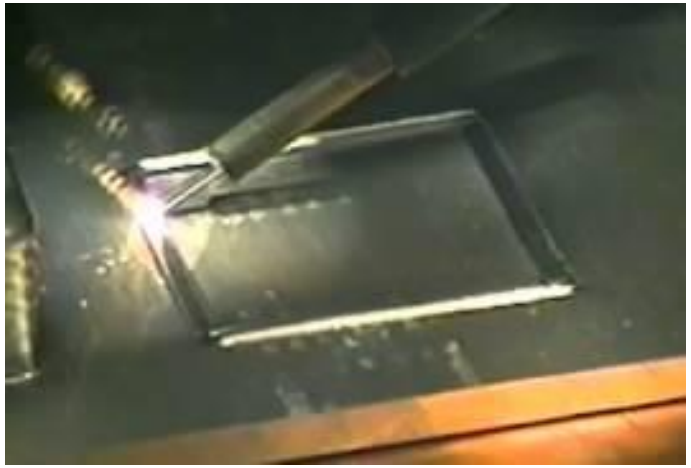
Electron Beam Wire DED (EBW-DED)

- 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



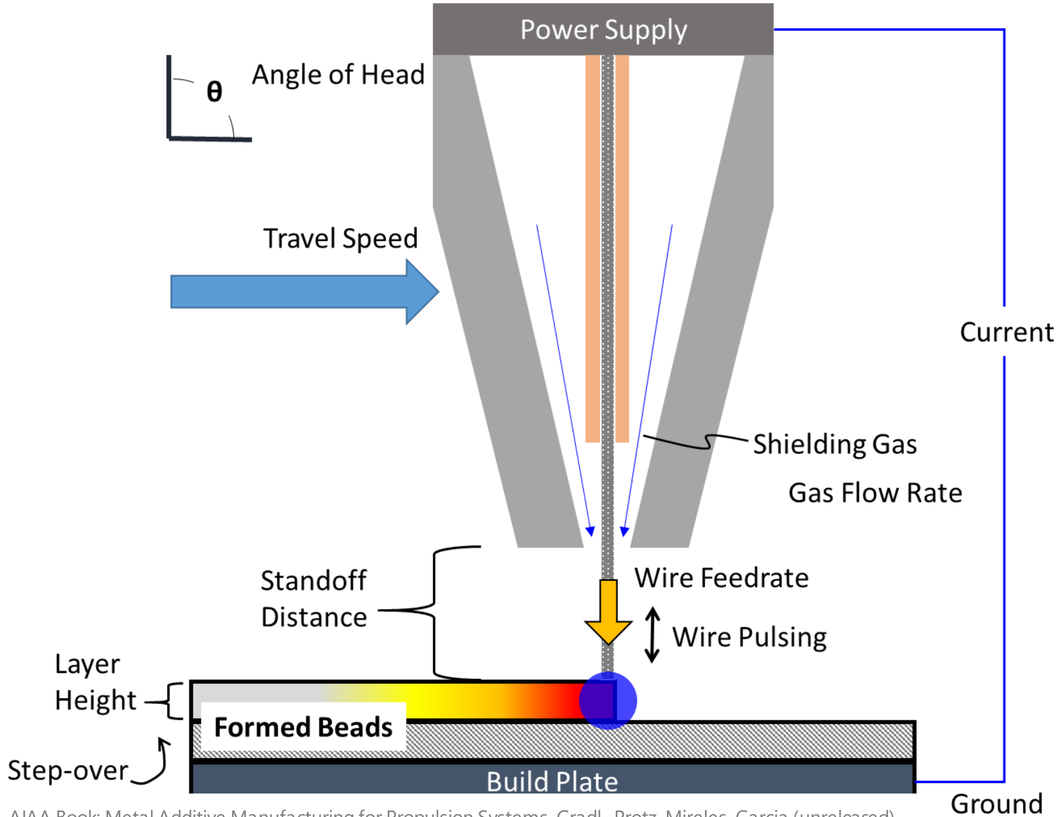
Monolithic EB-DED Freeform

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

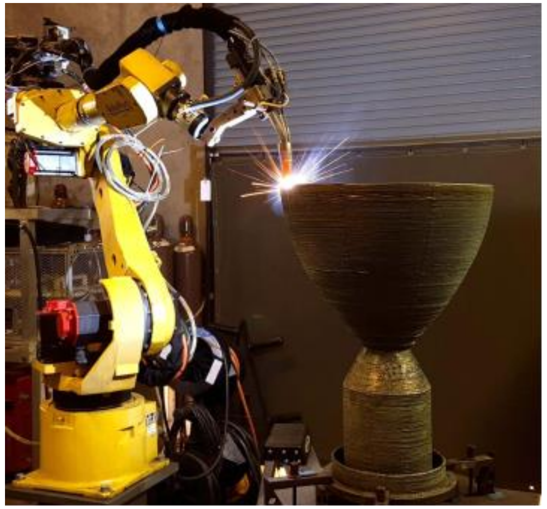


Arc Wire DED (AW-DED)

- 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



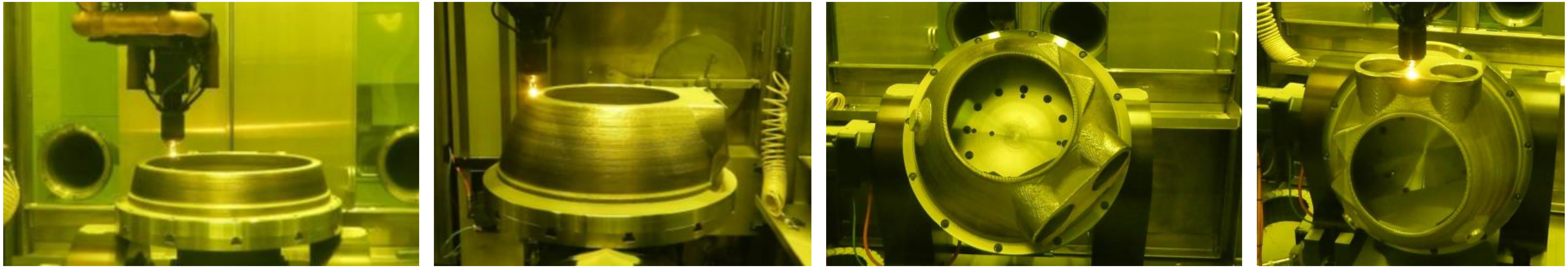
AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl , Protz, Mireles, Garcia (unreleased)

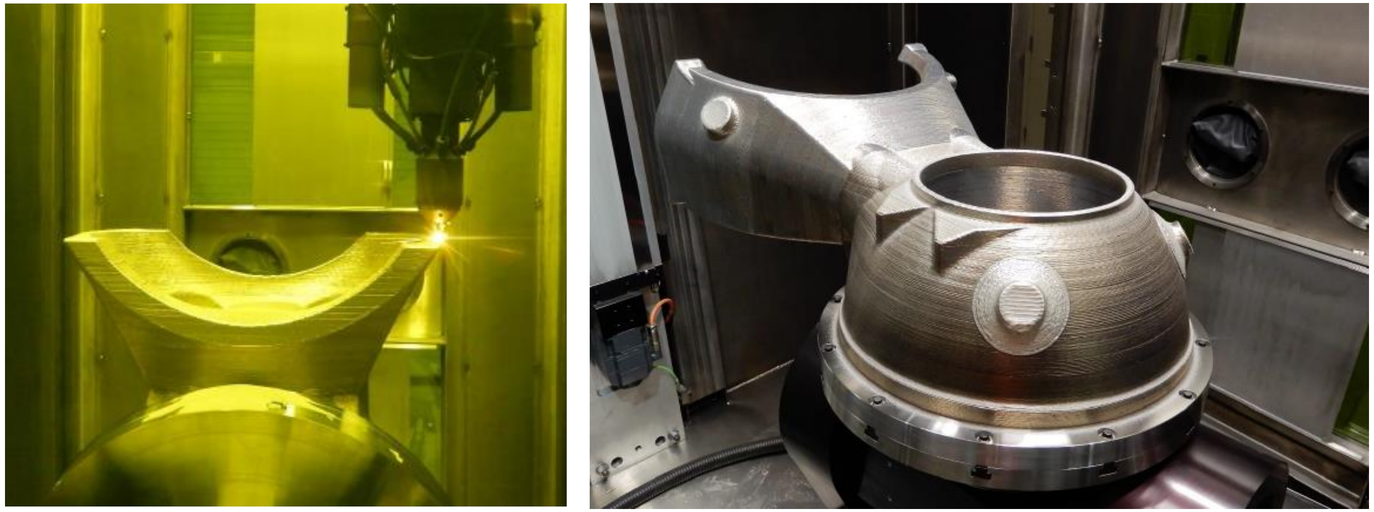


Courtesy: GEFERTEC

Freedom in DED design and deposition strategies

Ability to use multiple axes for complex features fabricated locally





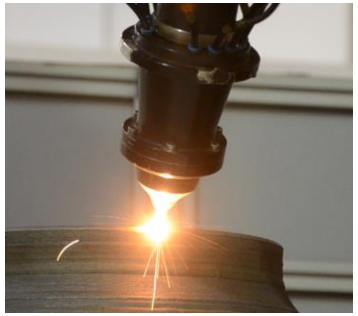
RS25 Powerhead demonstrator using LP-DED under NASA SLS Artemis Program (Courtesy: RPMI)

Comparison of L-PBF and DED

Different methods for different components!

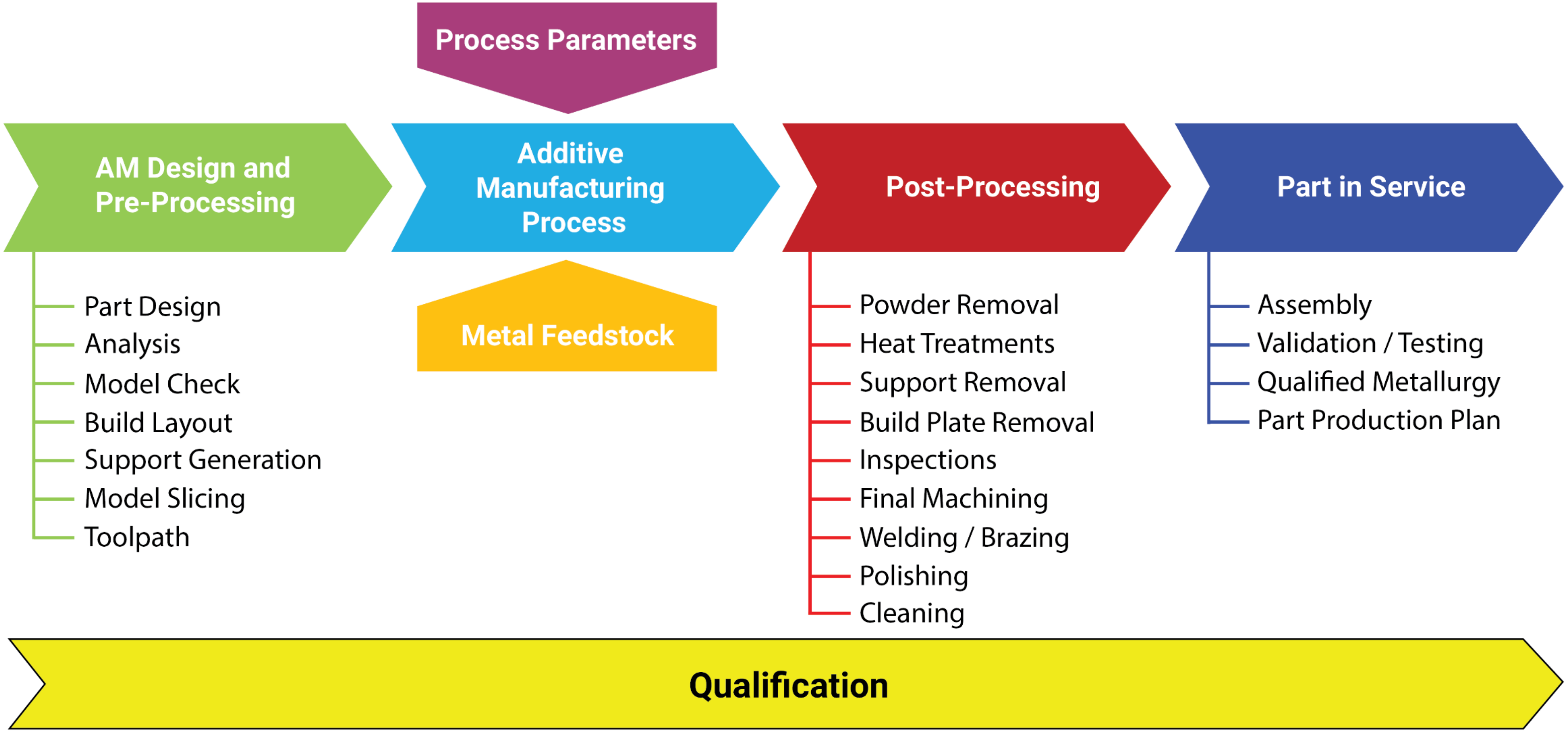
Laser Powder Bed Fusion (L-PBF)

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

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

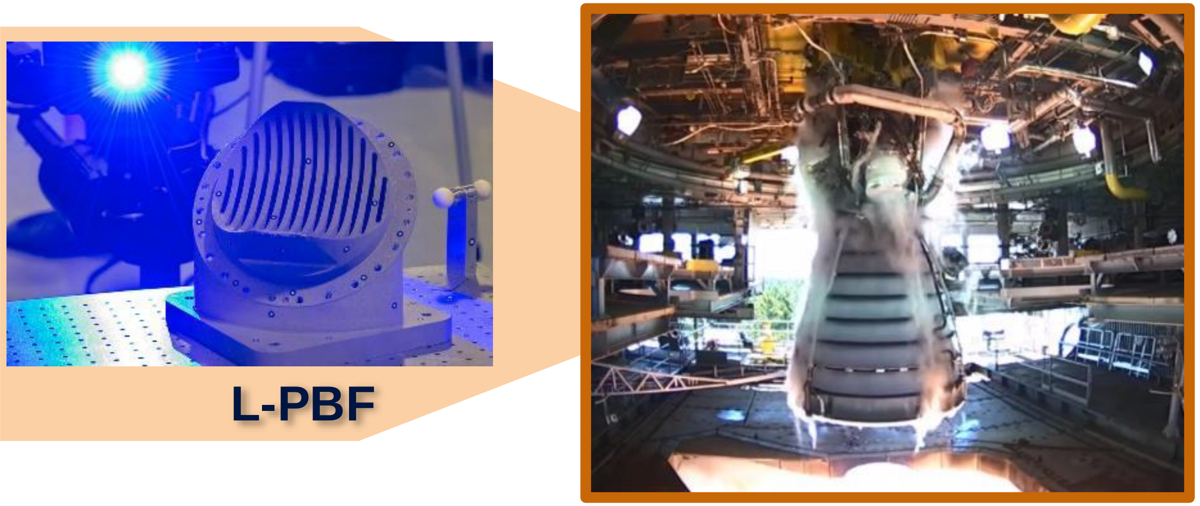
Post-Processing
- Powder Removal
- Heat Treatments
- Support Removal
- Build Plate Removal
- Inspections
- Final Machining
- Welding / Brazing
- Polishing
- Cleaning

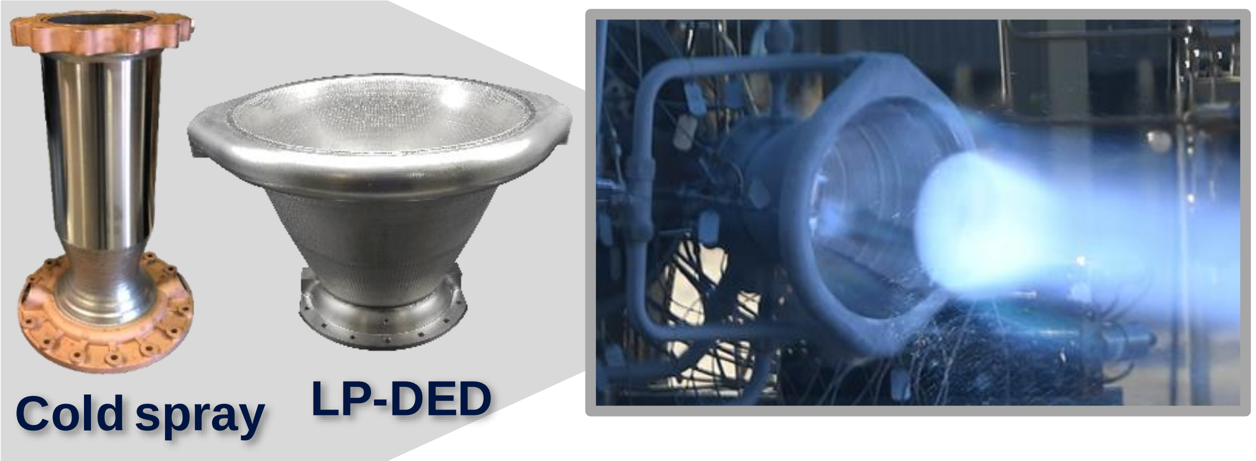
Part in Service
- Assembly
- Validation / Testing
- Qualified Metallurgy
- Part Production Plan

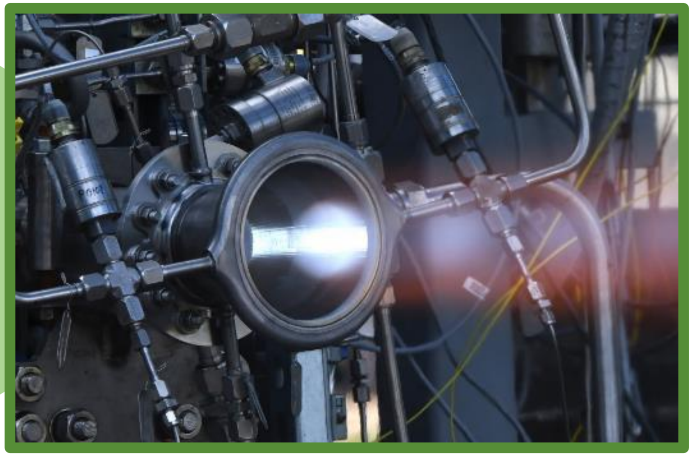
Qualification

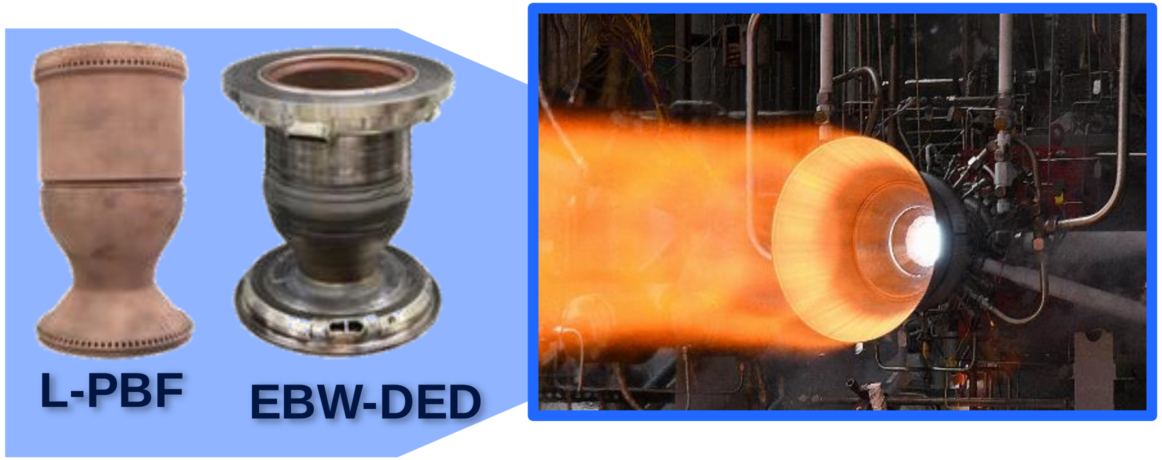
Proper AM process selection requires an integrated evaluation of all process lifecycle steps

Maturity of AM for Propulsion Applications







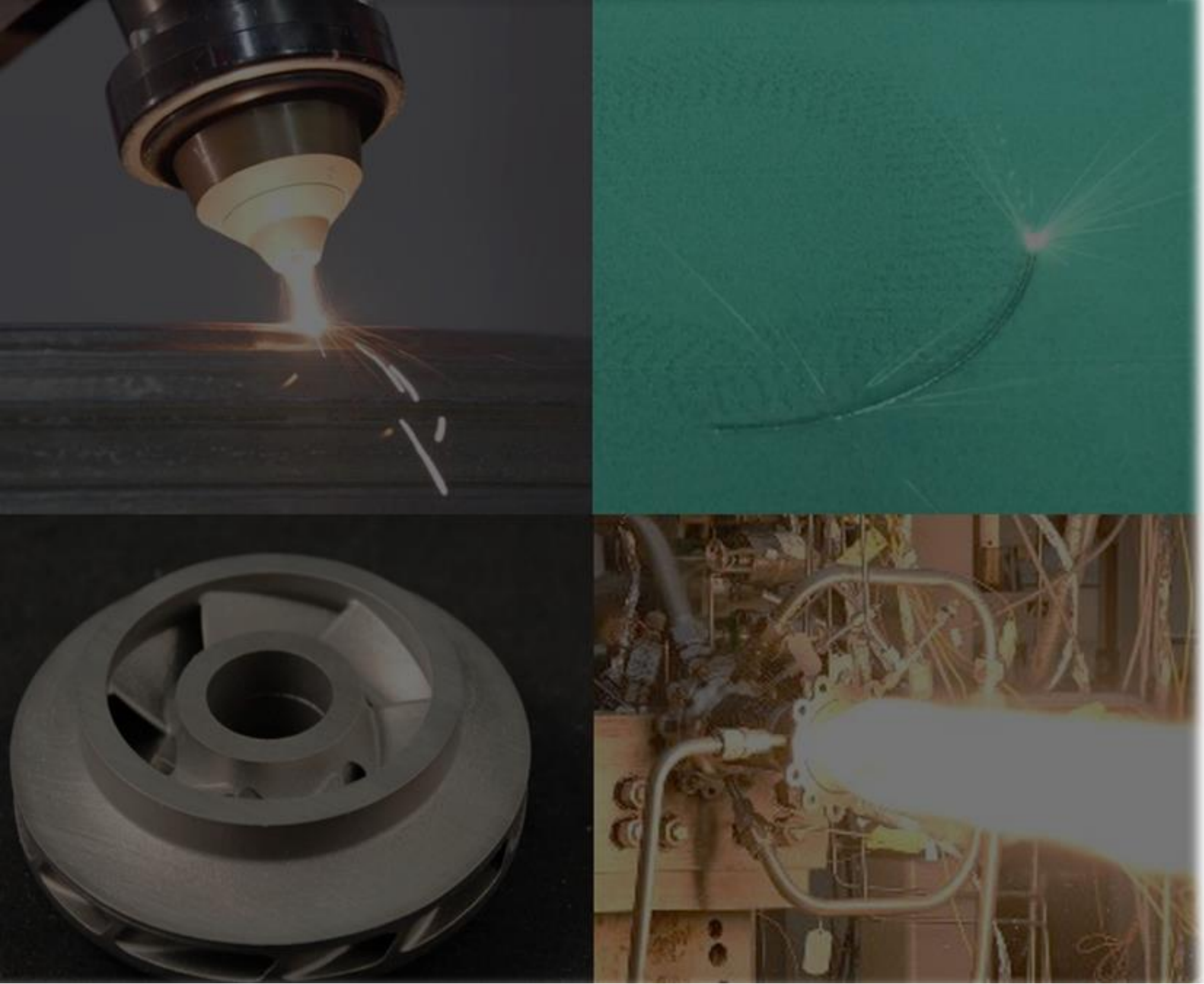


General Metal AM Summary

- 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.
- Various processes exist each with unique advantages and disadvantages
- Additive manufacturing takes practice!
- Post-processing is critical and integration of the entire AM lifecycle.
- Standards and certification of the AM processes in development.
- AM is evolving and there is a lot of work ahead.

Examples of Propulsion Applications

Image courtesy SWRI



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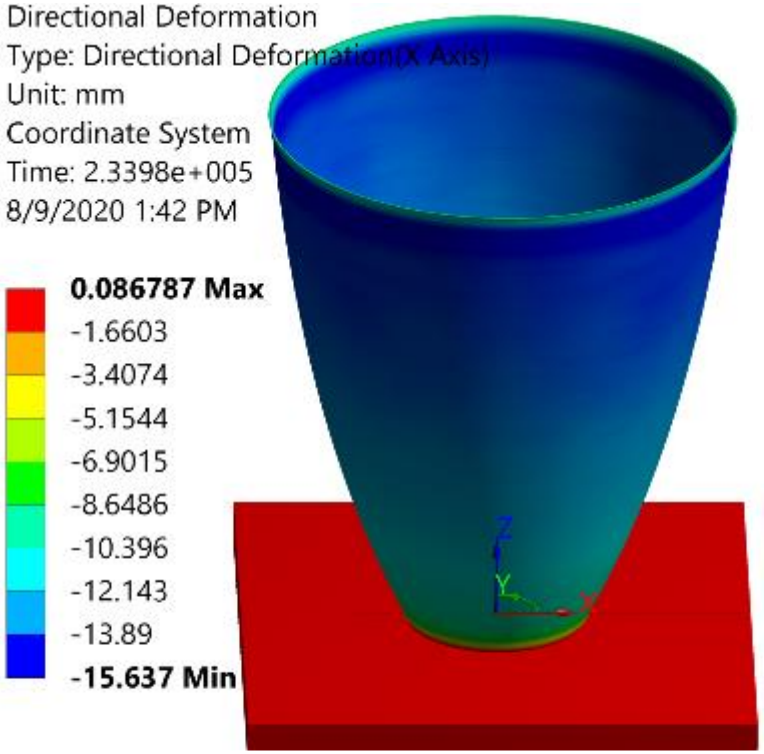
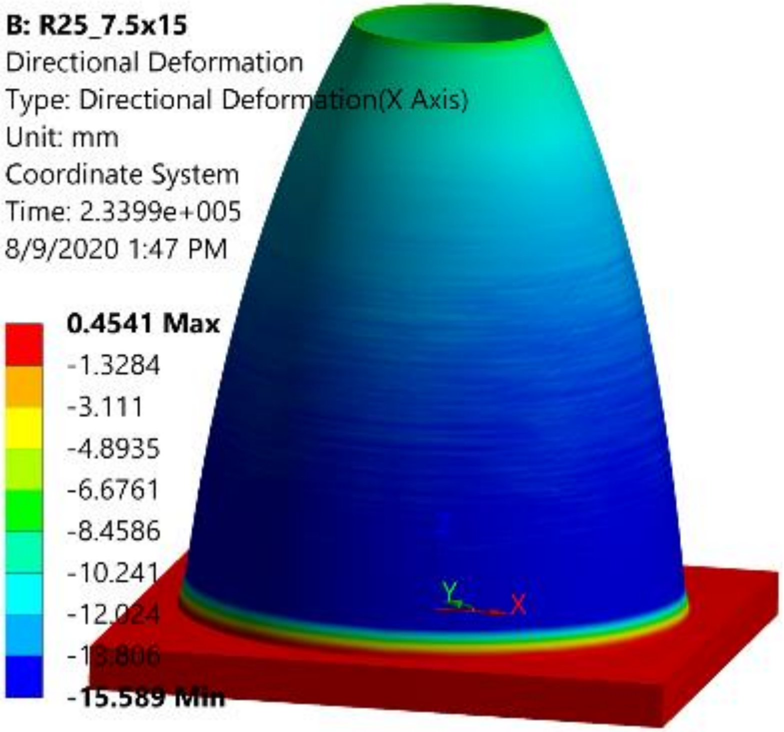
Challenges in Large Scale AM

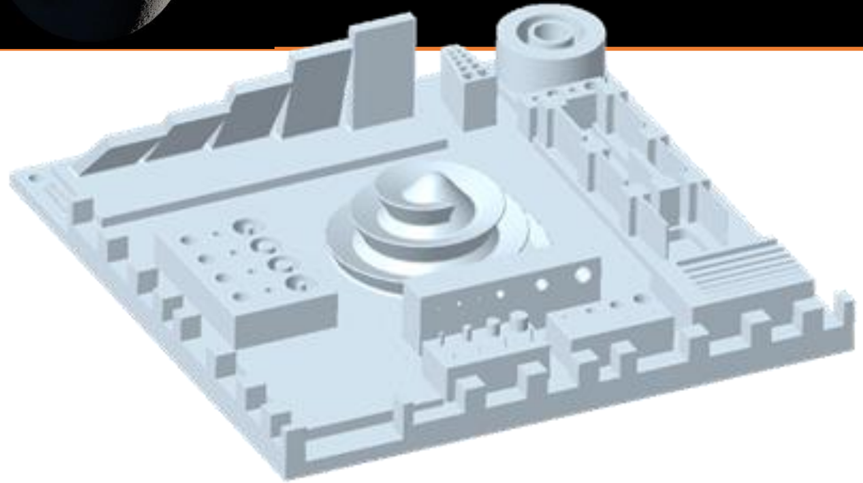
- Build durations are significantly increased with large scale AM due to amount of material being deposited
- Stops and starts will be more prevalent and re-starts may not be feasible
- Distortion is a concern with all AM processes, particularly at large scale

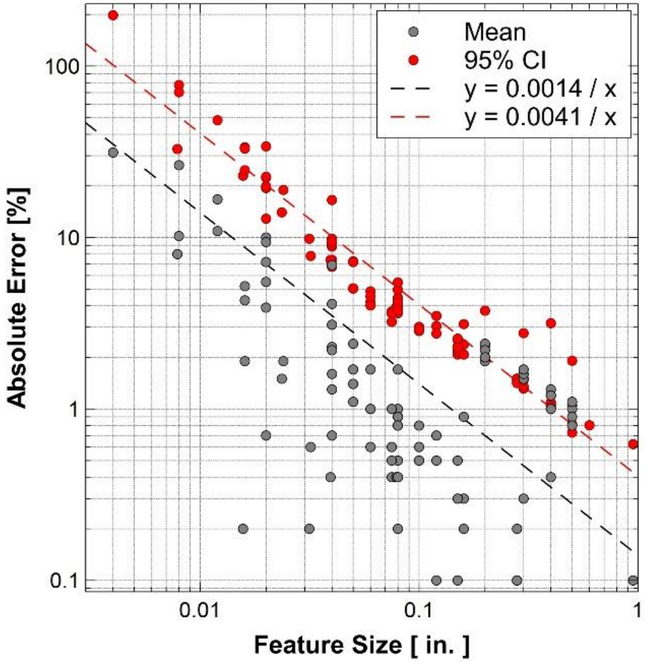


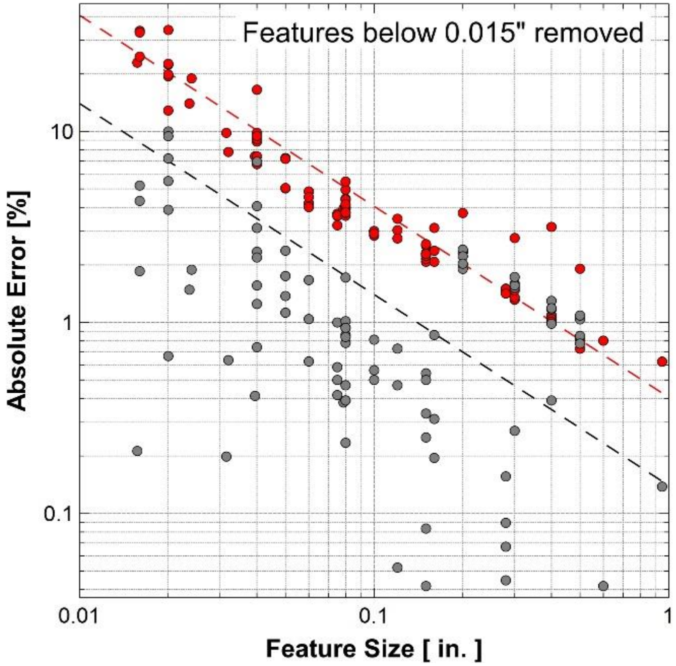


Ref: Kevin Wheeler / NASA Ames

Study on L-PBF Reproducibility – Inconel 718



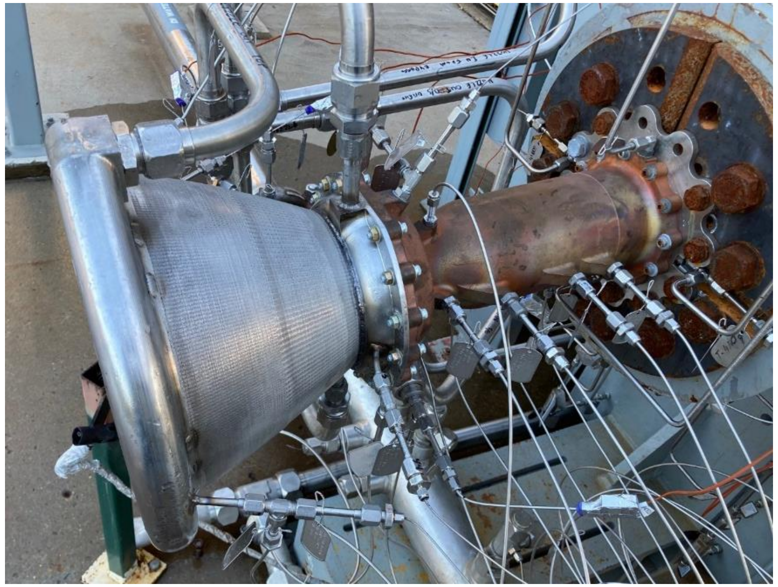


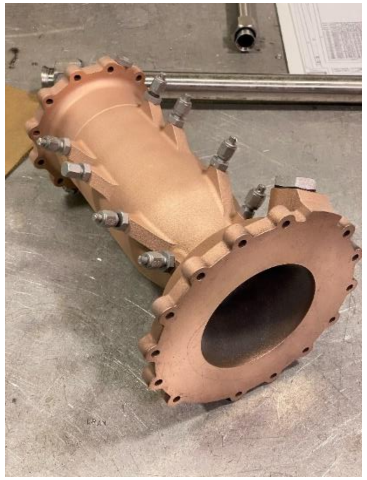


- A systematic mean tolerance across all features was 0.0014 inches (36 µm) with a 95% confidence interval (CI) of 0.0041 inches (104 µm). Therefore, relative error decreases inversely with feature size.
- Features sized at 0.004 inches (0.1 mm) failed to build for thin walls and slots
- Features sized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

Hot-fire Testing of Metal AM Parts





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