



EXPLORE MOON *to* MARS

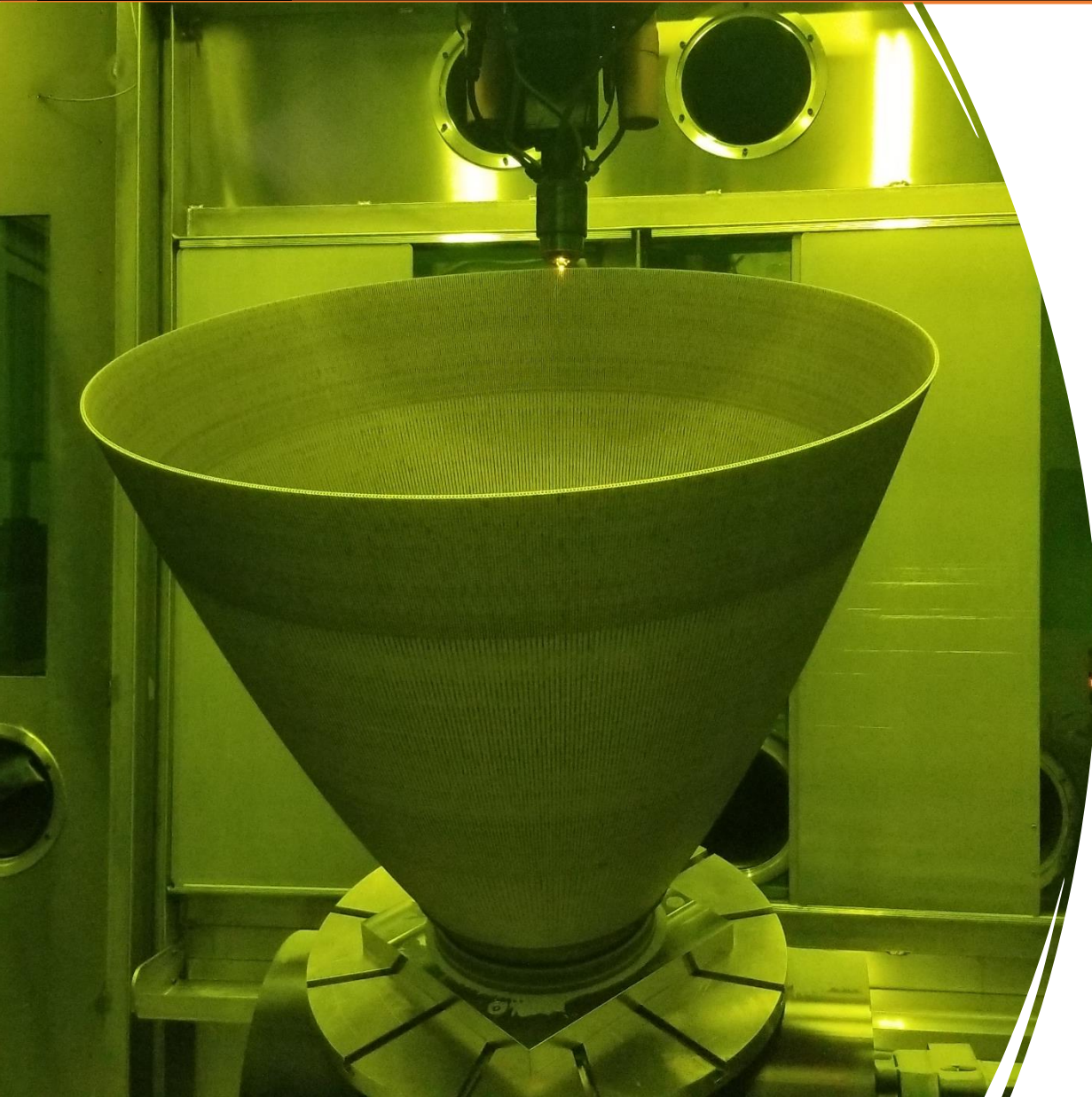
# Metal Additive Manufacturing for Rocket Propulsion Applications

Paul Gradl

23 September 2022



# Overview of Presentation

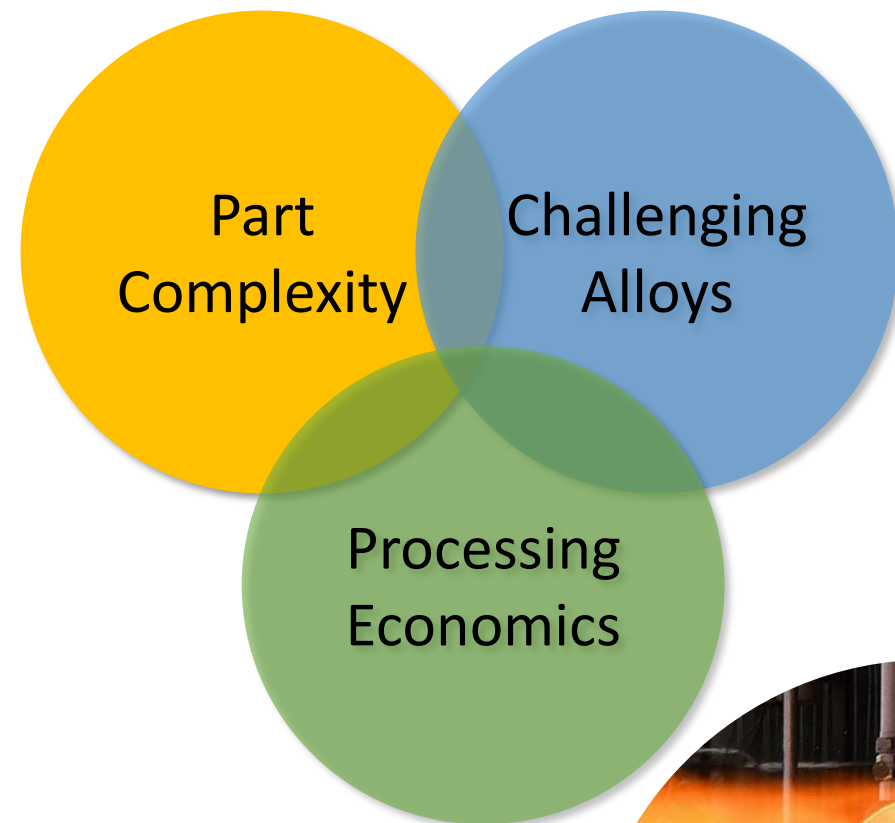


- Why additive manufacturing?
- AM Processes and Selection
- Large Scale AM Development
- Maturity of AM for Rocket Engines
- Gaps in Technology
- Heat Exchanger Research
- Summary



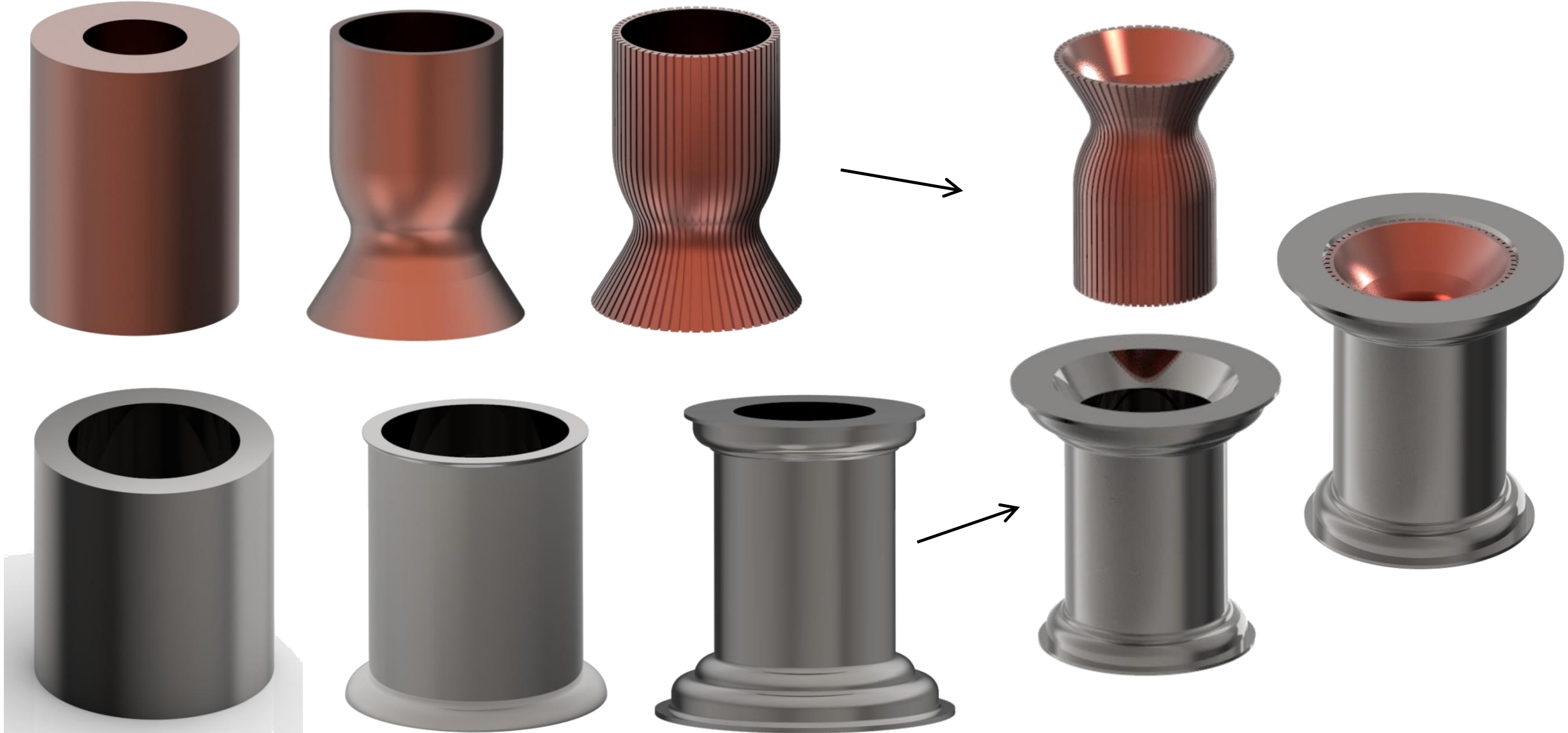
# The Case for Additive Manufacturing in Propulsion

- 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.





# Traditional Manufacturing...Forging to final assembly





# A rocket combustion chamber case study for AM

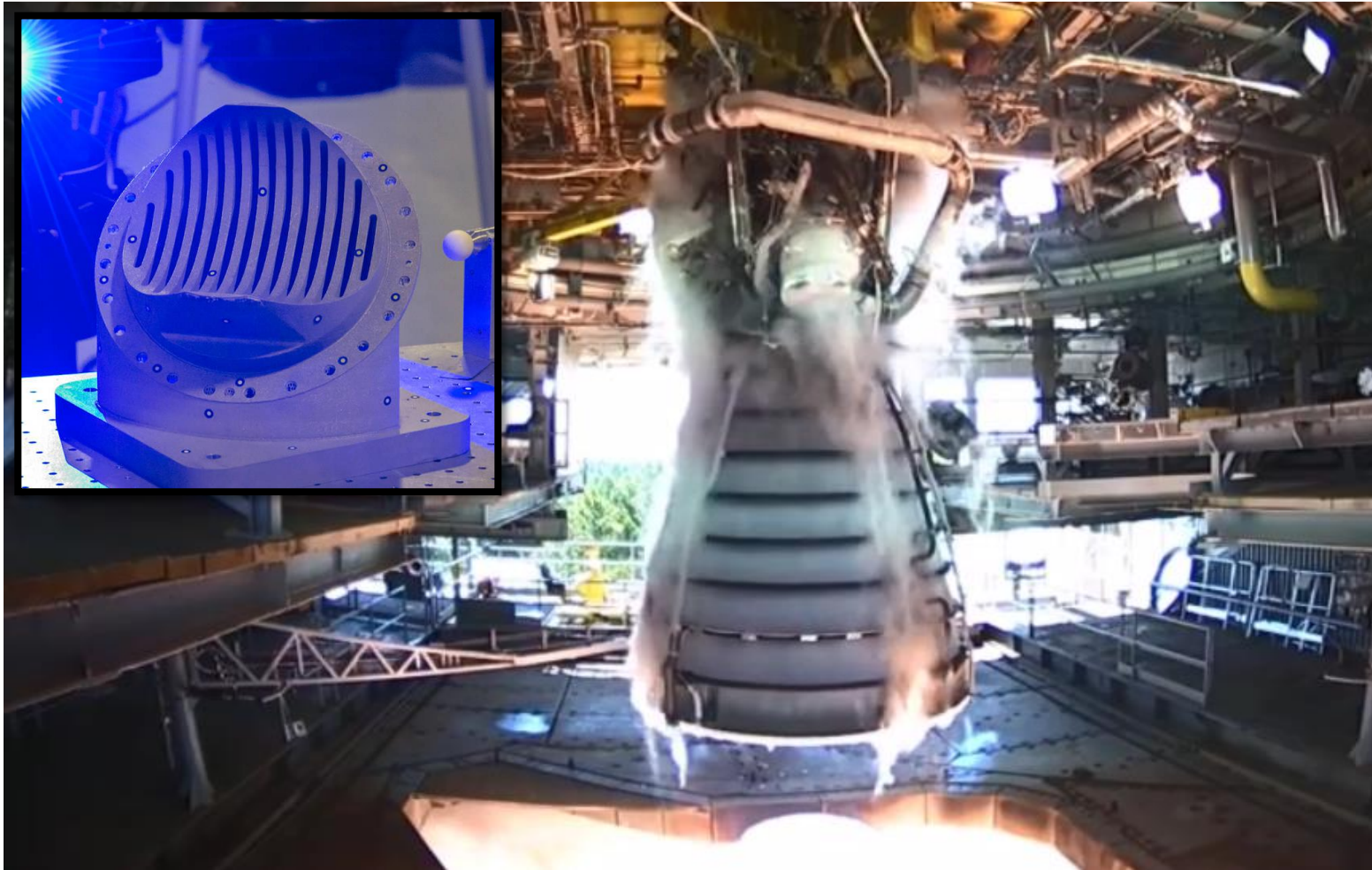


| Category                                 | Traditional Manufacturing                                                                                       | Initial AM Development                                                                                                                     | Evolving AM Development                                                                                                                                                 |
|------------------------------------------|-----------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Design and Manufacturing Approach</b> | 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 |
| <b>Schedule (Reduction)</b>              | 18 months                                                                                                       | 8 months (56%)                                                                                                                             | 5 months (72%)                                                                                                                                                          |
| <b>Cost (Reduction)</b>                  | \$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**



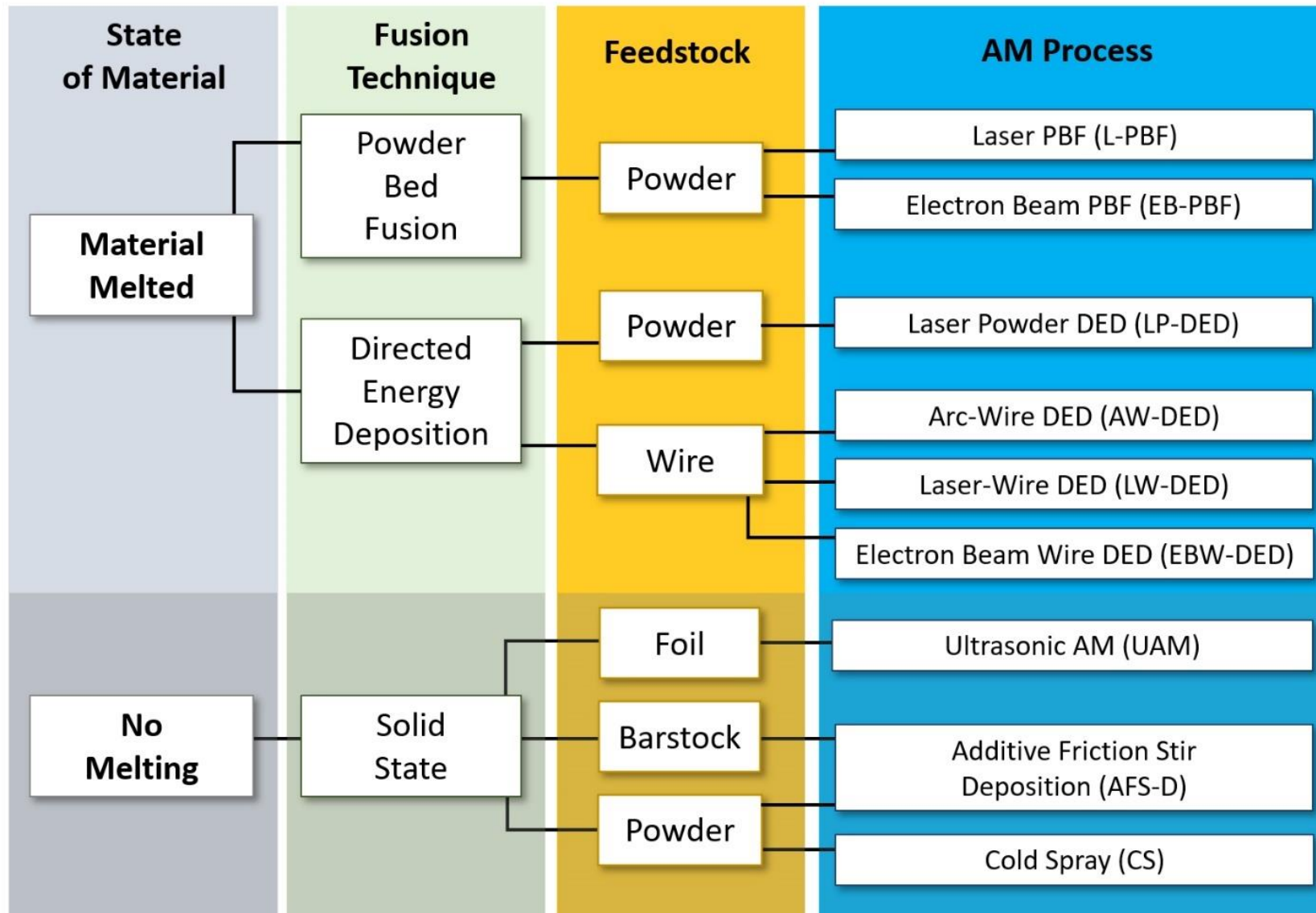
# Additive Manufacturing in use on NASA Space Launch System (SLS)



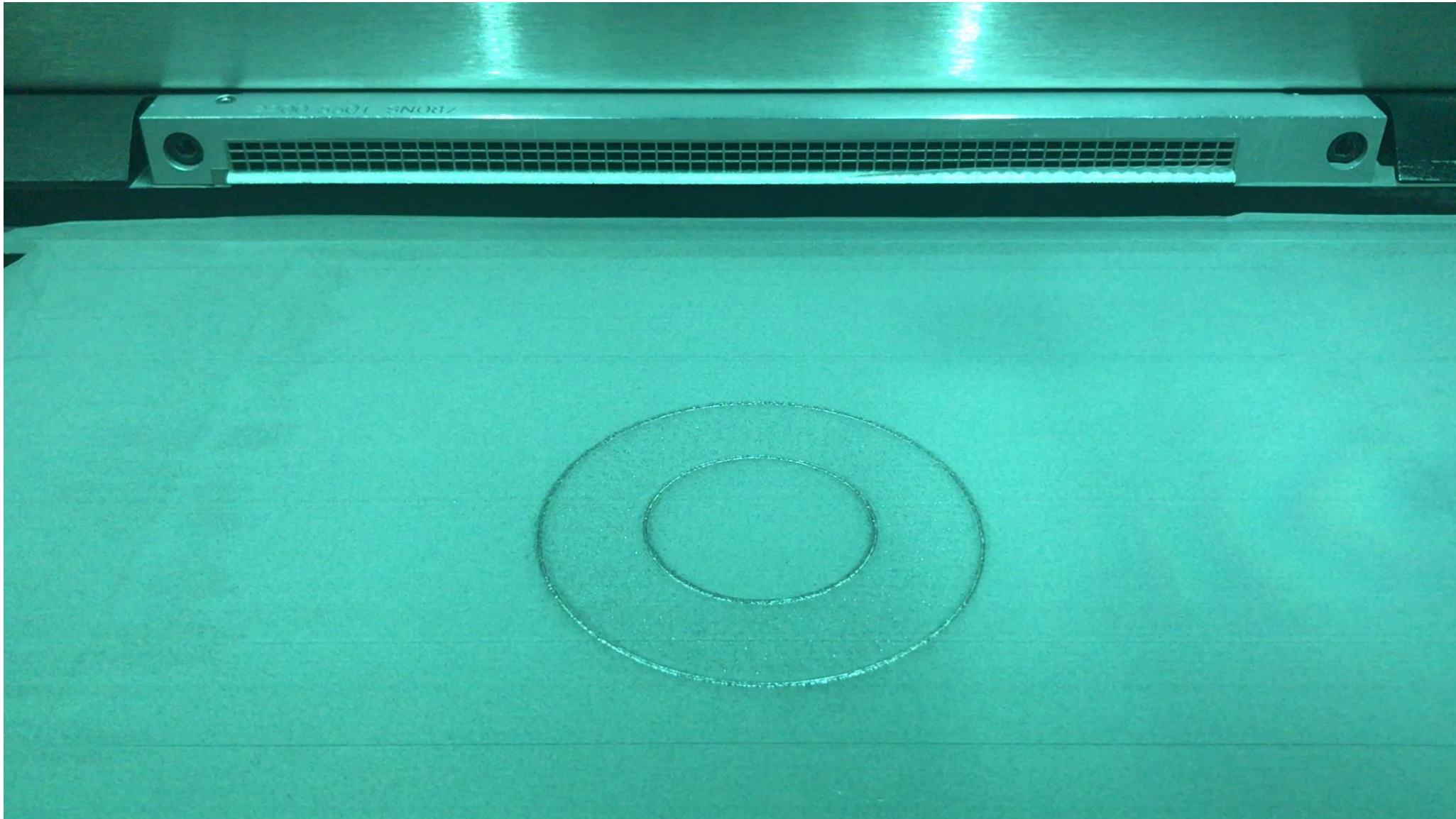
**Successful hot-fire testing of full-scale additive manufacturing (AM) Part to be flown on SLS RS-25**  
**RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from 127 welds to 4 welds**



# Various Metal AM Processes

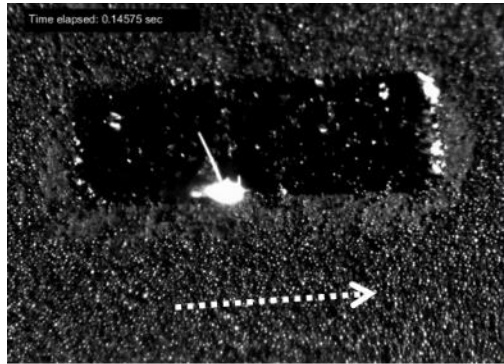


# Laser Powder Bed Fusion (L-PBF)

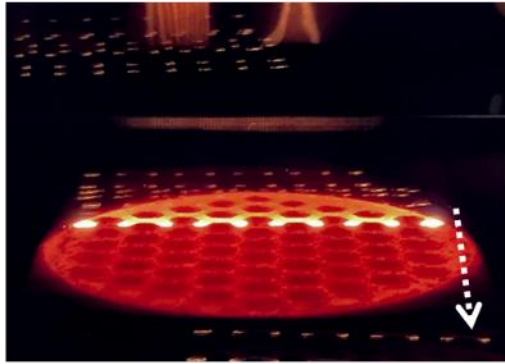




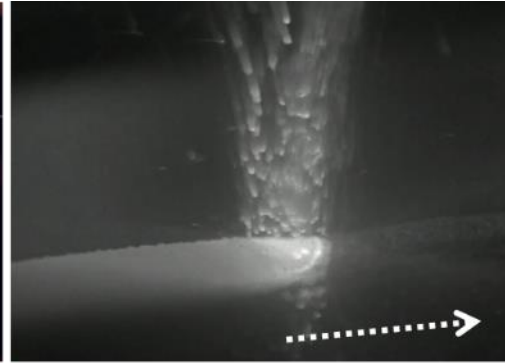
# AM Processes for various applications



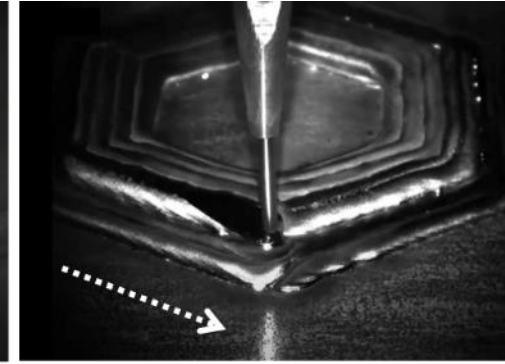
Laser Powder Bed Fusion



Electron Beam Powder Bed Fusion



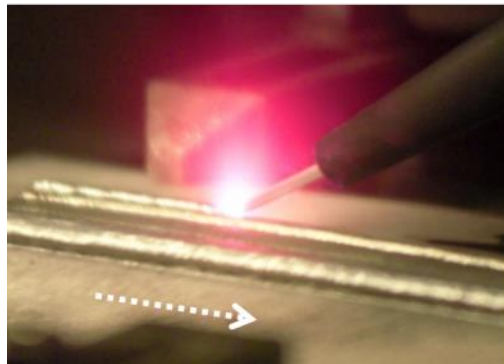
Laser Powder DED



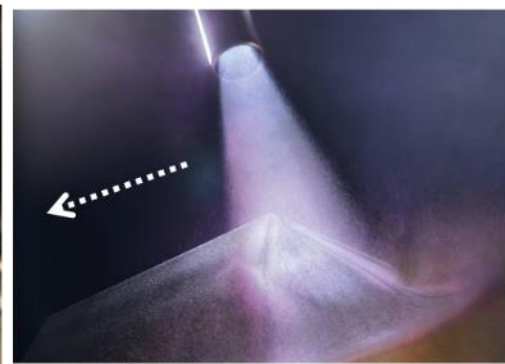
Laser Wire DED



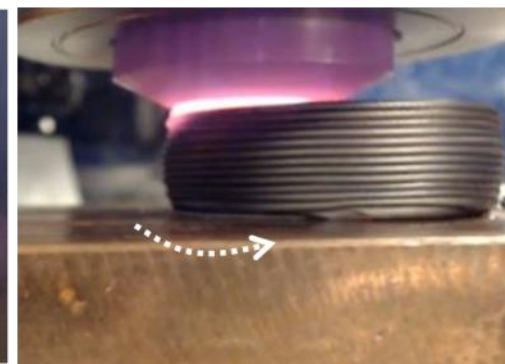
Arc Wire DED



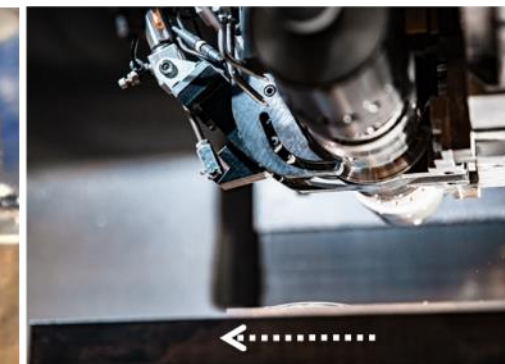
Electron Beam Wire DED



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: Formally], 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].



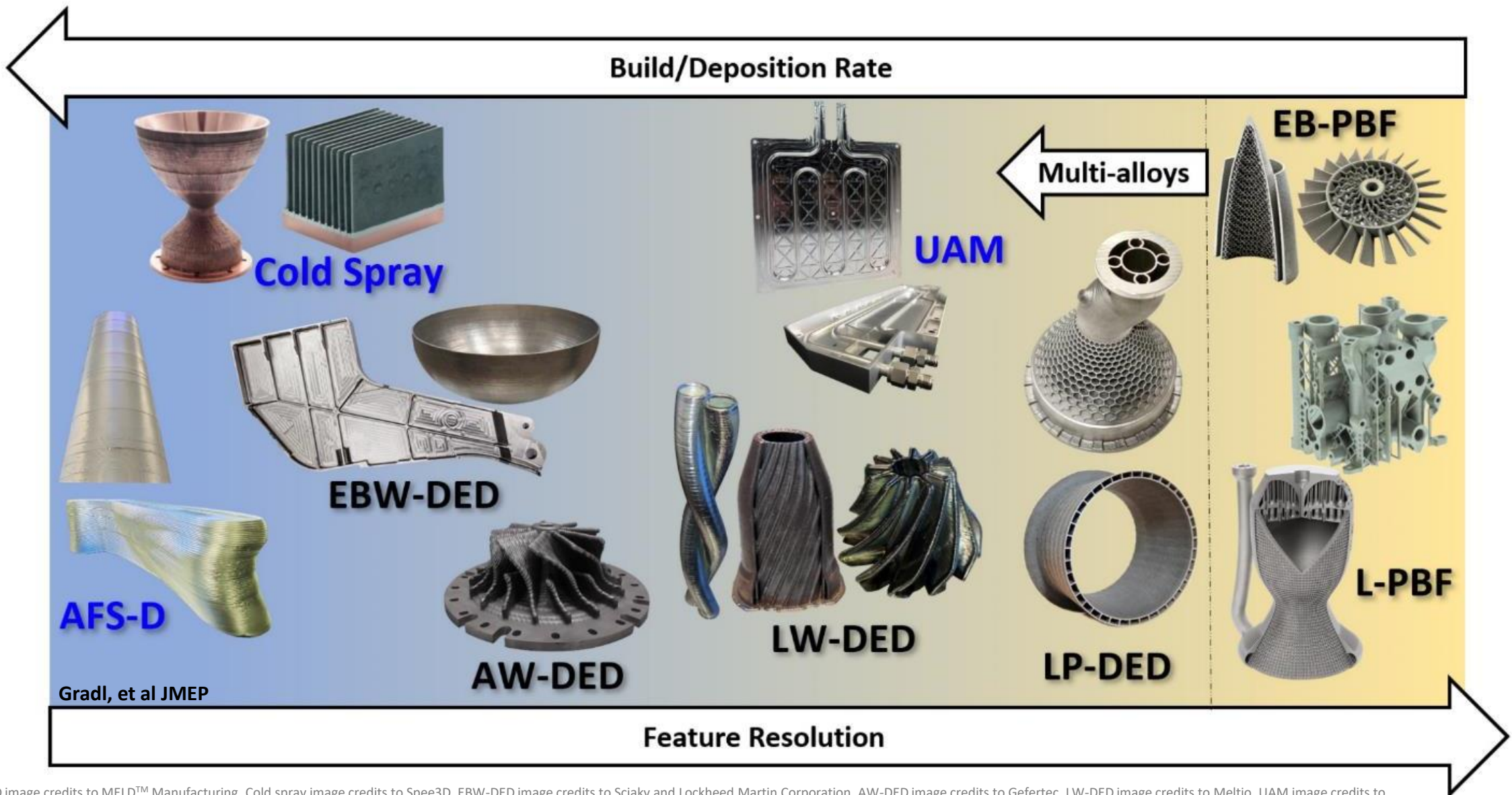
# Methodical AM Process Selection



- 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?



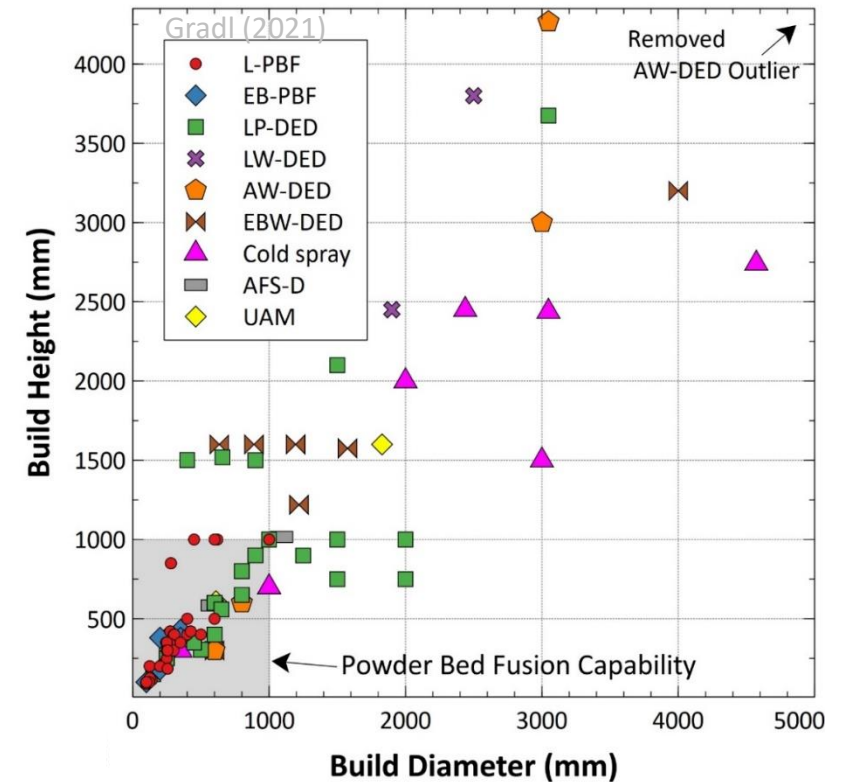
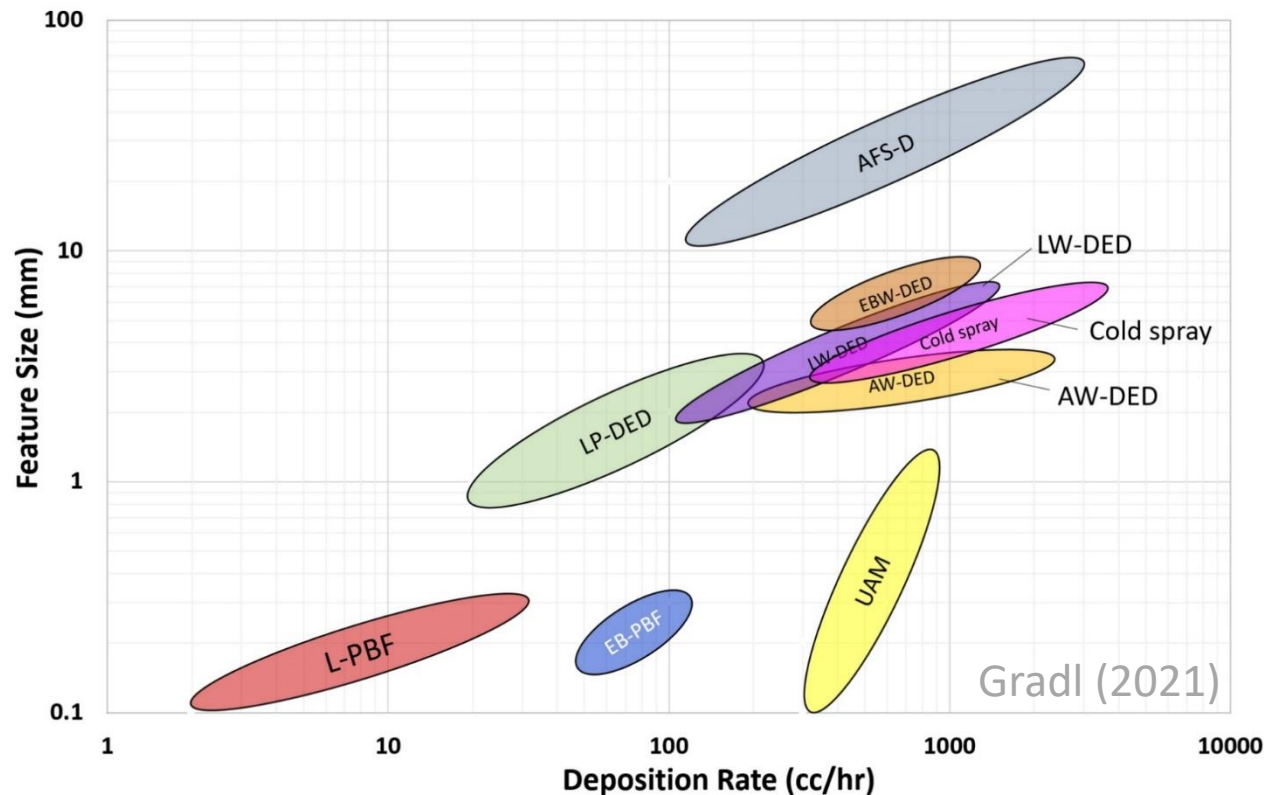
# Criteria and Comparison Various Metal AM Processes



**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 Formally, L-PBF image credits to Renishaw plc and CellCore GmbH/Sol Solutions Group AG, EB-PBF image credits to Wayland and GE Additive/Arcam.



# 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>
- 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>
- 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>



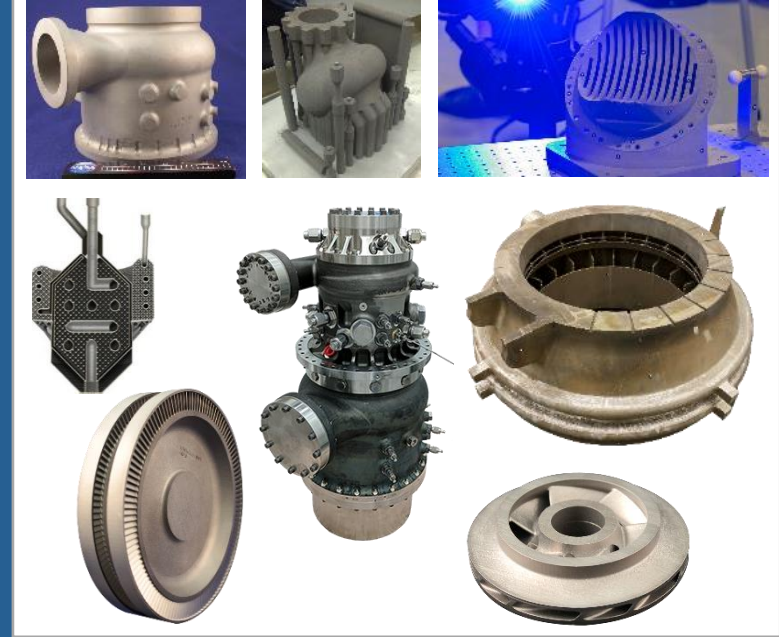
# Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines



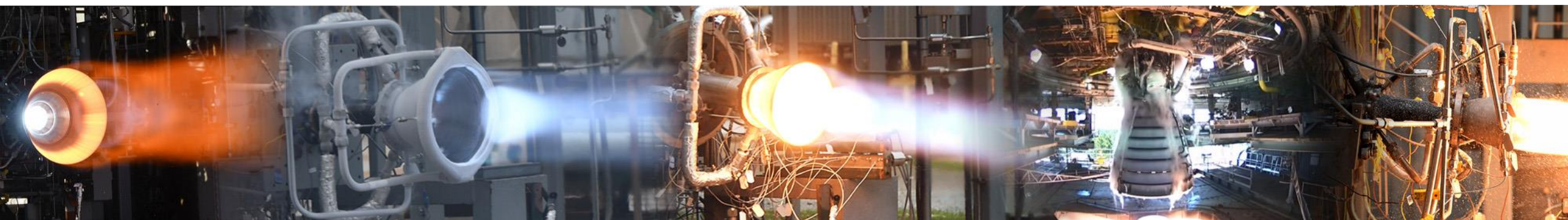
Laser Powder Bed Fusion (L-PBF)  
Copper Alloys combined with other  
AM processes to provide bimetalllic



Directed Energy Deposition



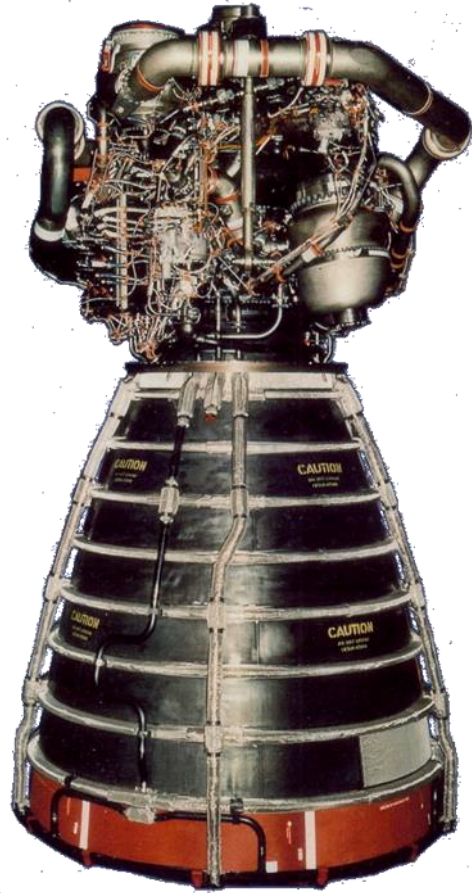
L-PBF of complex components, new  
alloy developments for harsh  
environment





# Large Scale Additive Manufacturing for Rocket Nozzles

SSME/RS-25



90"

RL-10A-4



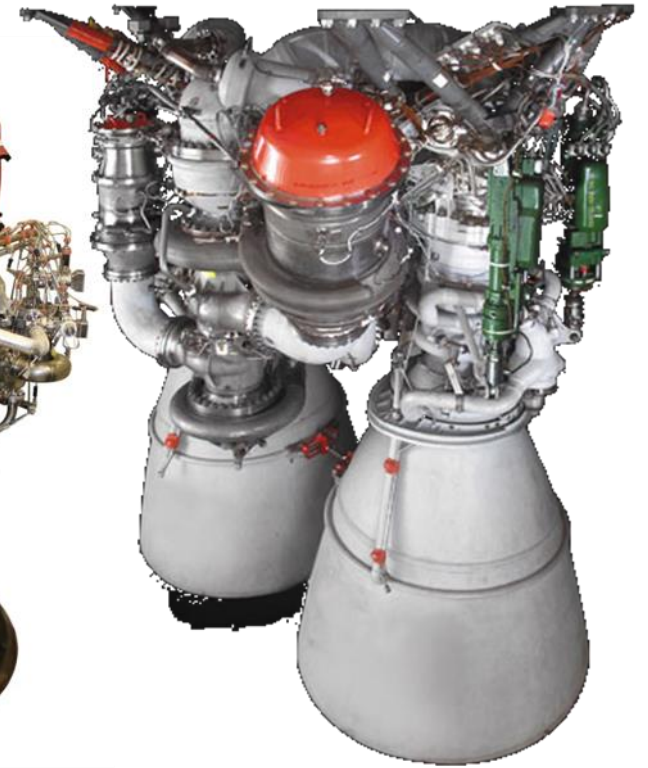
46"

J-2X, Regen Only



70"

RD-180

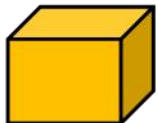


56"

L-PBF Build  
Boxes



10x10x10



15.5x24x19

(inches)

**Nozzle Exit Dia.**

# Laser Powder Directed Energy Deposition (DED)





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



**1.52 m diameter and 1.78 m height with  
integral channels  
90 day deposition**

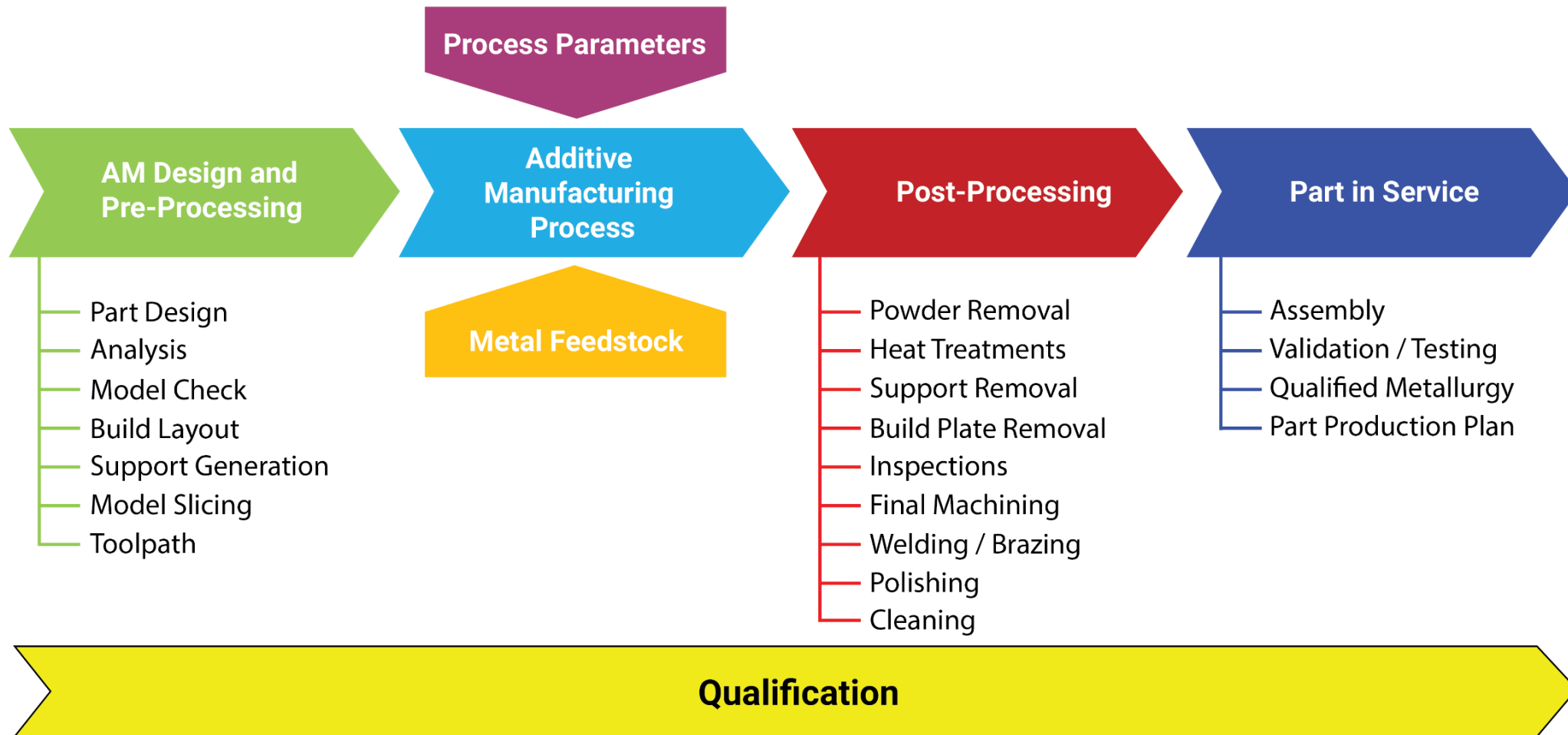


**2.41 m dia and 2.82 m height  
Near Net Shape Forging Replacement**

**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>.



# Additive Manufacturing Typical Process Flow

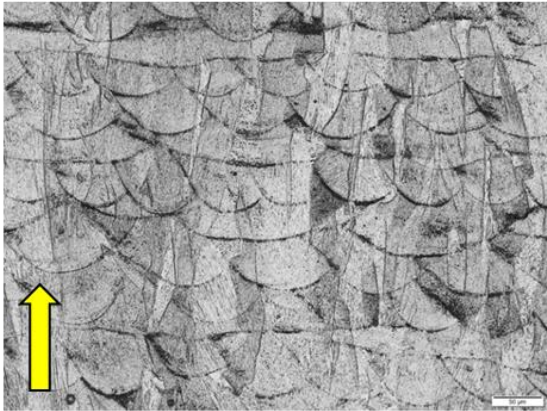


**Proper AM process selection requires an integrated evaluation of all process lifecycle steps**



# Microstructure of Various AM Processes

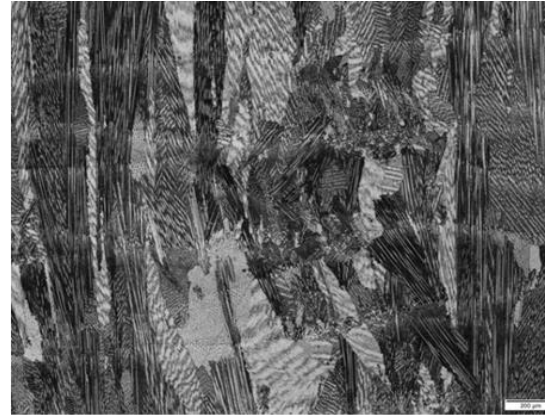
## Alloy 625 – **As-Built**



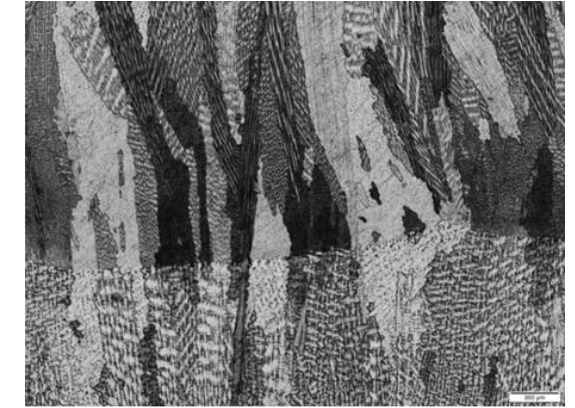
Laser Powder Bed Fusion



Electron Beam Powder Bed Fusion



Laser Powder DED (1070 W)



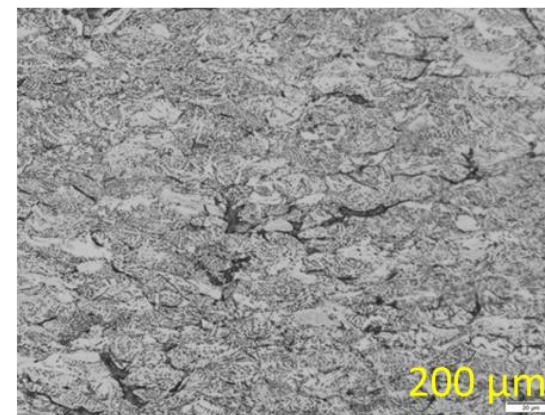
Electron Beam Wire DED



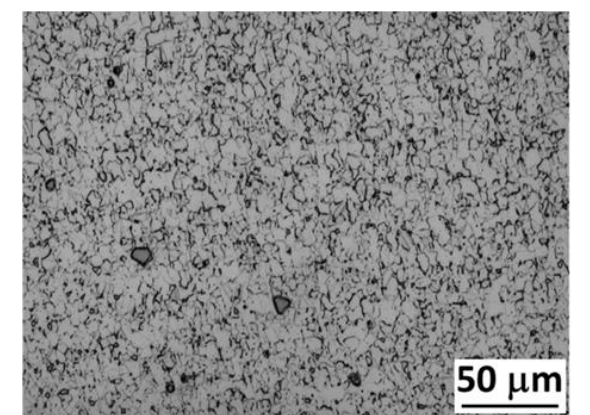
Laser Wire DED



Arc Wire DED



Cold Spray



Additive Friction Stir Deposition

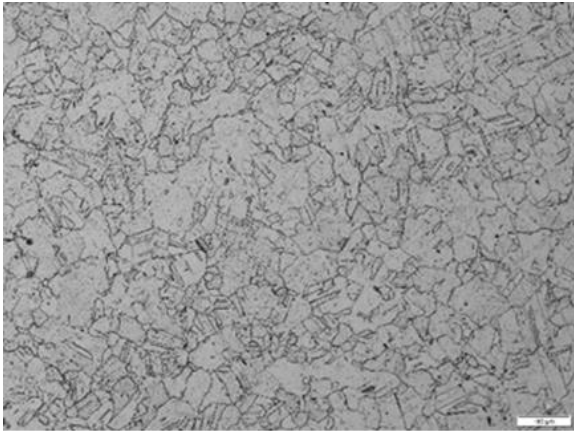
Each AM process results in different grain structures, which ultimately influence properties

- 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, 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.
- Image from Mark Norfolk, Fabrisonic

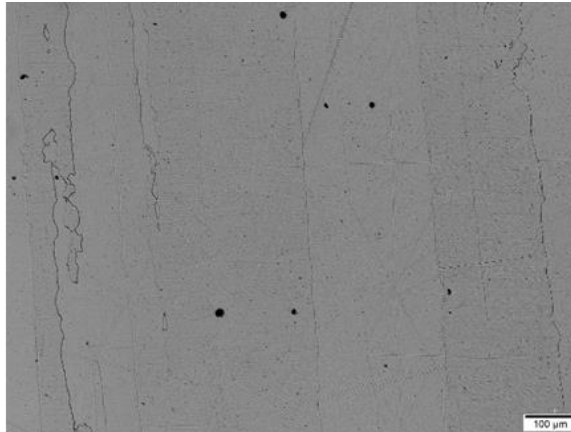


# Microstructure of Various AM Processes

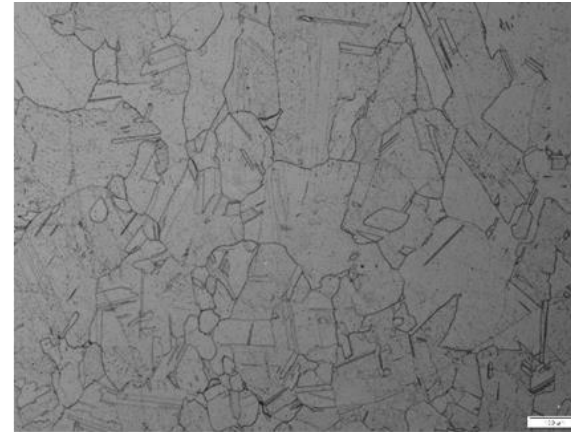
## Alloy 625 – Stress Relief, HIP, Solution per AMS 7000



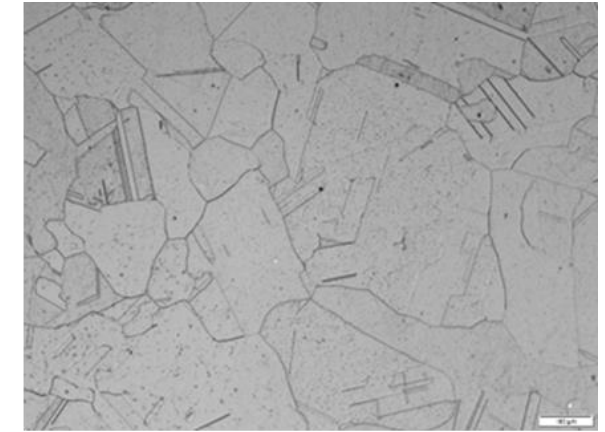
Laser Powder Bed Fusion



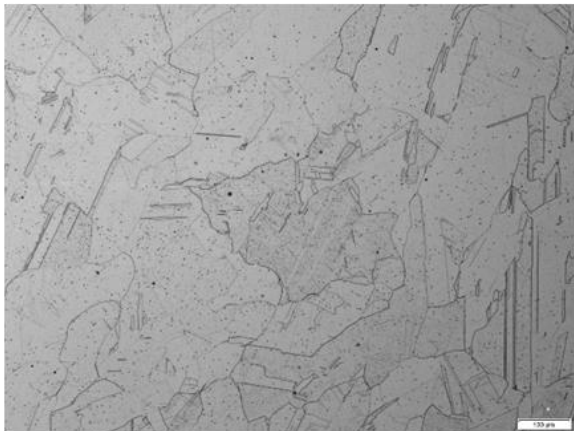
Electron Beam PBF



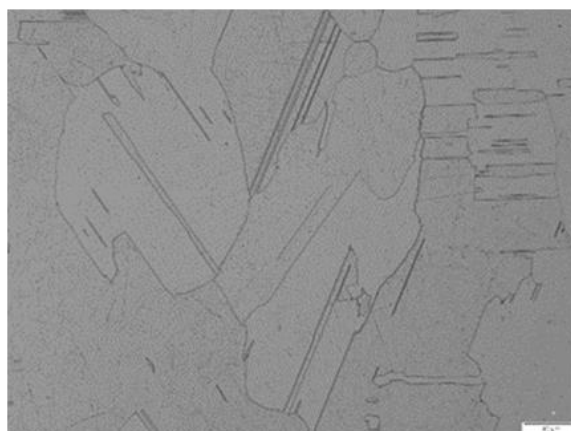
Laser Powder DED (1070 W)



Electron Beam Wire DED



Laser Wire DED



Arc Wire DED



Cold Spray

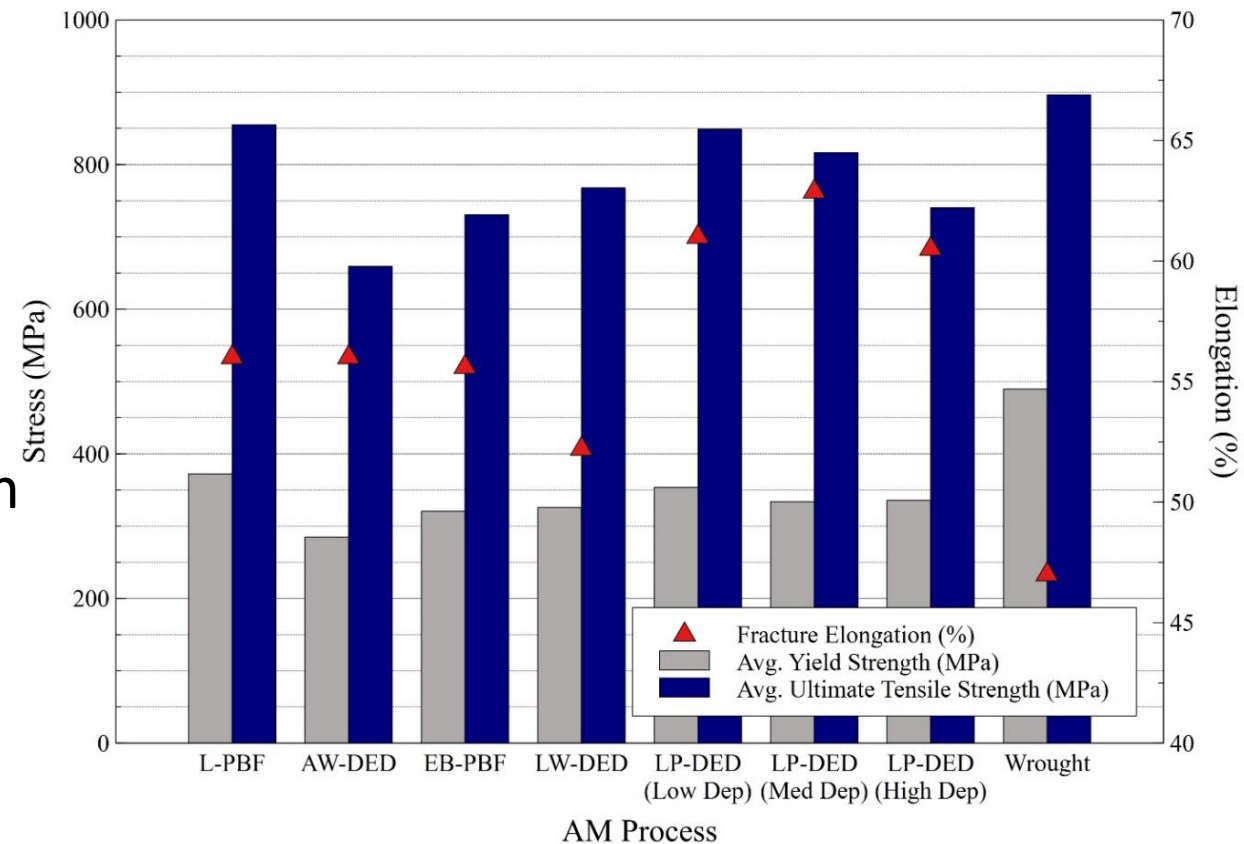
- Gamon, A., Arrieta, E., Gradl, P.R., Katsarelis, C., Murr, L.E., Wicker, R.B., Medina, F., 2021. Microstructure and hardness comparison of as-built Inconel 625 alloy following various additive manufacturing processes. Results in Materials 12. <https://doi.org/10.1016/j.rinma.2021.100239>
- Gradl, P., Tinker, D., Park, A., Mireles, 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.



# 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.

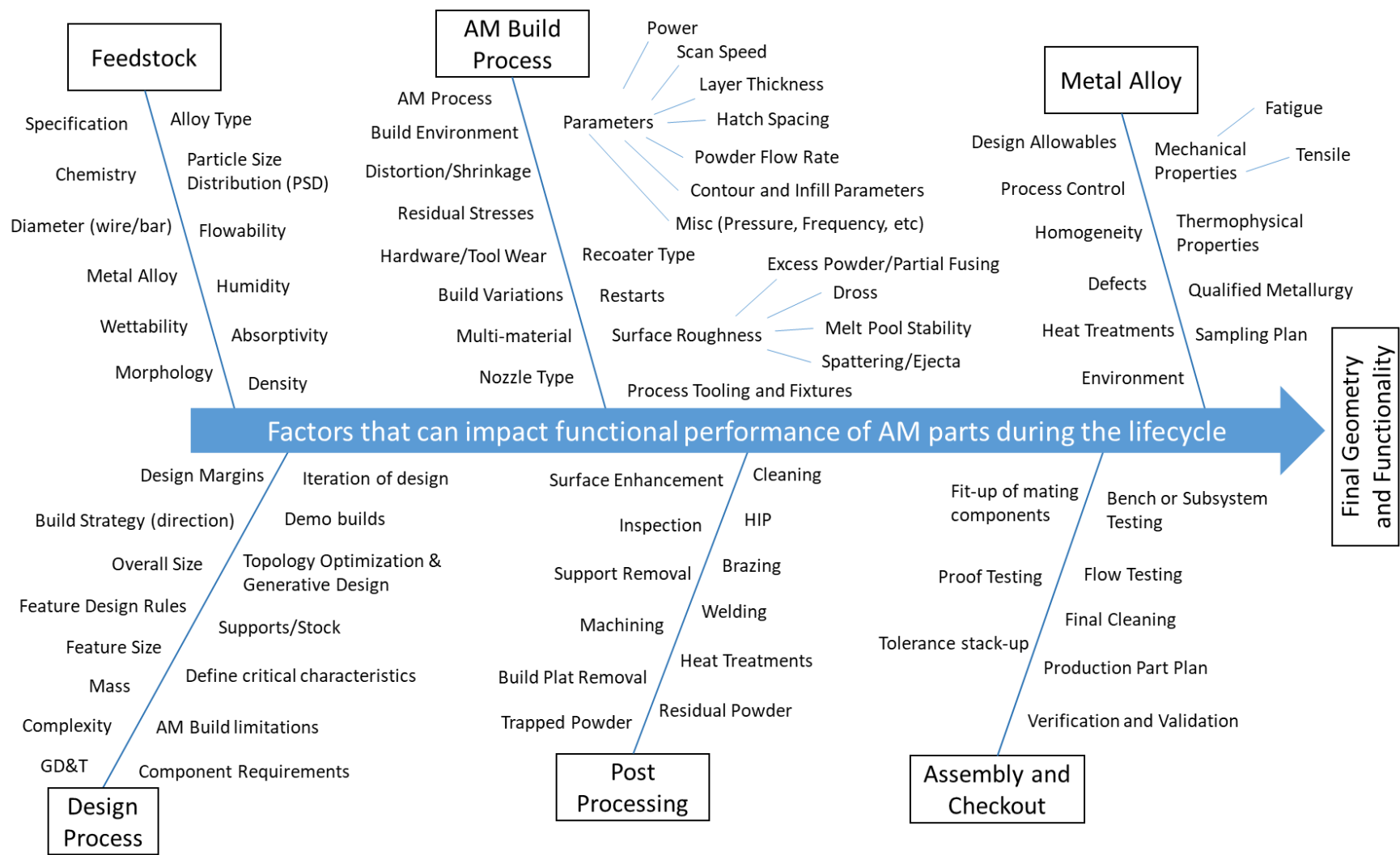
## Alloy 625, Heat Treated per AMS 7000 Room Temperature UTS



\*Not design data and provided as an example only



# 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

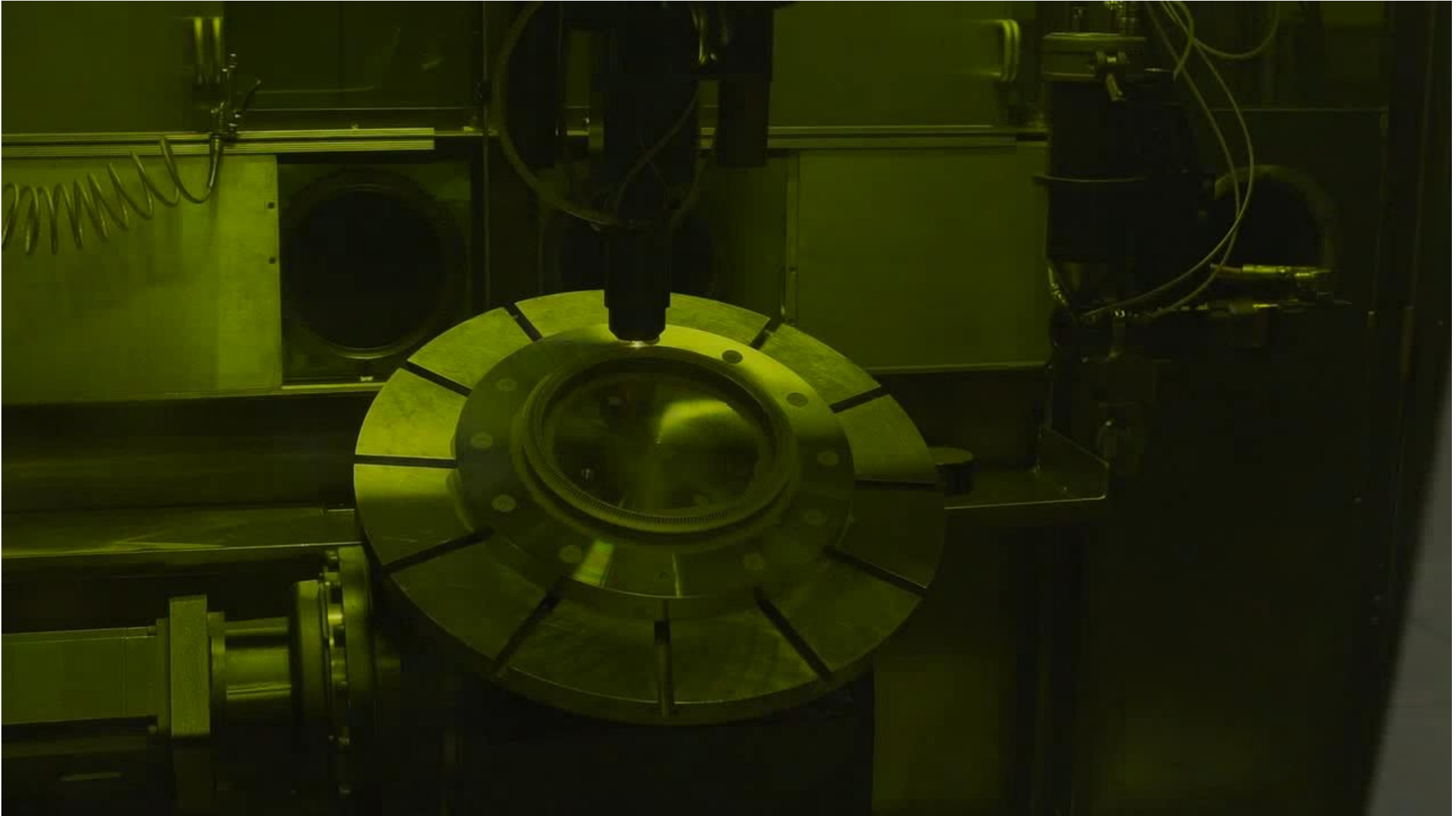


# Challenges in AM

- Surface Texture
- Repeatability of the process (across designs, machines, facilities...)
- Inspection of components
- Residual stresses and distortion
- Properties of alloys and common usage (databases)
  - Anisotropy based on build direction
  - Differences between processes
  - Mechanical, thermophysical, texture, etc...
- Design of AM parts and systematic application of AM
  - Education of AM for proper infusion
  - Understand of the entire lifecycle
- Standards and certification of process

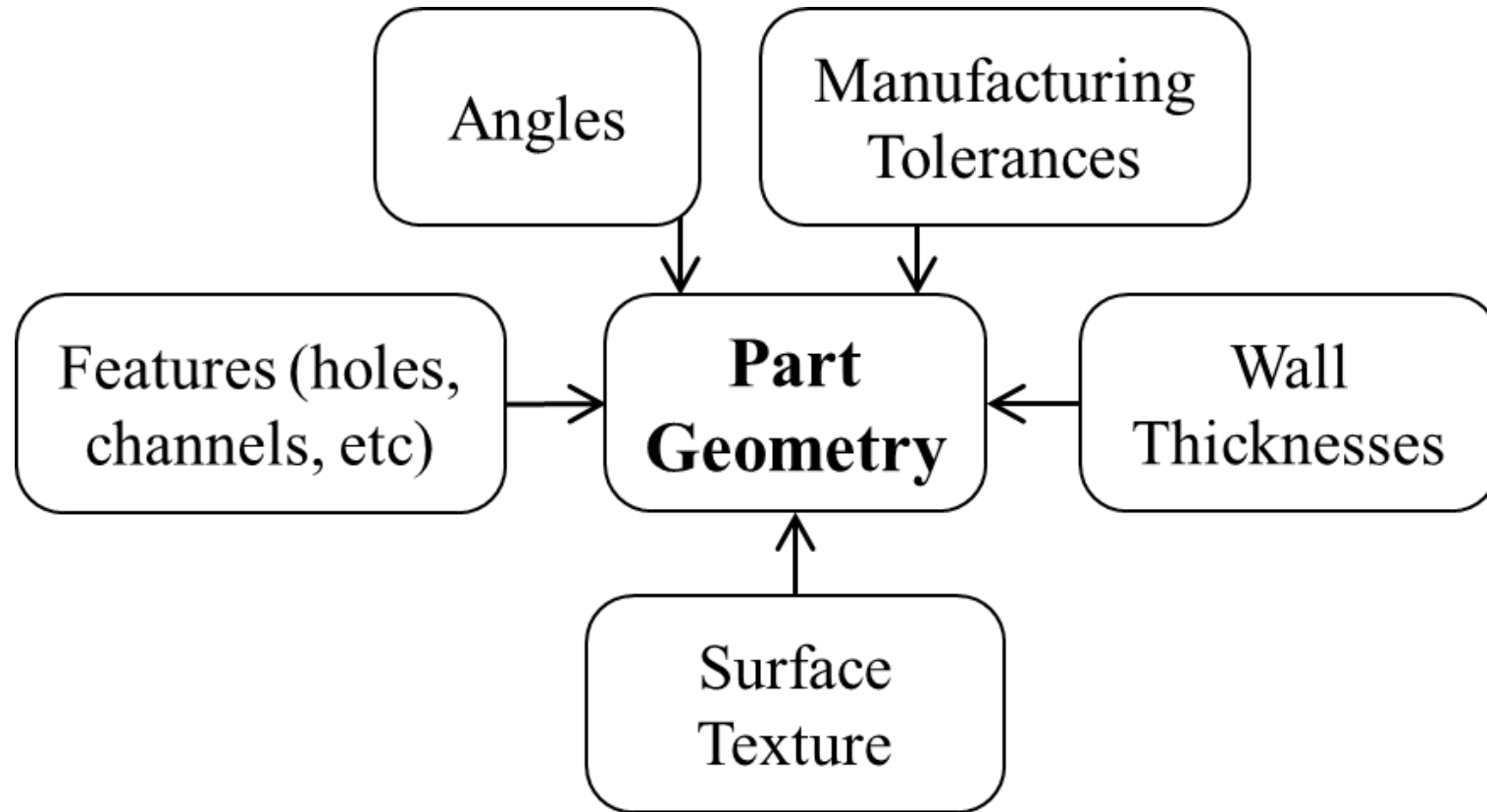


# Focus of Research – LP-DED Heat Exchangers





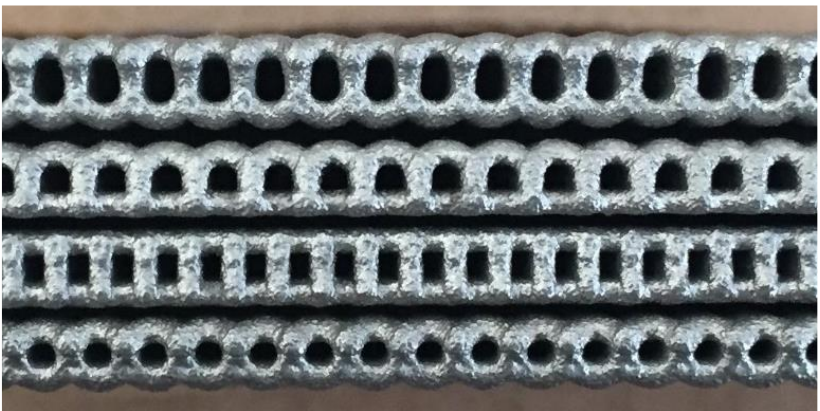
# Geometry Limitations in AM Processes



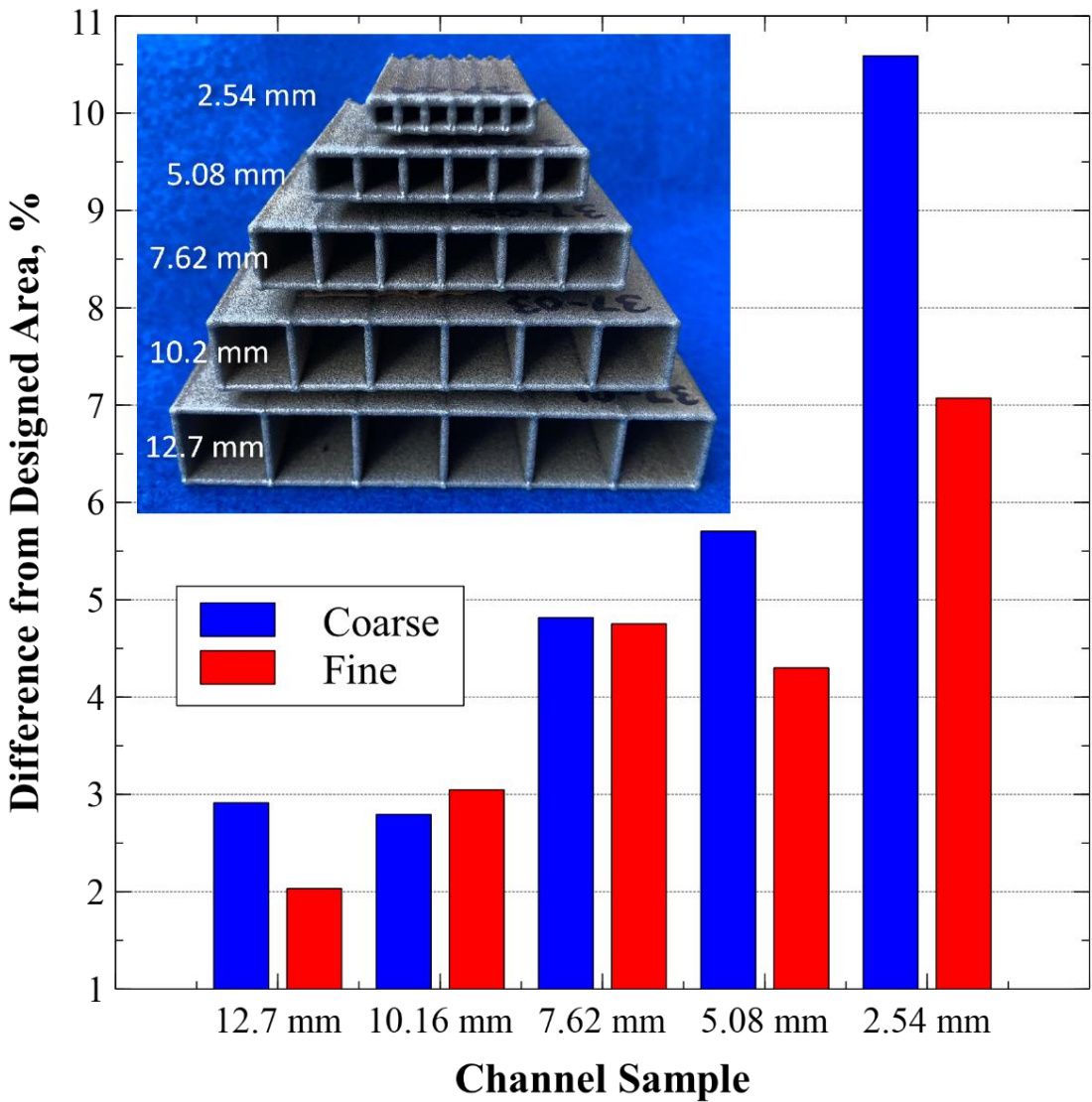
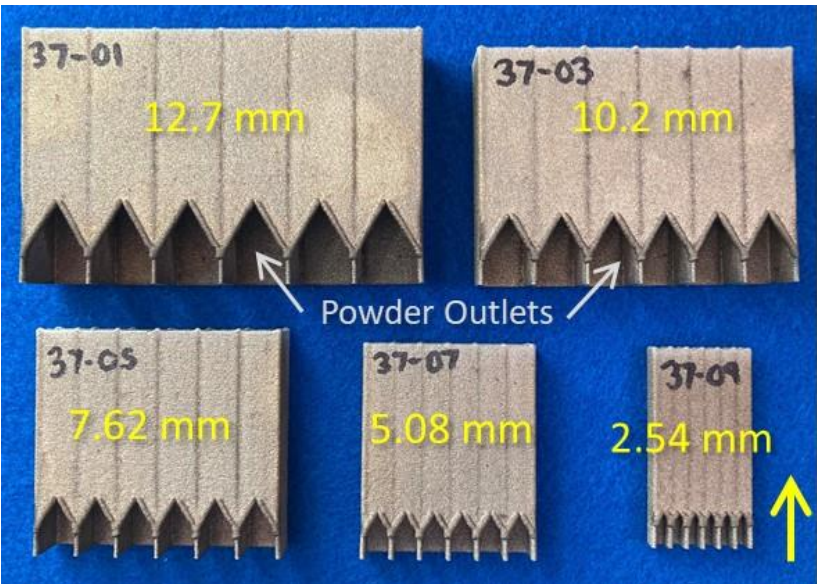
**AM process limitations consider several aspects that constitute the as-built geometry (ie. no post-processing) for heat exchanger applications.**

# LP-DED Channel Geometry

Various channel geometries using LP-DED



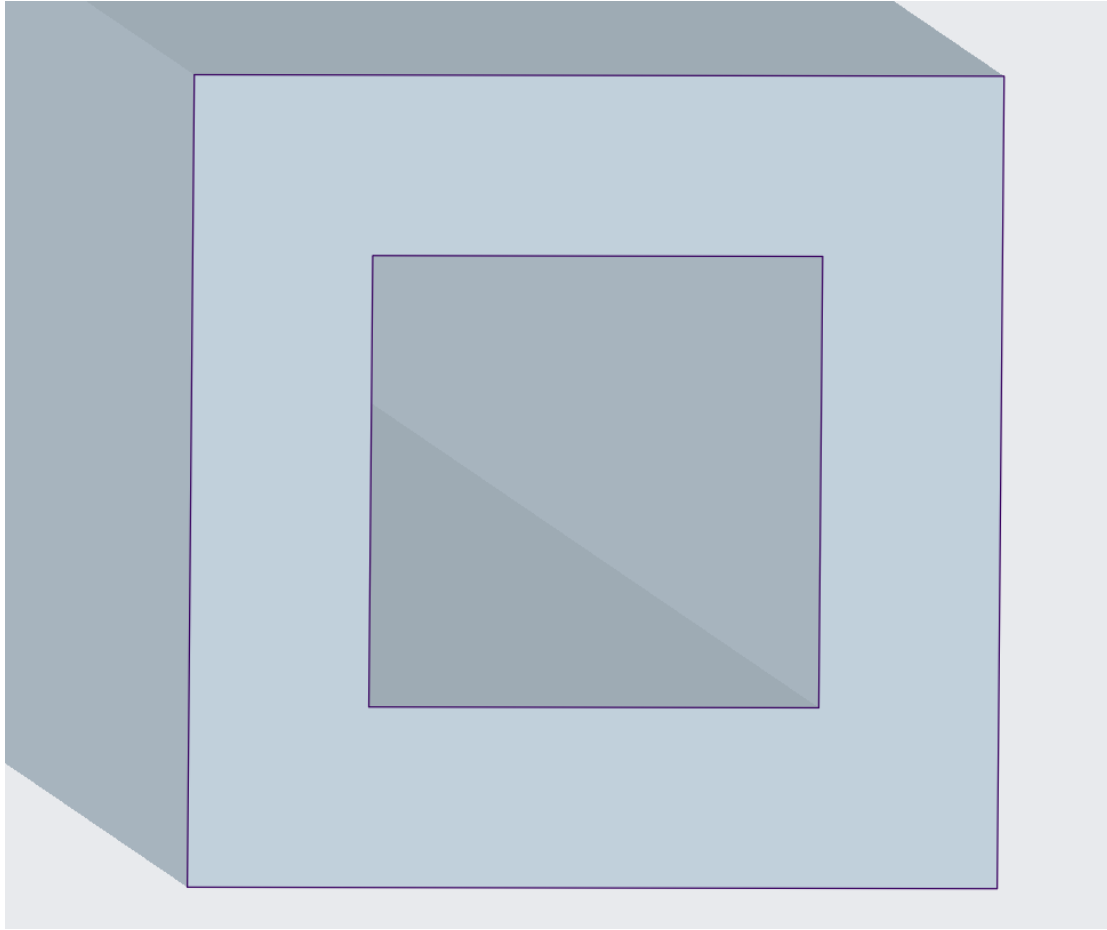
Various channel sizes LP-DED



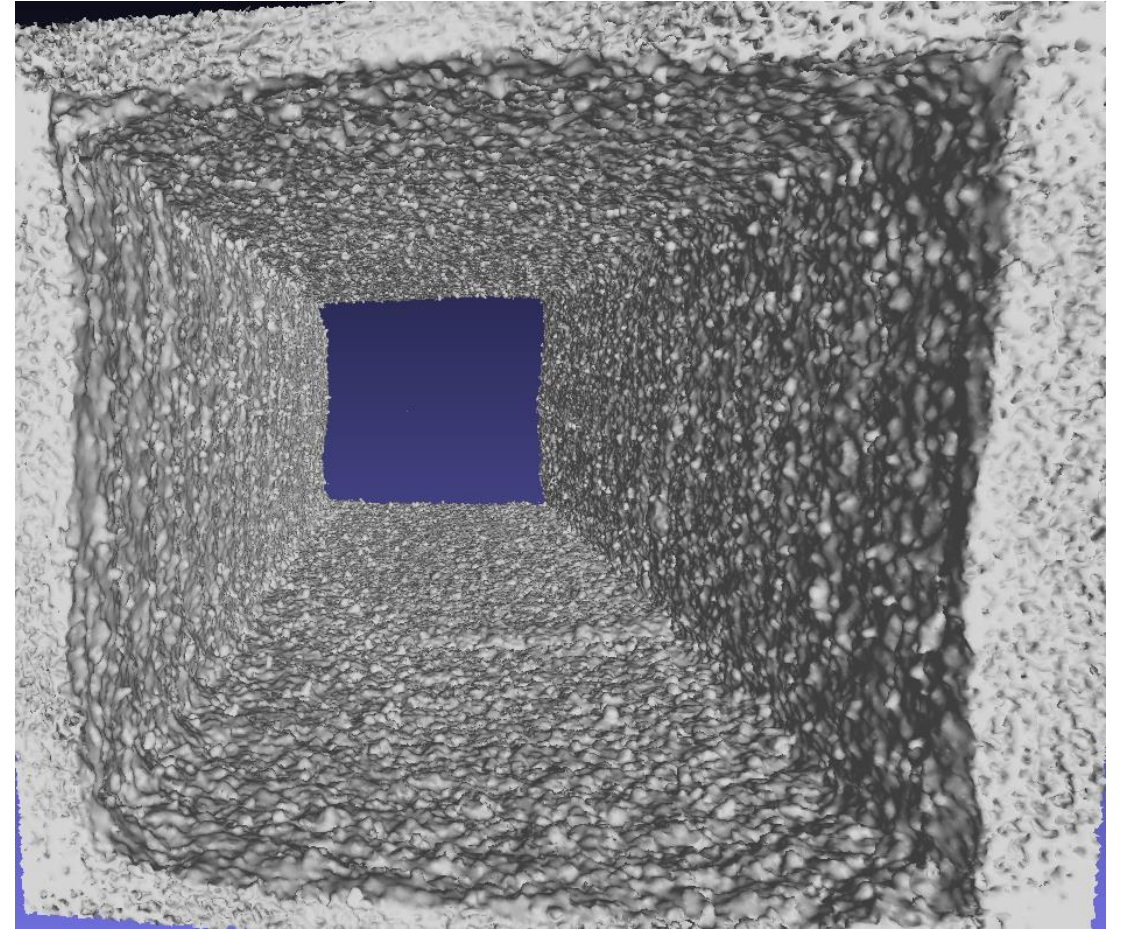
\*Fine (10 – 45 μm) and coarse (45 – 105 μm) refers to powder sizes



# LP-DED Surface Texture



**The Design Intent**



**Reality**

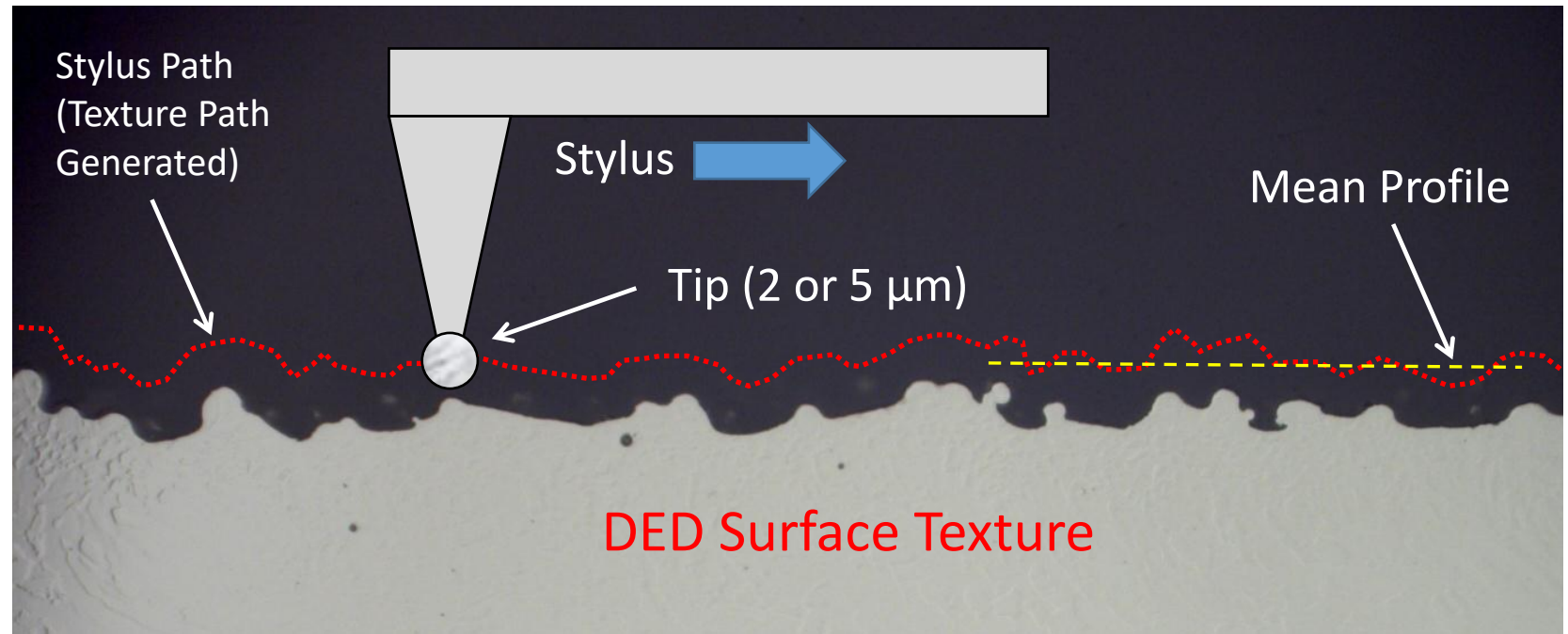
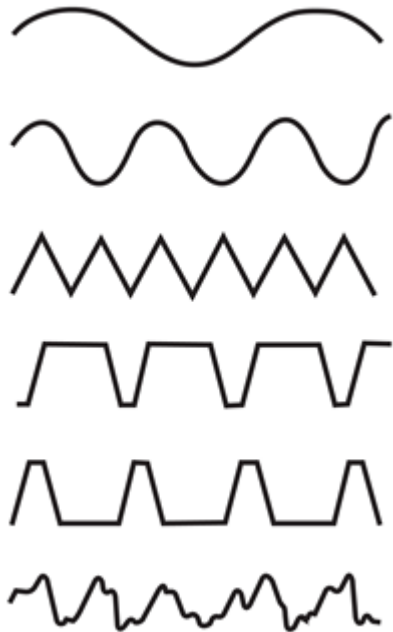


# Is a single value for surface roughness appropriate?

Ra (average directional roughness), or equivalent sand grain roughness, is the standard parameter used for friction factors calculations.

Various parameters are relevant to characterize a surface.

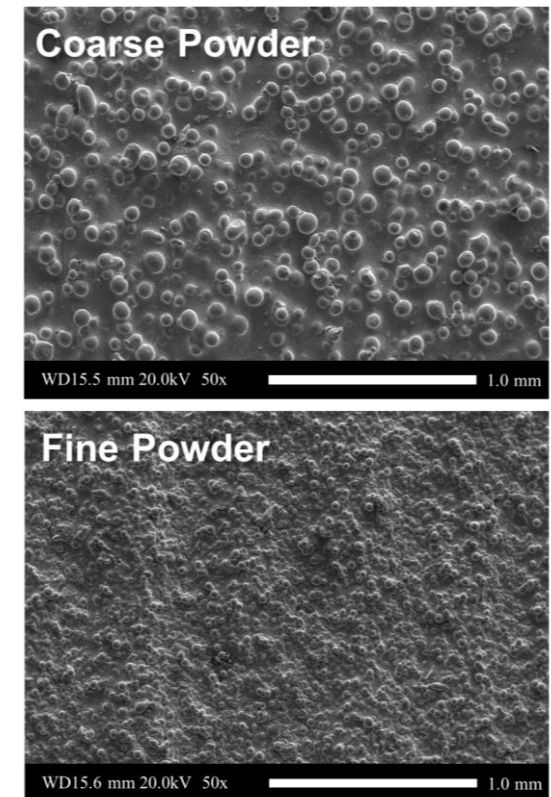
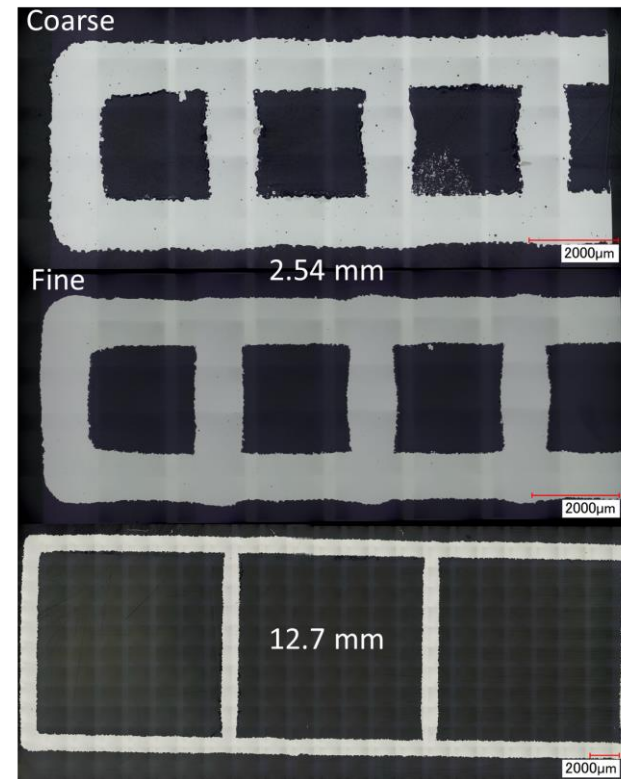
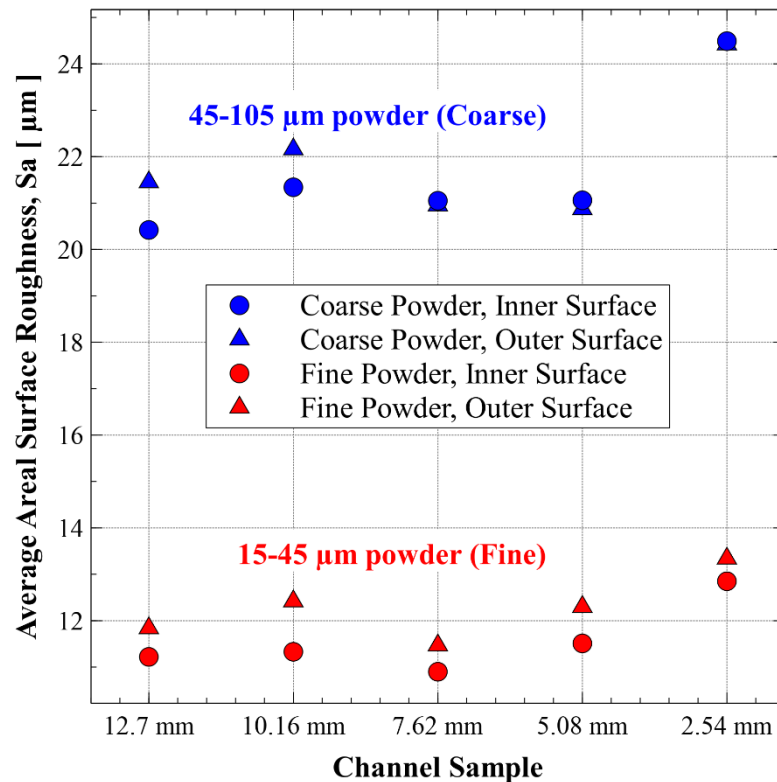
Same Ra



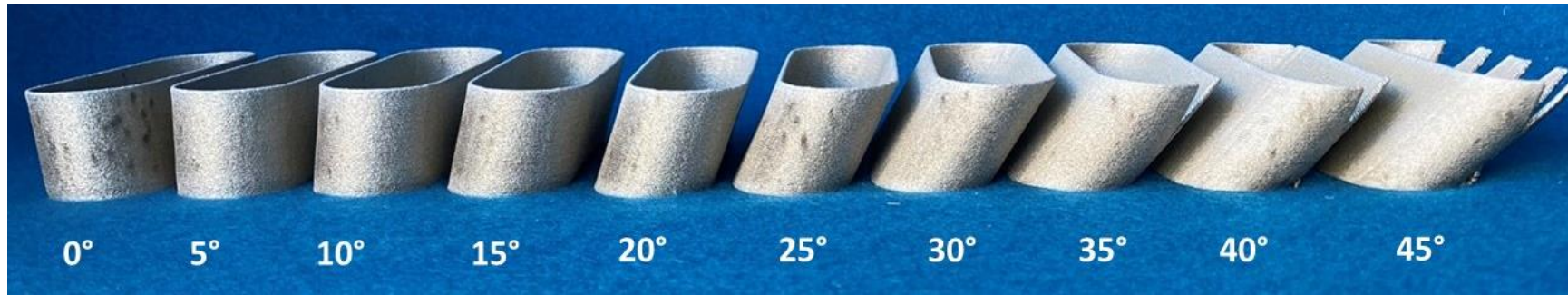


# Surface Texture of LP-DED Process

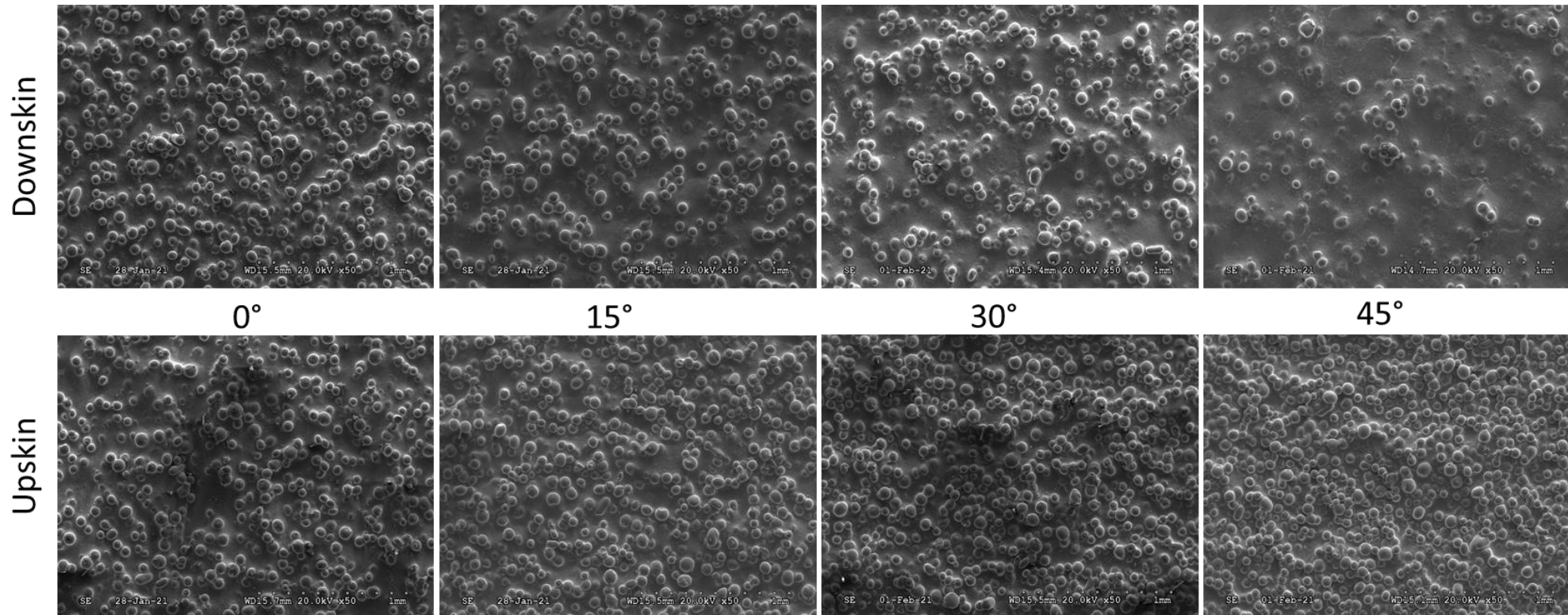
- Surface texture is a critical aspect of design due to impacts fatigue life, friction factors affecting pressure drop for fluid flow, mating surfaces, heat transfer.
- Area surface roughness ( $S_a$ ) is higher in coarse powder samples compared to coarse powder.
- There are some, but minor differences in channels between internal and outside surfaces.



# Example of Angle Influence on Texture for LP-DED



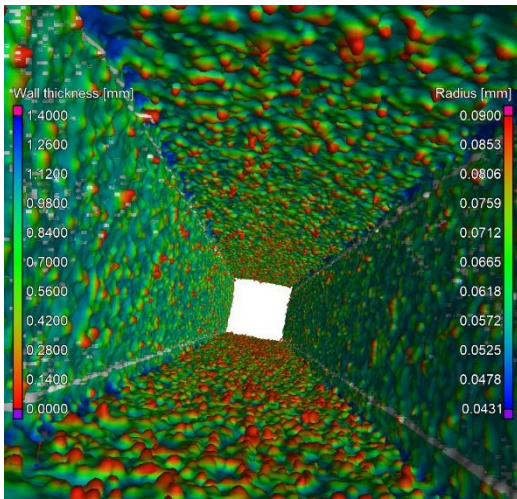
↑ Angle relative to build direction



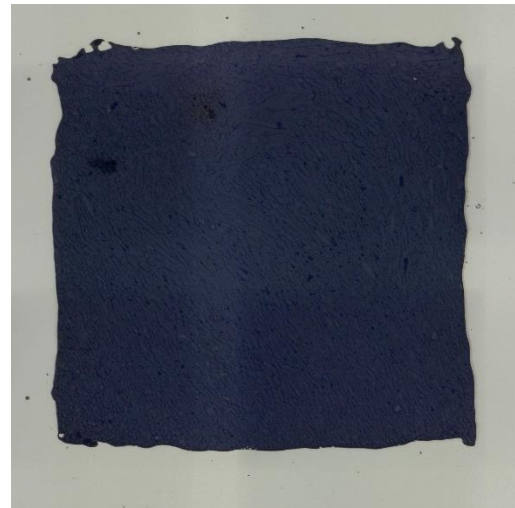
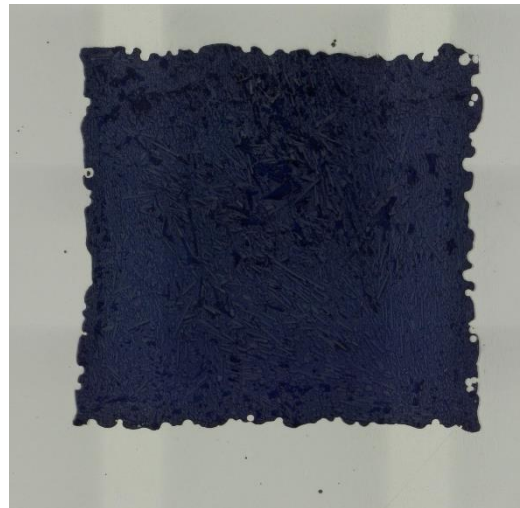


# Opportunity to Understand and Improve Texture

- Improvement opportunities for surface enhancements to reduce friction factors.
  - Chemical milling (CM), chemical mechanical polishing (CMP), abrasive flow machining (AFM), dissolvable surface sensitization, electropolishing or electrochemical polishing/machining (EP/ECM), magnetic abrasive finishing (MAF)
- One research goal is to be able to tune the surface roughness as needed for performance (heat transfer, friction factors, fatigue, aesthetics...)



**As-Built Surface**

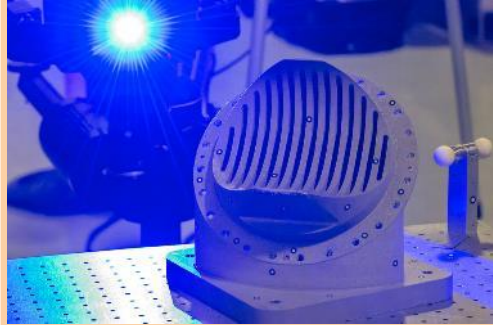


**Abrasive Flow Machining**



**Chemical Milling**

# Industrial Maturity and TRL of AM Processes



**L-PBF**

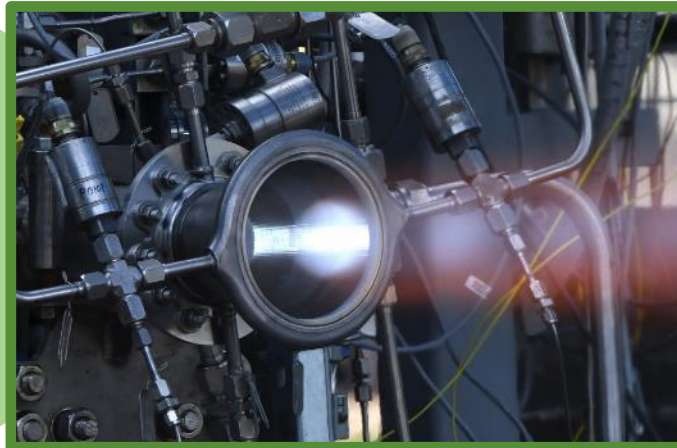


**Cold spray**

**LP-DED**



**L-PBF**



**L-PBF**

**EBW-DED**

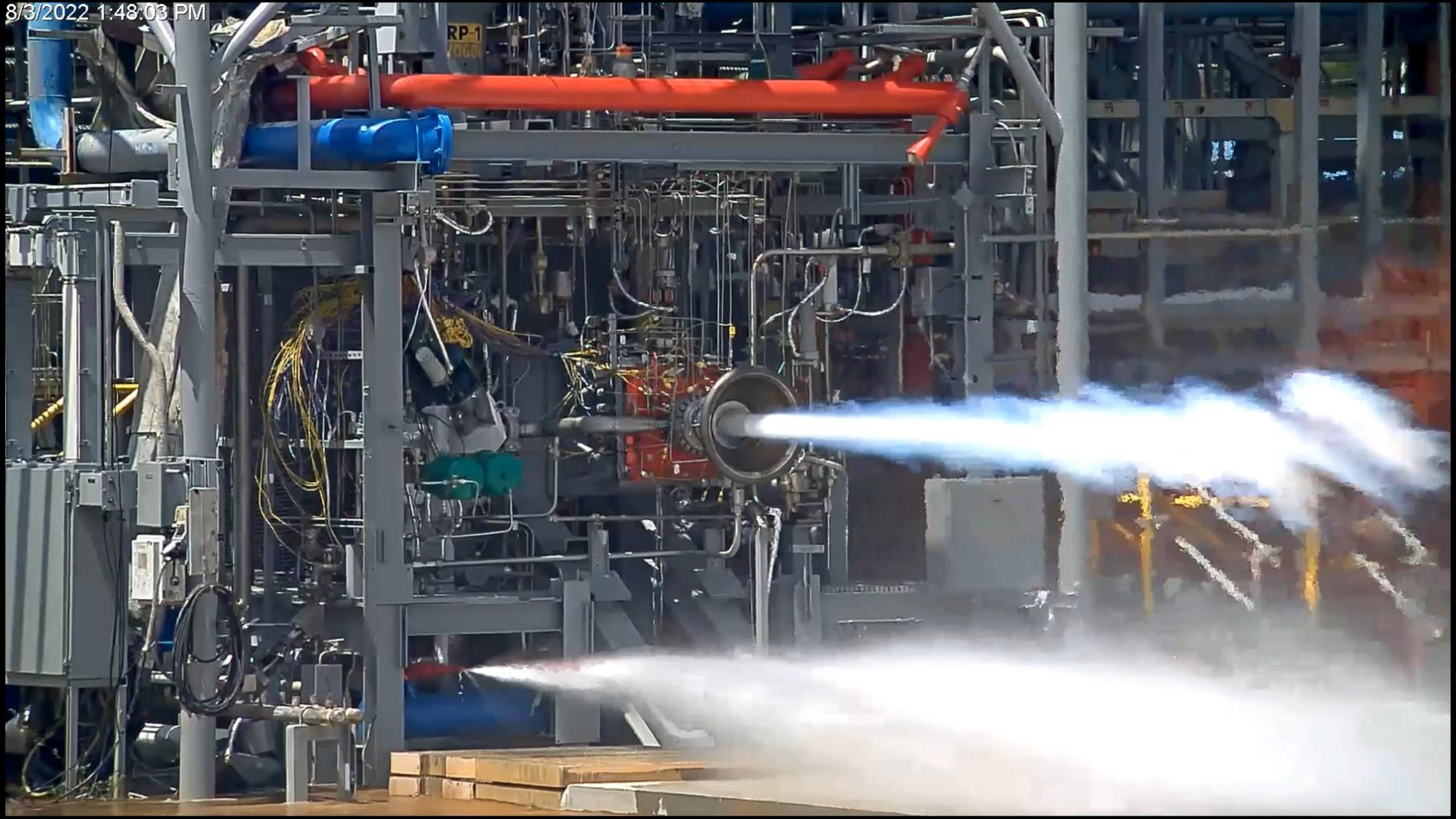


**AW-DED**



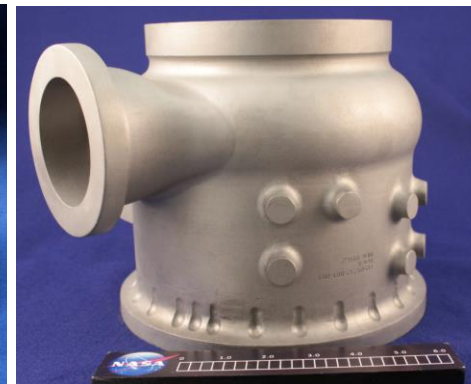
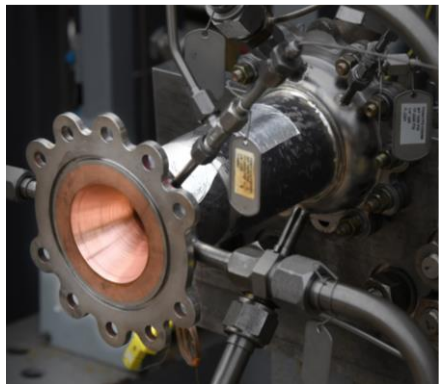
**LW-DED**

8/3/2022 1:48:03 PM



# General Summary of Additive Manufacturing

- Various AM processes exist each with unique advantages and disadvantages.
- Additive manufacturing is not a solve-all; consider trading with other manufacturing technologies and use only when it makes sense.
- Complete understanding of design process, build-process, and post-processing critical to take full advantage of AM.
- Additive manufacturing takes practice!
- Standards and certification of the AM processes are in-work.
- Several opportunities to improve the process based on various gaps.
- AM is evolving and imagination is the limit.



Contact:

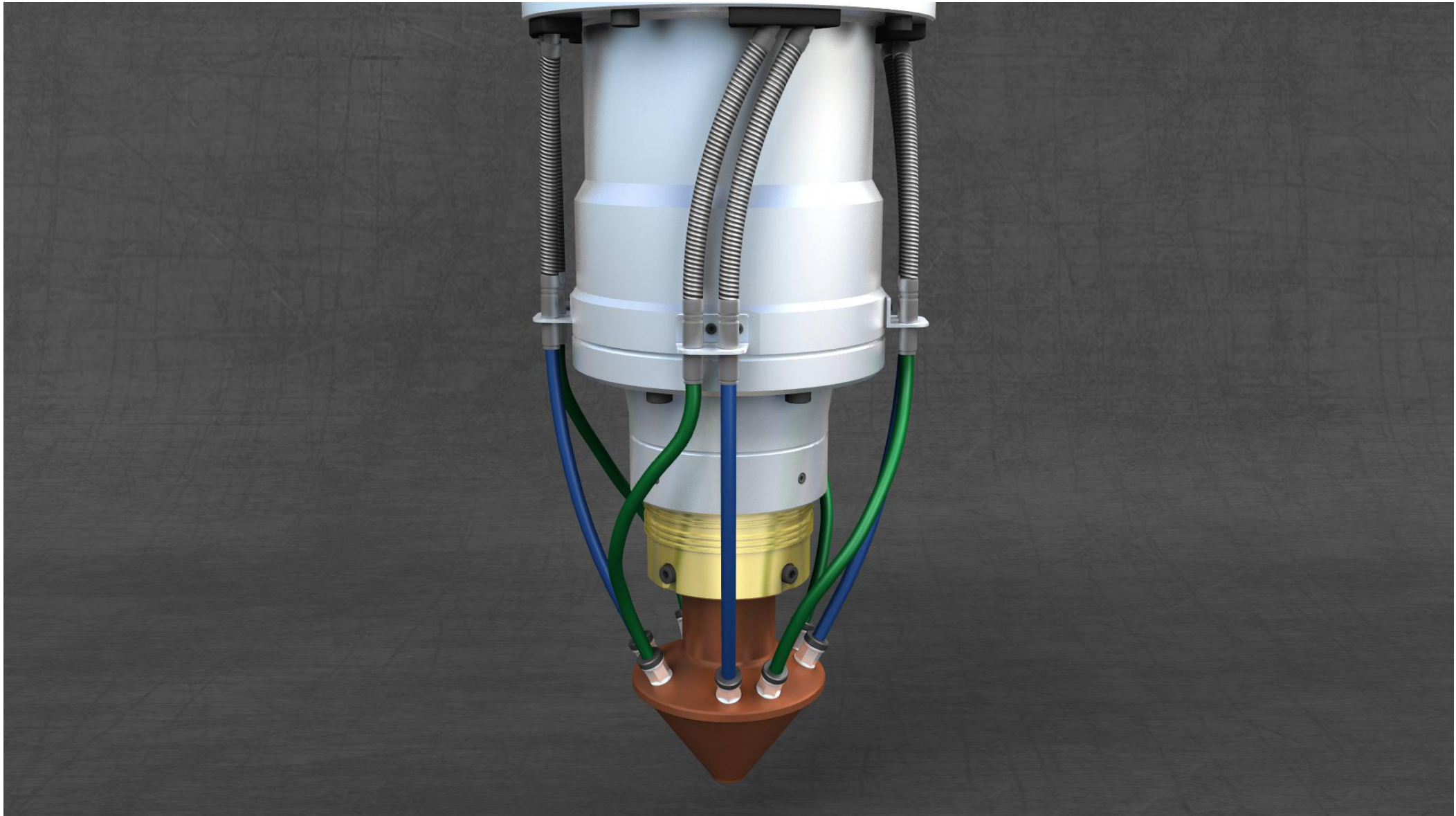
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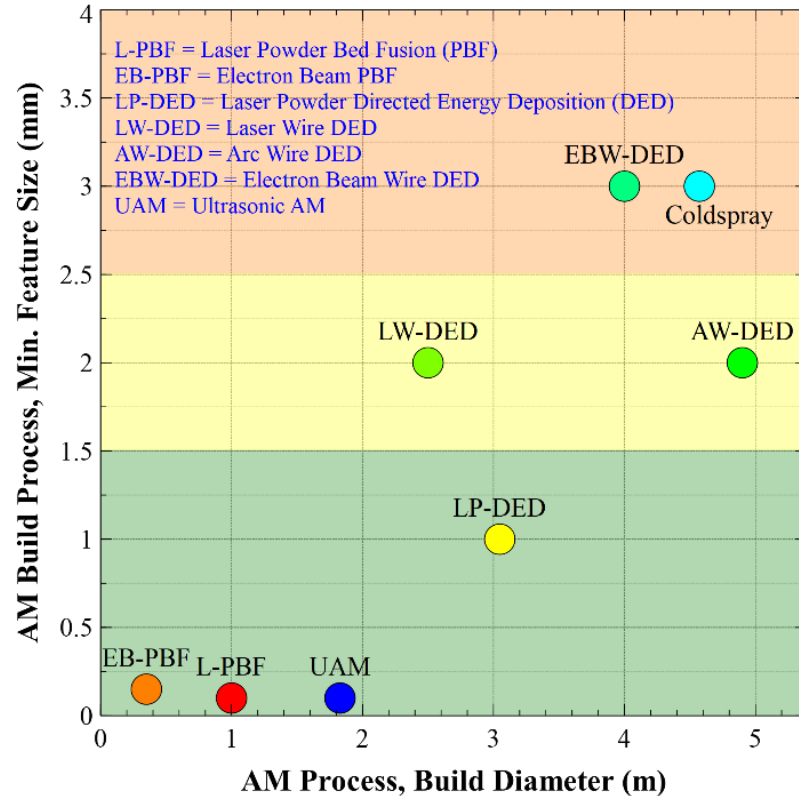


# Animation of LP-DED Process





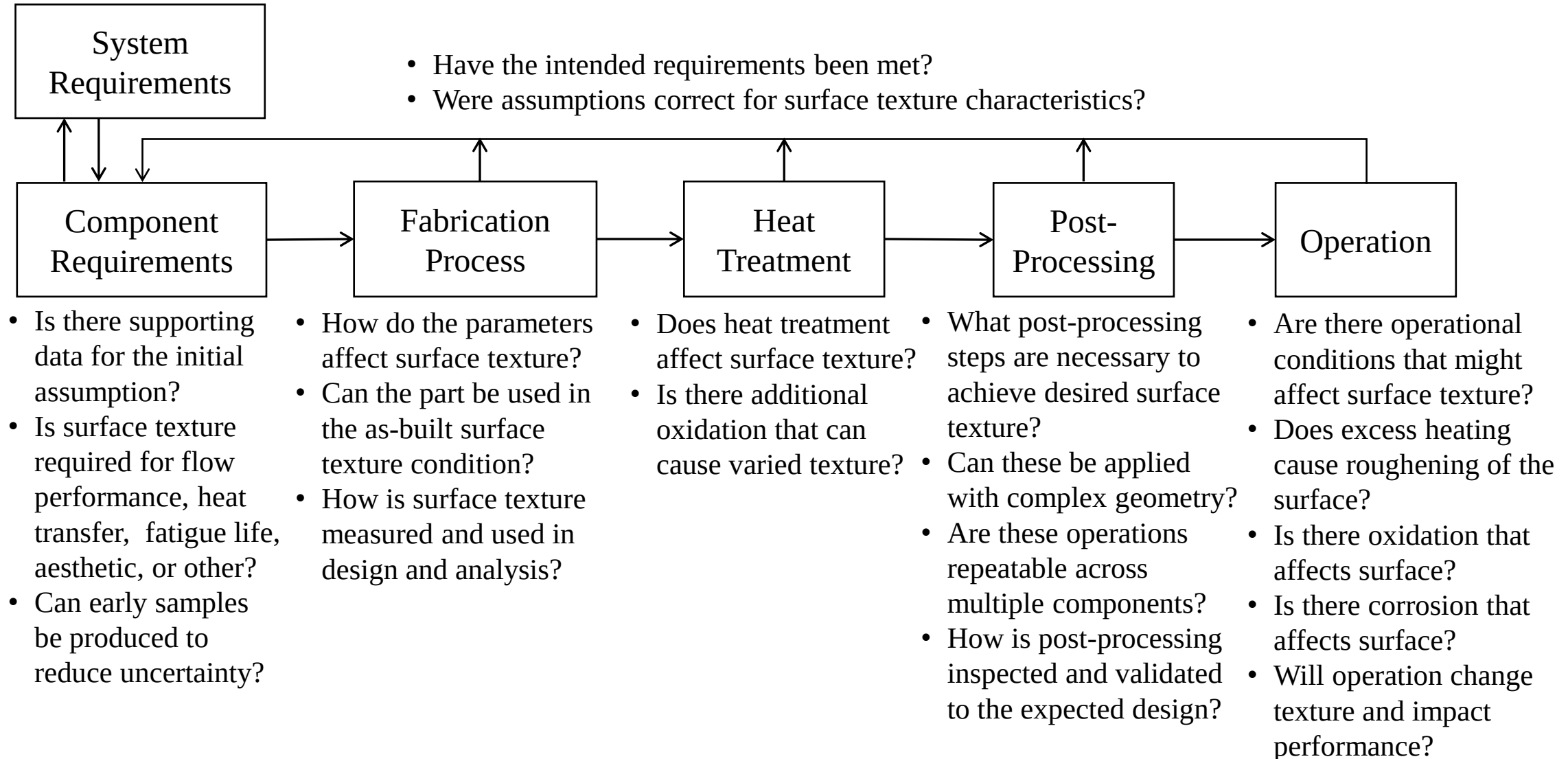
# Laser Powder Directed Energy Deposition (LP-DED)



**AM process selection must balance component requirements and the process limitations along with programmatic requirements**



# Surface Texture throughout the entire lifecycle





# NASA led book on Metal Additive Manufacturing

## Metal Additive Manufacturing for Propulsion Applications

Edited by  
Paul R. Gradl, Omar R. Mireles,  
Christopher S. Protz, and Chance P. Garcia



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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.



# Metal Additive Manufacturing for Propulsion Applications



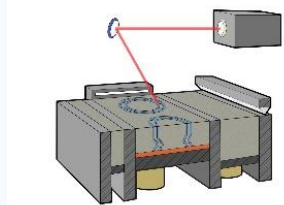
## Metal Additive Manufacturing for Propulsion Applications

Editors: Paul Gradl, Chris Protz, Chance Garcia, Omar Mireles



### Chapter 1

Introduction and Applications of Additive Manufacturing for Propulsion



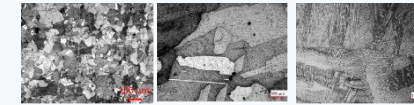
### Chapter 2

Metal Additive Manufacturing Processes and Selection

| Properties                                                                                                                                                               | Availability                                                                                                                             | Economics                                                                                                             |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| Mechanical <ul style="list-style-type: none"><li>Strength</li><li>Stress</li><li>Stiffness</li><li>Hardness</li><li>Wear</li></ul>                                       | Powder Supply Chain <ul style="list-style-type: none"><li>On-site and Off-site</li></ul>                                                 | Material Cost                                                                                                         |
| Physical <ul style="list-style-type: none"><li>Chemical</li><li>Thermal Expansion</li><li>Thermal Conductivity</li><li>Weldability</li></ul>                             | Special Powder Processing <ul style="list-style-type: none"><li>Proprietary Isolators</li><li>Material processing requirements</li></ul> | Machine Build Time                                                                                                    |
| Environment <ul style="list-style-type: none"><li>Corrosion resistance</li><li>High temperature environment</li><li>Common isolators</li><li>Heat conductivity</li></ul> | Machine Capability/Part Quality                                                                                                          | Anticipated Service Life                                                                                              |
|                                                                                                                                                                          | Known Build Parameters                                                                                                                   | Post processing (heat treat) <ul style="list-style-type: none"><li>Heat treatment</li><li>Thermal treatment</li></ul> |

### Chapter 3

Selection and Overview of Additive Manufactured Metals and Metal Alloys



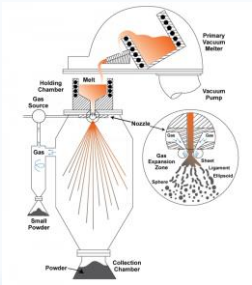
### Chapter 4

Microstructure and Properties of Additively Manufactured Metal Alloys



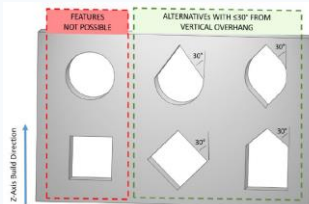
### Chapter 5

Post-Processing of Metal Additively Manufactured Components



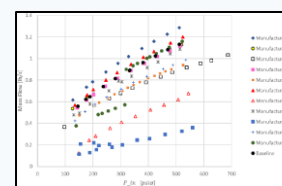
### Chapter 6

Feedstock for Metal AM



### Chapter 7

Functional Design for Metal Additive Manufacturing



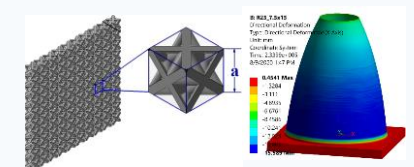
### Chapter 8

Component Performance and Application Characteristics



### Chapter 9

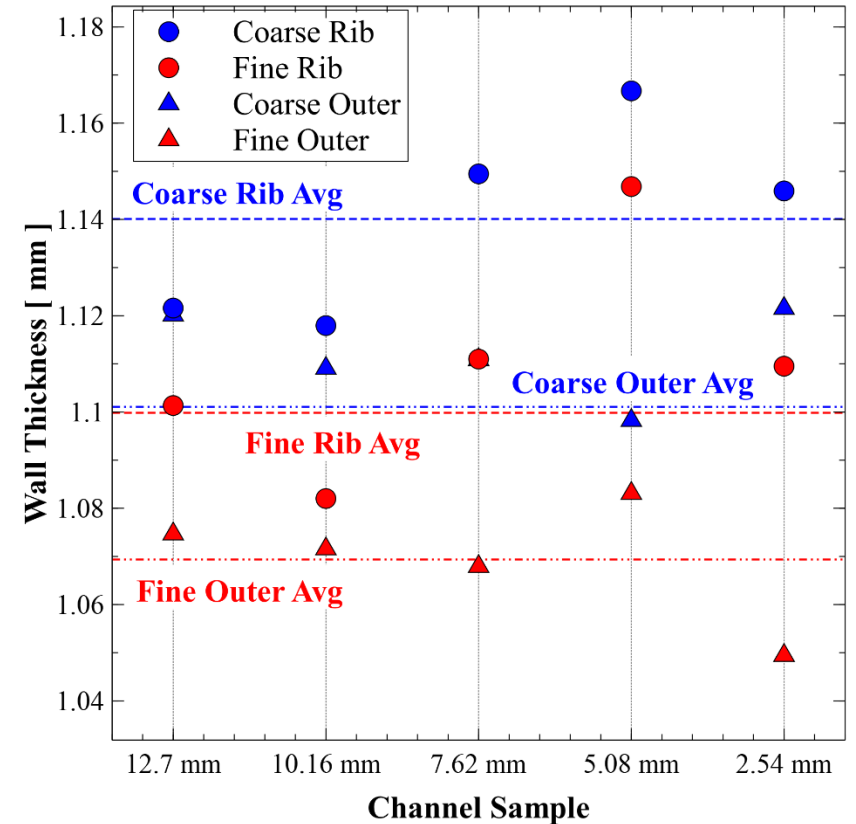
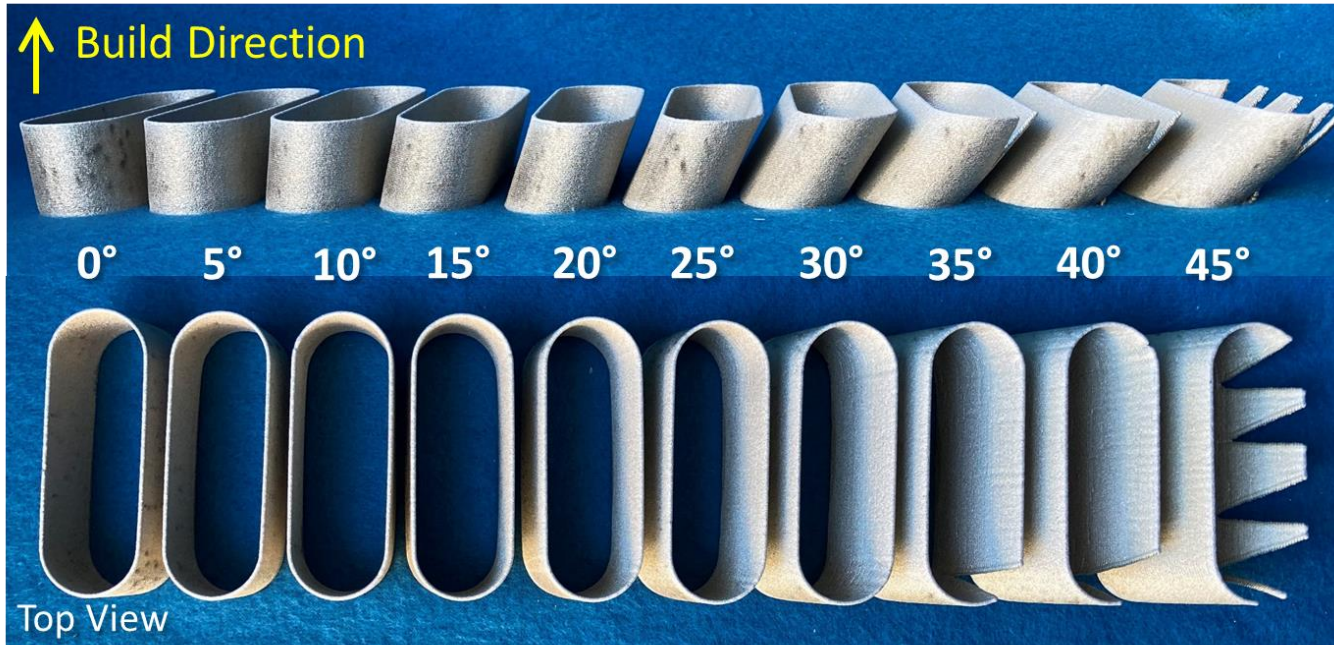
Certification of Metal Additive Manufacturing: A NASA Perspective



### Chapter 10

Emerging Additive Manufacturing Technology for Propulsion

# Geometric Build Limitations – Angles and Wall Thickness



- Angles beyond 30° for 1 mm wall thickness (relative to the build direction) were challenging and caused deposition failures.
- Wall thickness slightly varied between powder sizes and the inner channel ribs and outer walls.



# Comparison of L-PBF and DED

**Different methods for different components!**

## Laser Powder Bed Fusion (L-PBF)



## Directed Energy Deposition (DED)



|                                          |                                                                    |                                                                   |
|------------------------------------------|--------------------------------------------------------------------|-------------------------------------------------------------------|
| <b>Feature Resolution / Complexity</b>   | High resolution of features<br>Wall thicknesses and holes <0.25 mm | Medium resolution of features<br>Walls >1 mm and limited holes    |
| <b>Deposition Rate</b>                   | Low build rates<br><0.14 kg/hr                                     | High Build rates<br>lbs per hour (some systems >10 kg/hr)         |
| <b>Multi-alloys / Gradient Materials</b> | Monolithic materials in single build                               | Option for multi-alloys or gradients within single build          |
| <b>Materials Available</b>               | High number of materials available and being developed             | High number of materials available and being developed            |
| <b>Production Rates</b>                  | Higher volume with several parts in a single build                 | Generally limited to single builds; longer programming/setup time |
| <b>Scale / Size of components</b>        | Limited to existing build volumes<br><400mm up to 600 mm           | Scale is limited to gantry or robot size                          |
| <b>Added Features / Repair</b>           | No (limited) ability to add material to existing part              | Can add material or features to an existing part                  |



# Emerging Areas of AM Development

- Maturing each of the AM processes and understanding of microstructure, properties, build limitations, and methods for design and post-processing.
- Ongoing development for large scale AM using DED and other processes.
- Continuous hot-fire and component testing to advance various combustion chambers, injectors, nozzles, ignition systems, turbomachinery, valves, lines, ducts, in-space thrusters.
- Polishing (surface enhancements internally) and post-processing development.
- Combining various AM processes for multi-alloy solutions or additional design options.
- Advancement of commercial supply chain for unique alloys (GRCop-42, NASA HR-1, JBK-75).
- New alloy development (Refractory, Ox-rich environments, AM-specific alloys).
- Material databases of metal AM properties to allow for conceptual design – tensile, fatigue, and thermophysical.
- Design complexity using lattices, topology optimization, generative design, and thin-wall structures.
- Standards and certification of metal AM are evolving for human spaceflight.