EXPLORE MOON to MARS

Principles of Directed Energy Deposition for Aerospace Applications

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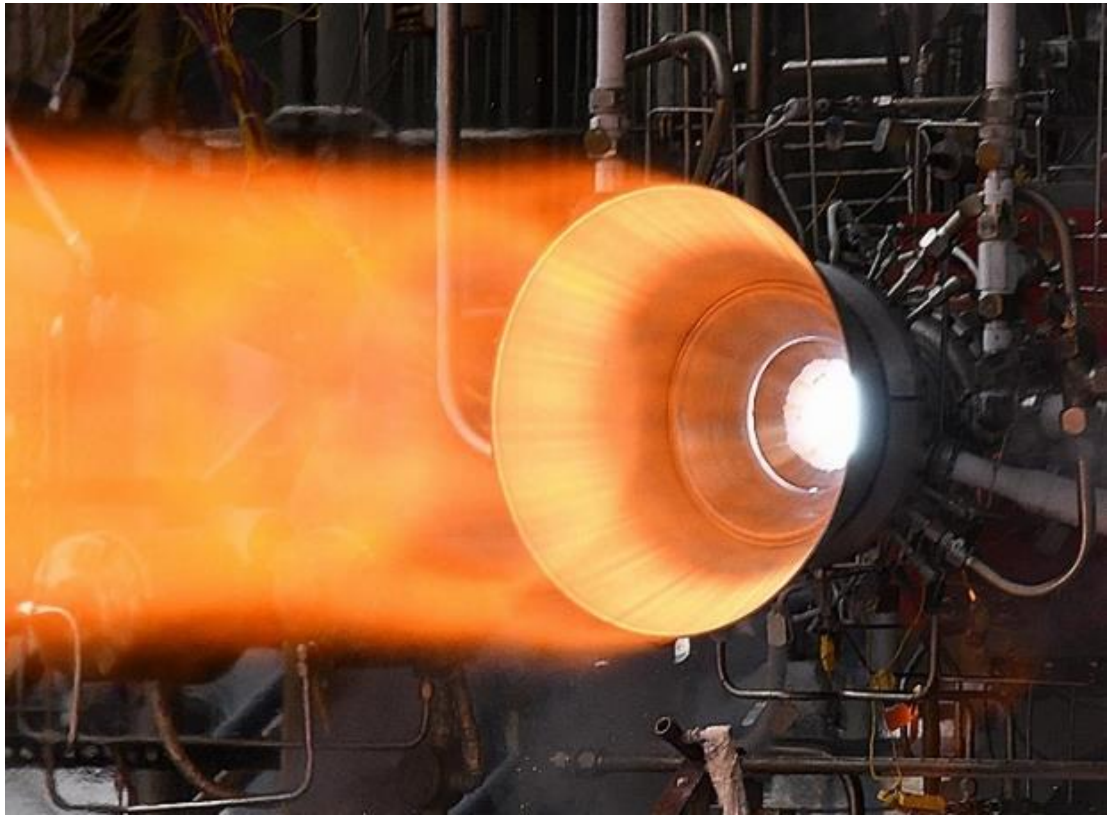
Presentation to:

W.M. Keck Center for 3D Innovation

University of Texas El Paso (UTEP)

Introduction and Agenda

- Introduction of Metal AM
- Case Study using DED
- Introduction to Metal AM Processes
- Comparisons to L-PBF
- Why the need for DED?
- Materials for DED
- DED Process Overview
- Other Considerations
- Wrap-up



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

Terminology

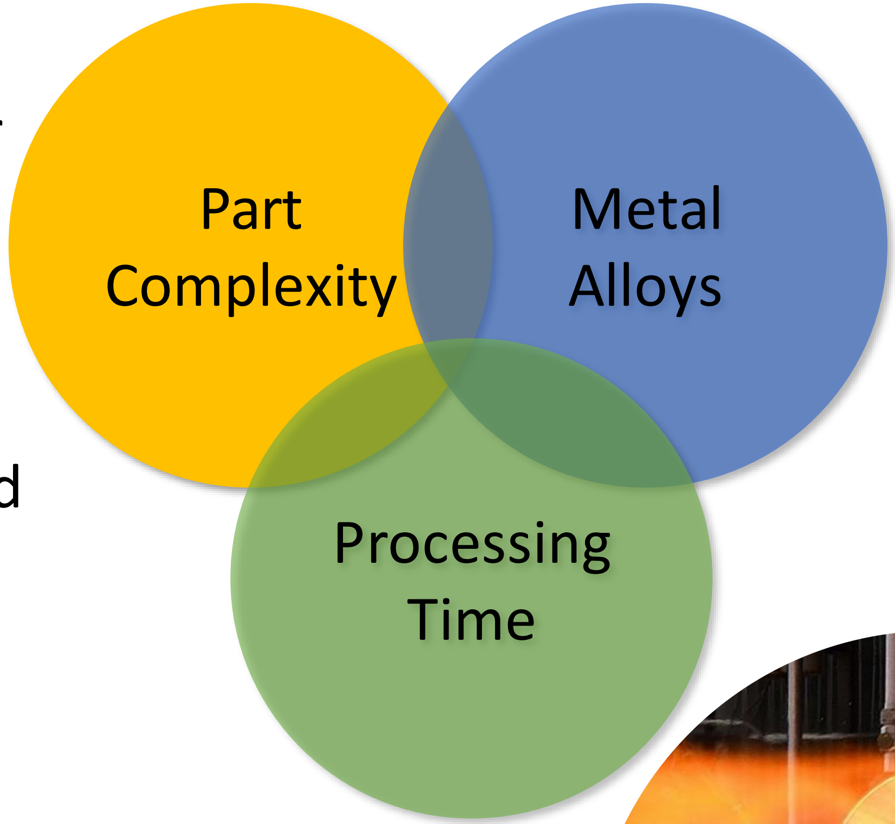
Course will focus exclusively on metal additive manufacturing

- **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 (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.



Case Study for AM – Combustion Chambers

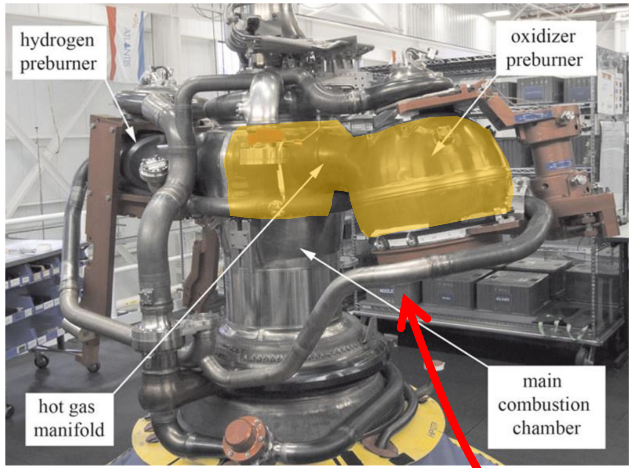
Category	Traditional Manufacturing	Initial AM Development	Evolving AM Development
Design and Manufacturing Approach	Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly	Four-piece assembly using multiple AM processes; limited by AM machine size. 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

Case Study – RS25 Powerhead

Traditional Manufacturing

Forged => Machined

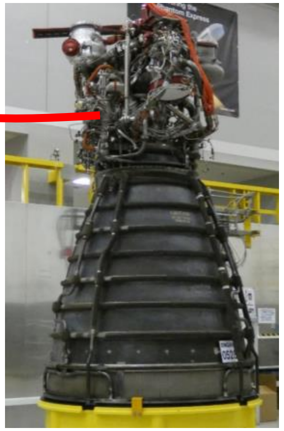


L-PBF Development

>90 days using L-PBF (Large Platform)

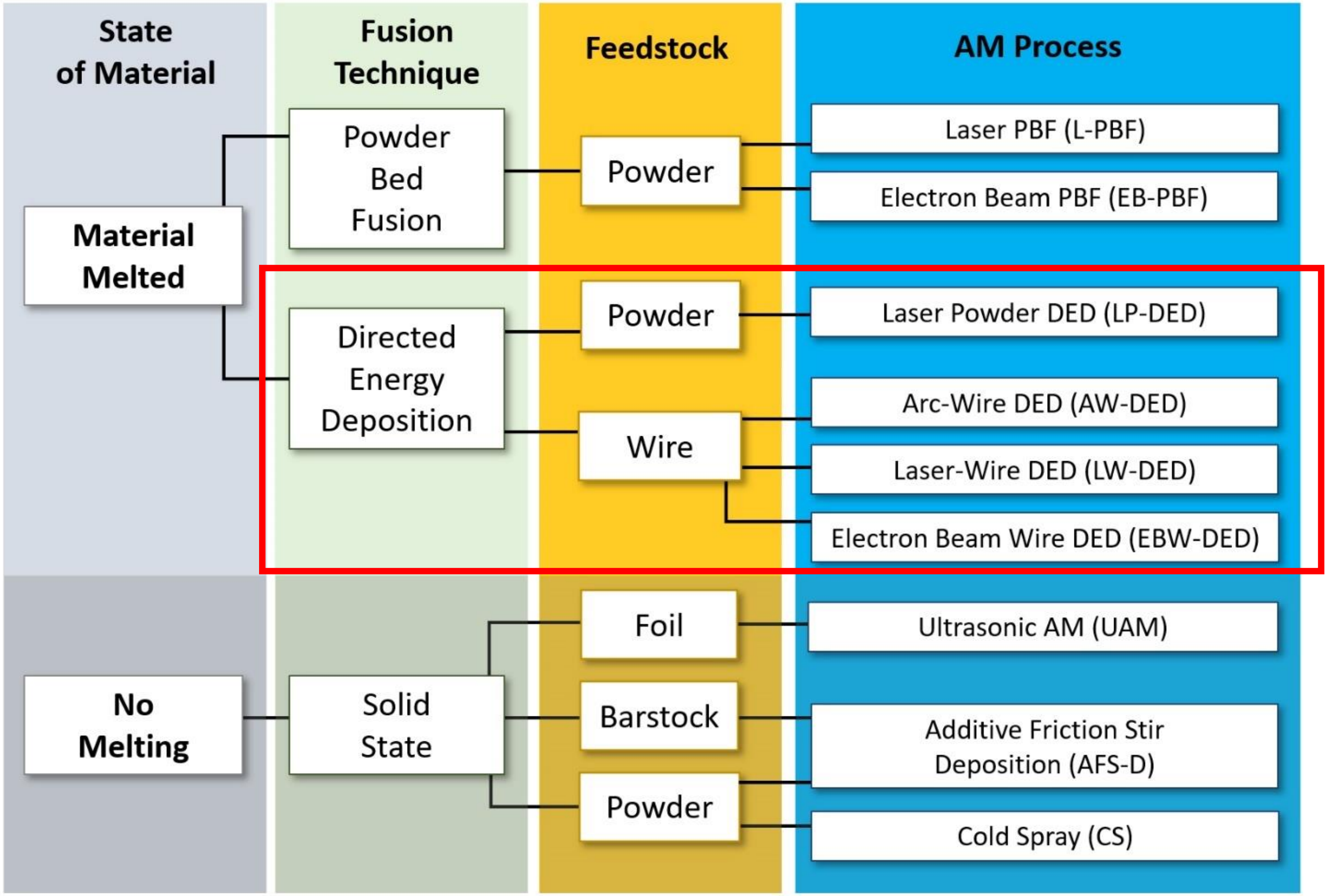
LP-DED Development

<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

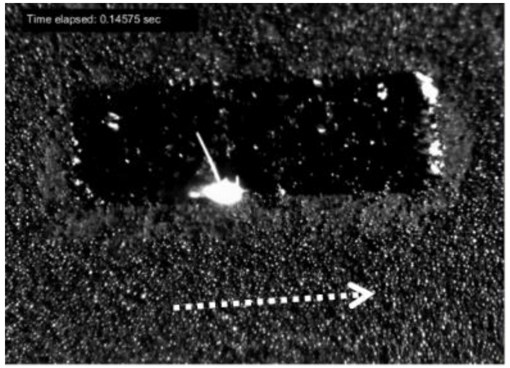


*Does not include all metal AM processes

Based on Ref:

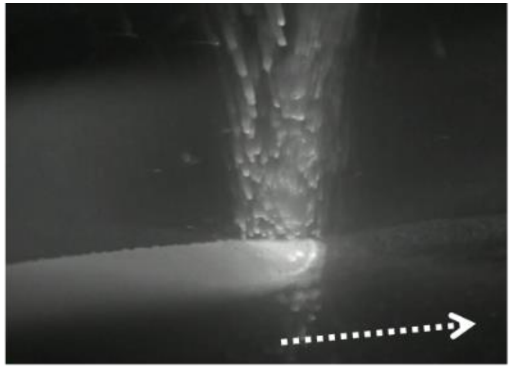
- Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2022). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". Journal of Material Engineering and Performance (JMEP). Article in Review.
- ASTM Committee F42 on Additive 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).

AM Processes for various applications

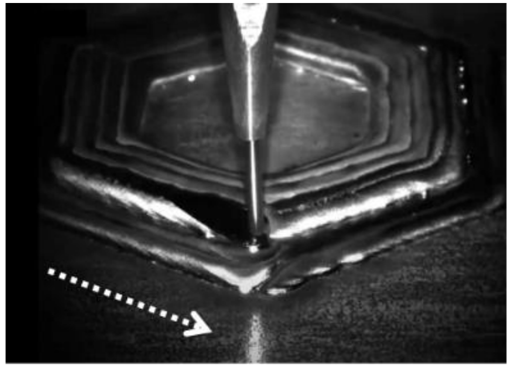


Laser Powder Bed Fusion

Electron Beam Powder Bed Fusion

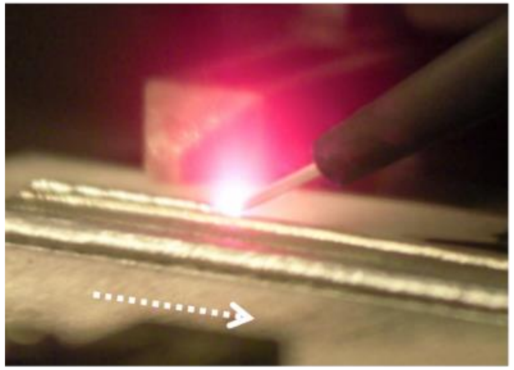


Laser Powder DED

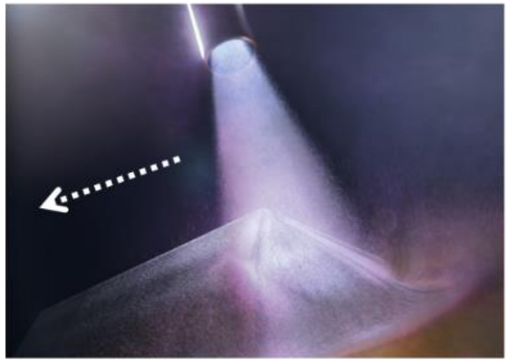


Laser Wire DED

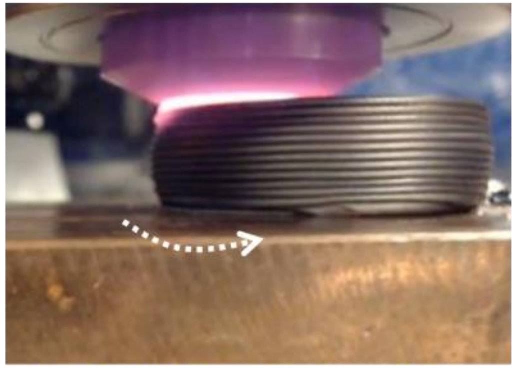
Arc Wire DED



Electron Beam Wire DED



Cold Spray



Additive Friction Stir Deposition

Ultrasonic Additive Manufacturing

Image Credits: 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. (2022). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". Journal of Material Engineering and Performance (JMEP). Article in Review.

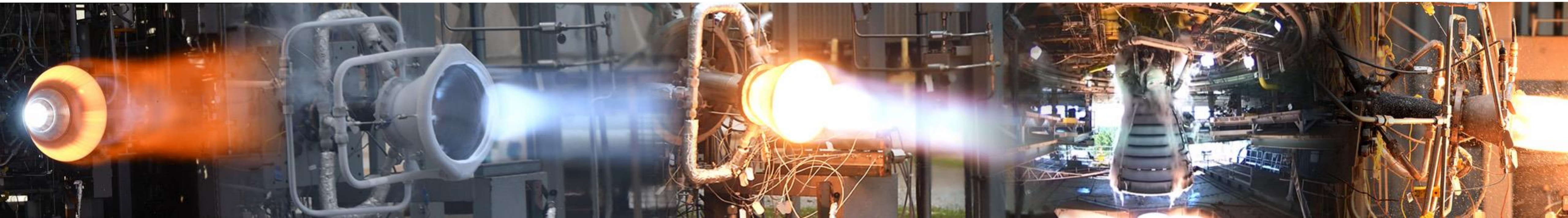
EXPLORE MOON to MARS

AM Component 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

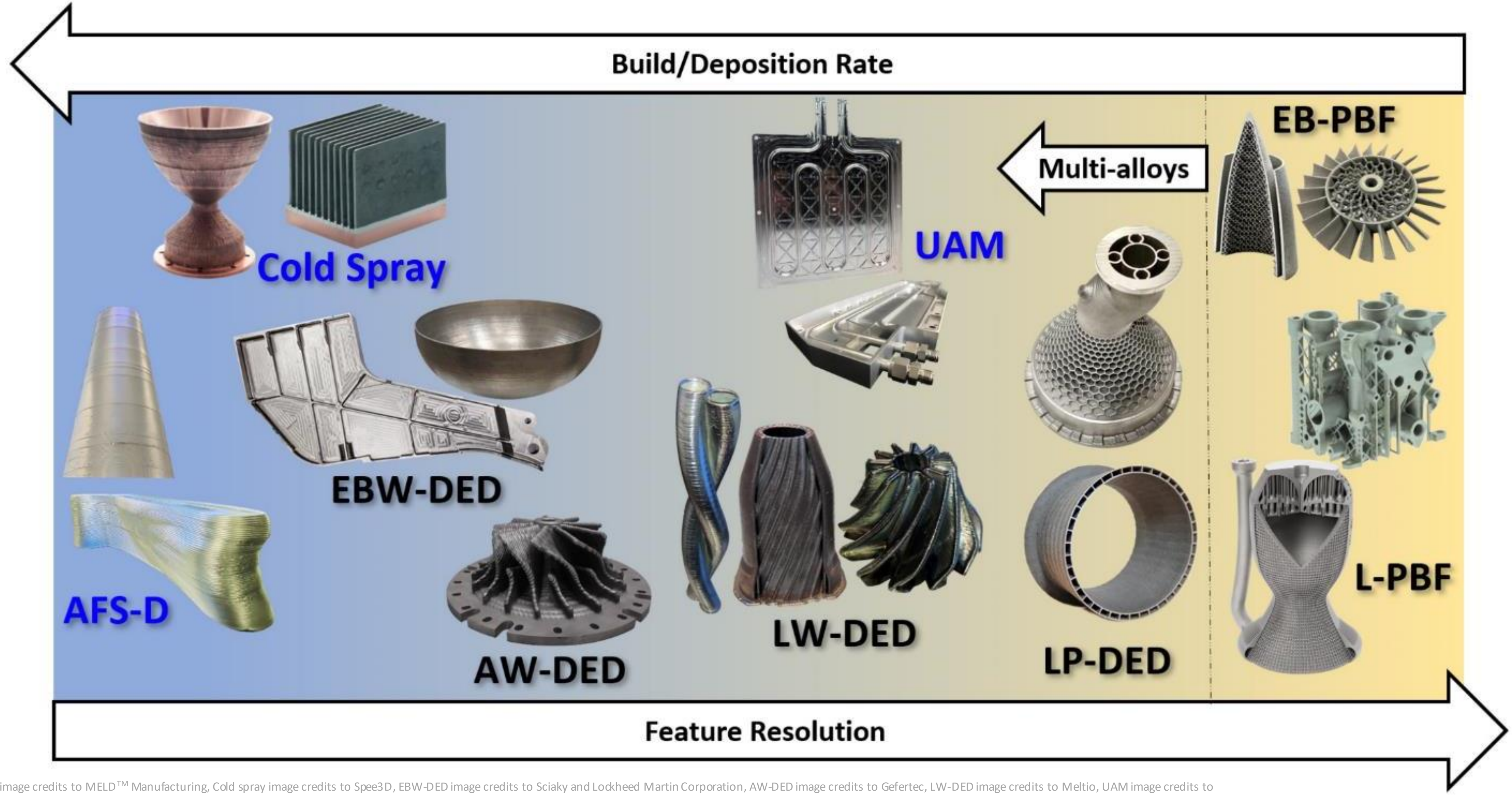


How do we select the proper AM process?

- 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?

Reference: Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2022). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". Journal of Material Engineering and Performance (JMEP). Article in Review.

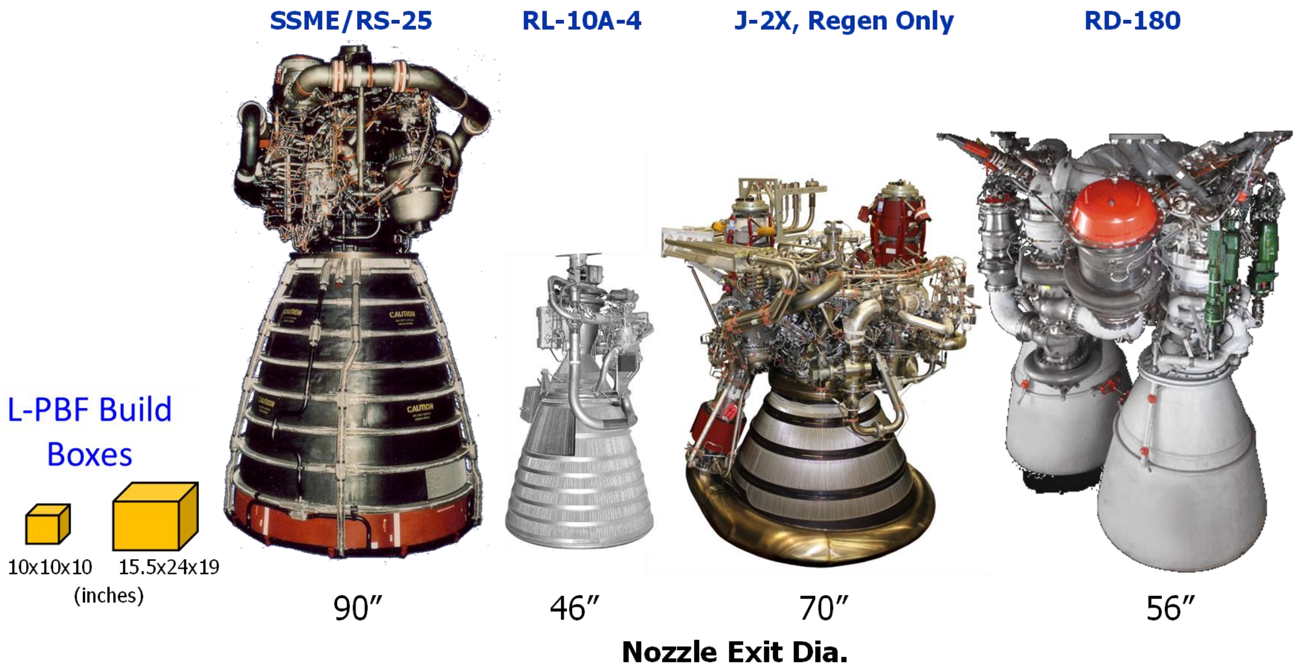
Criteria and Comparison Various Metal AM Processes



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

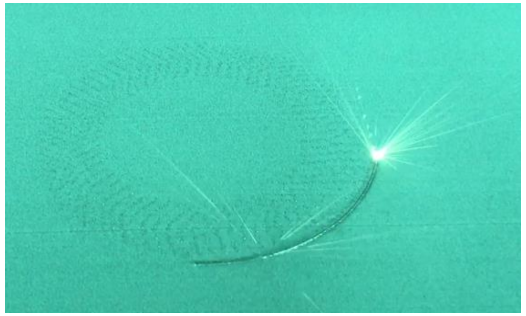
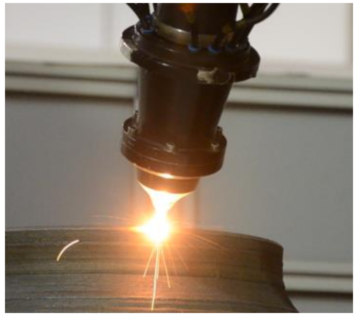
Why DED?

- 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



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

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 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

Bimetallic
GRCop-84/IN625
C-18150/IN625

MMC
Al-base
Fe-base
Ni-base

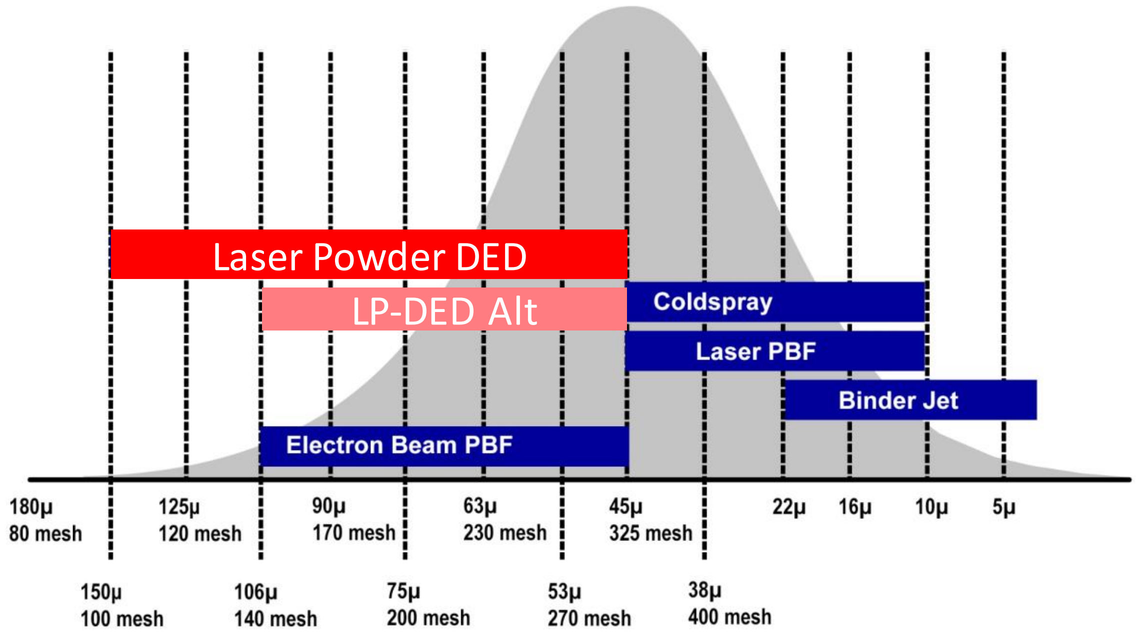
Industry Materials developed for L-PBF, E-PBF, and DED processes (*not fully inclusive*)

Feedstock Material for DED

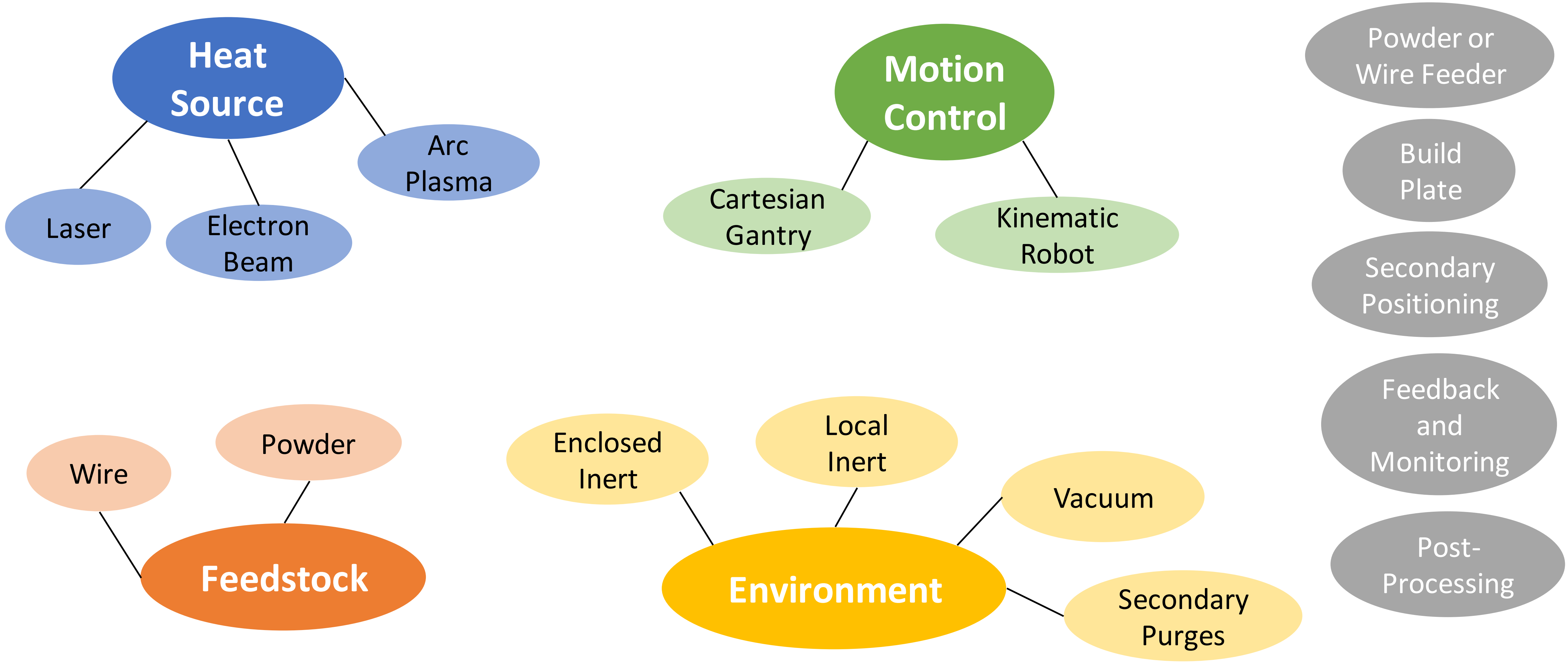
Feedstock can be Powder or Wire

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

*UAM = Ultrasonic Additive Manufacturing



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.

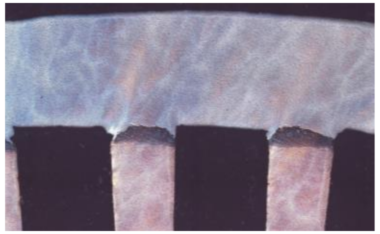
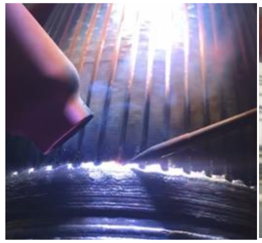
Laser Powder DED (LP-DED)

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

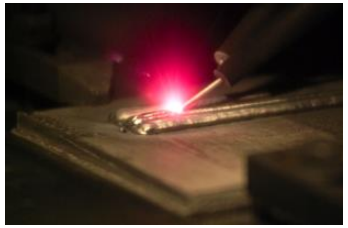
Arc Wire DED (AW-DED)

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



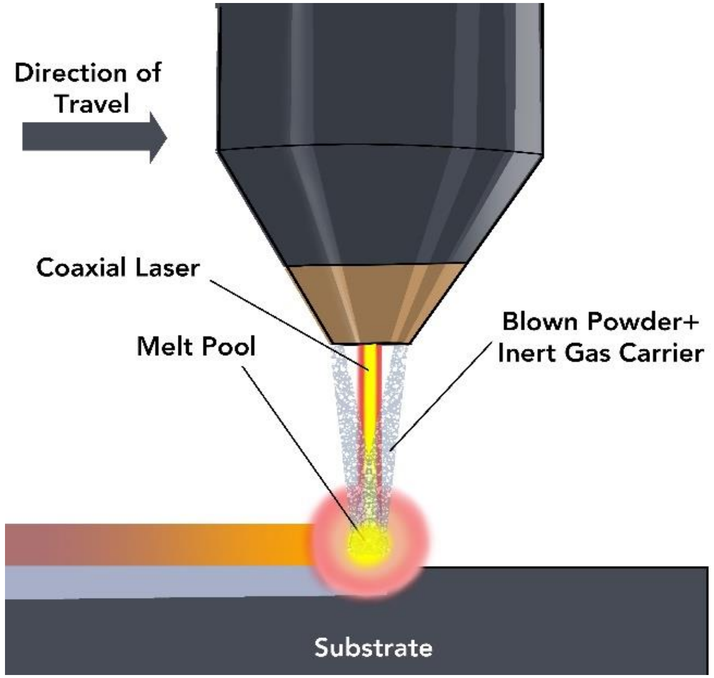
Electron Beam DED (EB-DED)

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

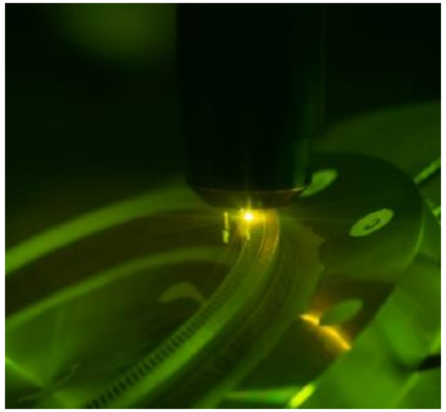


Laser Powder DED

- 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

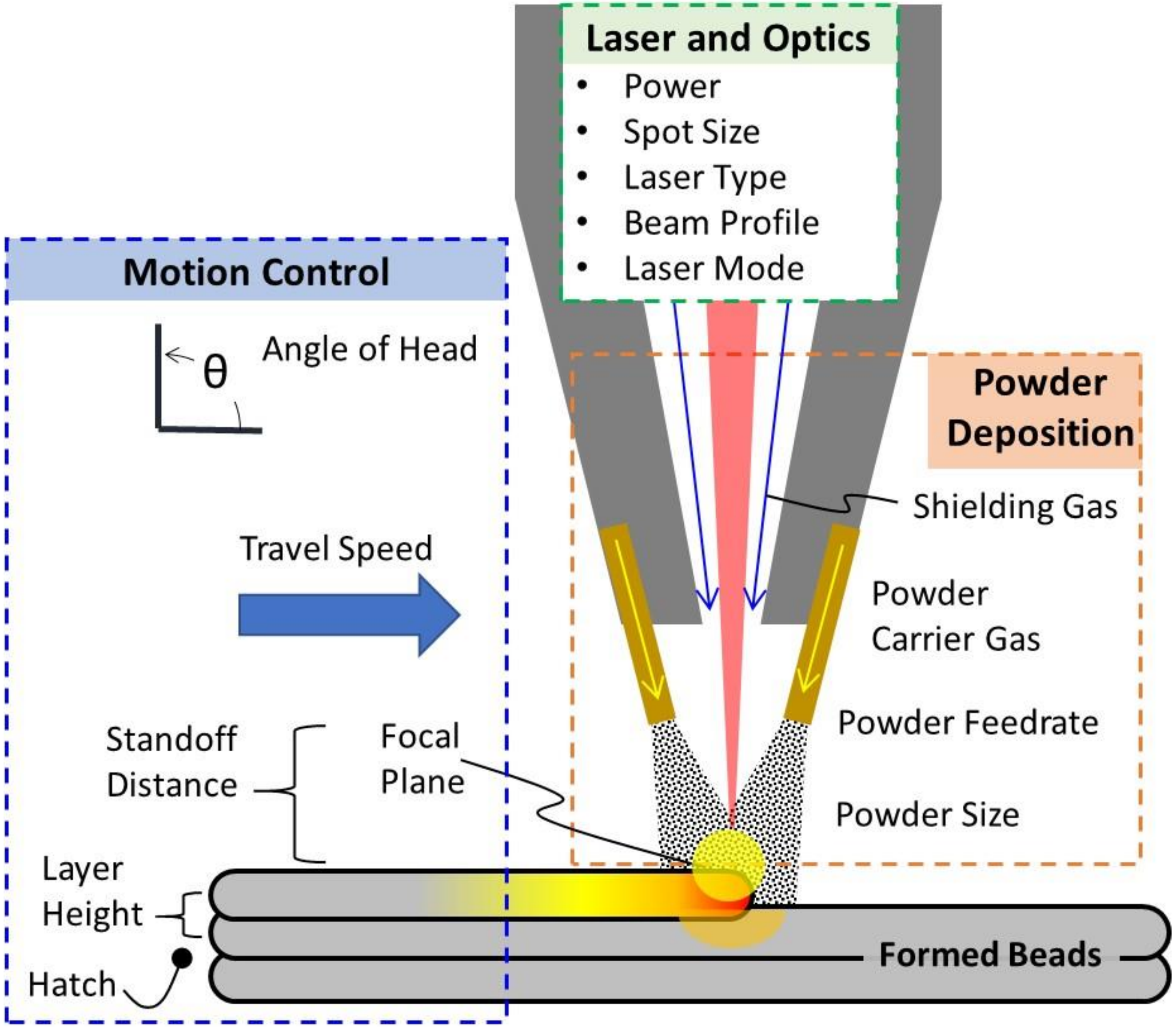

Integrated Channel DED Nozzle

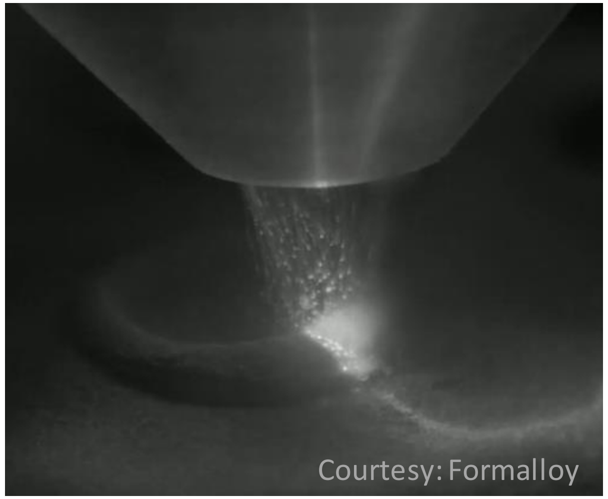

Inco 718, 1:4 Scale


JBK-75, IN625, NASA HR-1 Manifolds


JBK-75 Integrated Channel

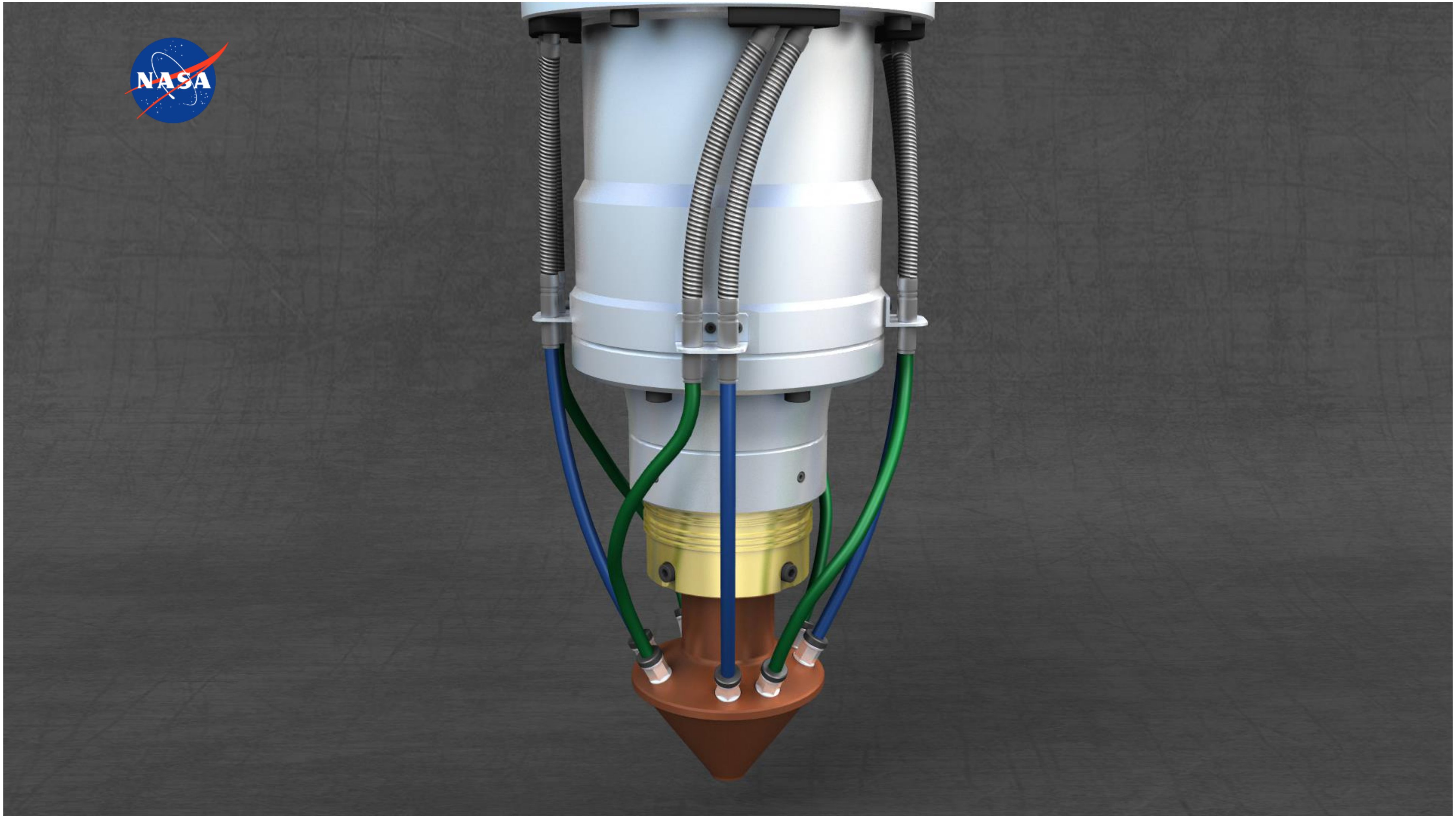
LP-DED Process and Parameter Overview



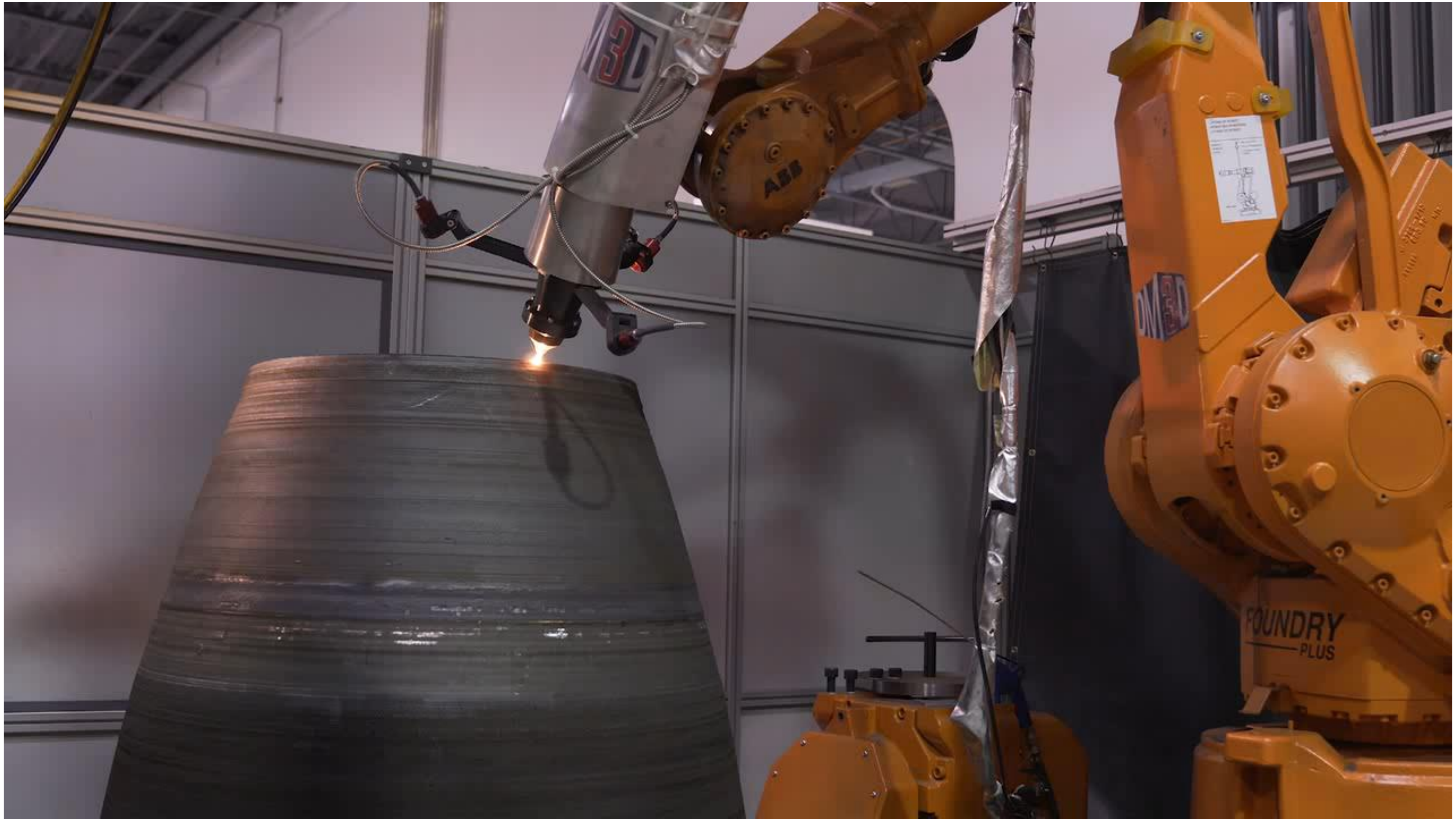


- Gradl, P. R., & Protz, C. S. (2020). Technology advancements for channel wall nozzle manufacturing in liquid rocket engines. *Acta Astronautica*. https://doi.org/10.1016/j.actaastro.2020.04.067
- AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl et al (unreleased)

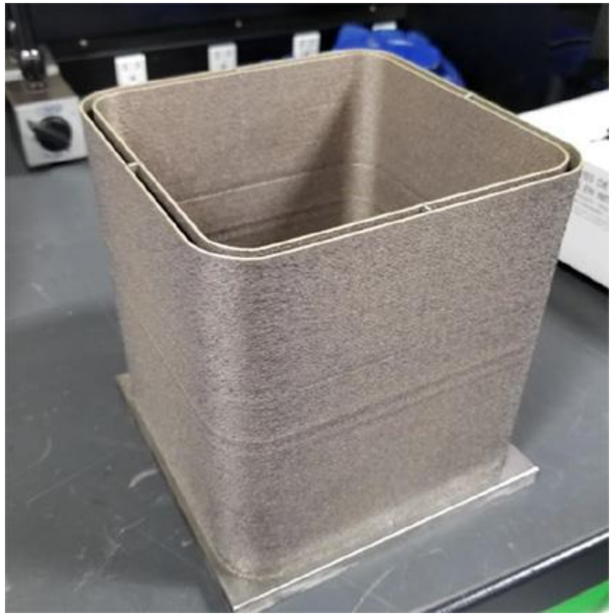
Animation of LP-DED Process

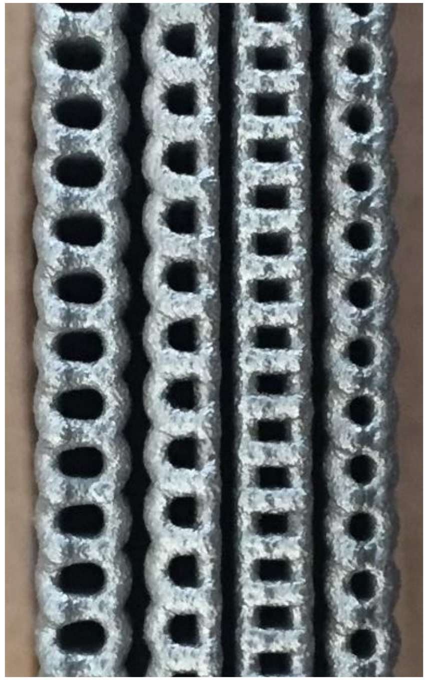


Example of LP-DED for large scale

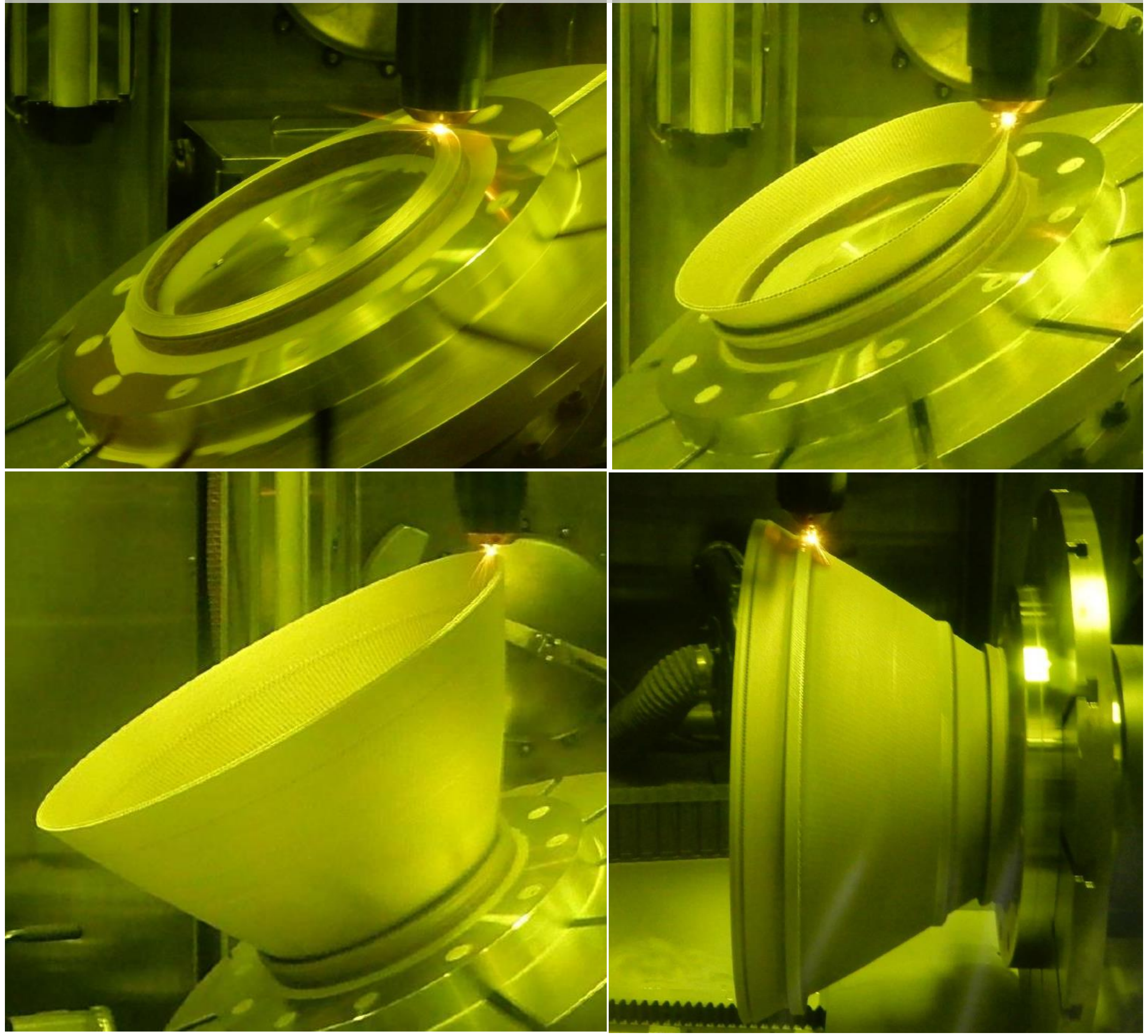


Large-scale Thin Wall Deposition of Nozzles



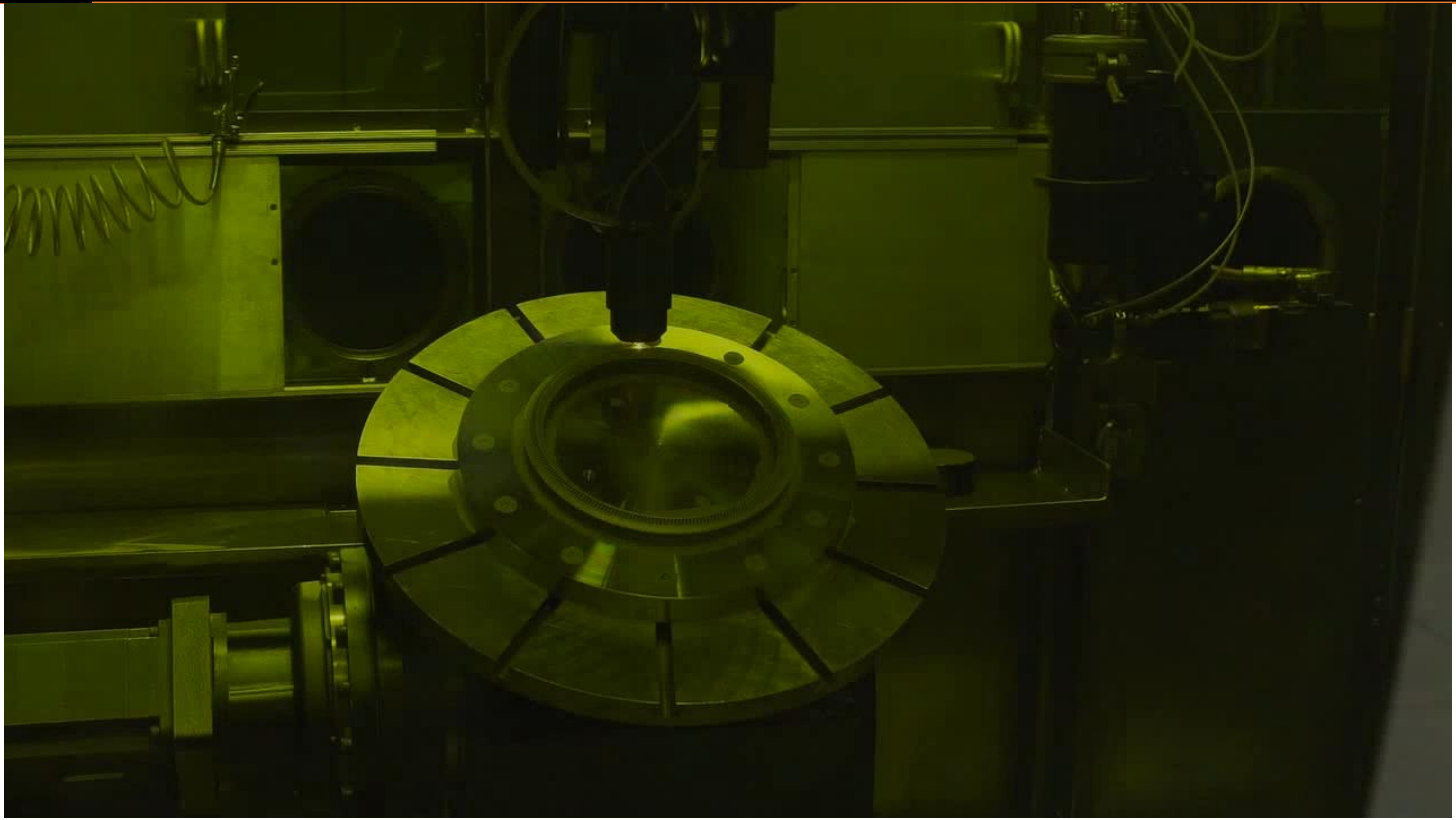


Process Development for DED of nozzles



RPM Innovations (RPMI) under NASA-RAMPT Project

Example of LP-DED with small features



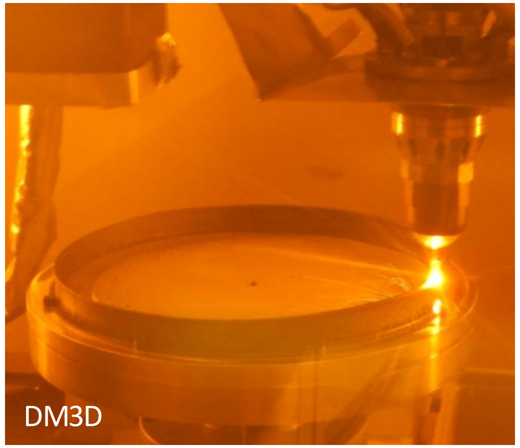
Laser Powder Directed Energy Deposition (LP-DED) Large Scale Nozzles

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: 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.

Component Applications using LP-DED



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)

Deposition Rate and Geometry

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

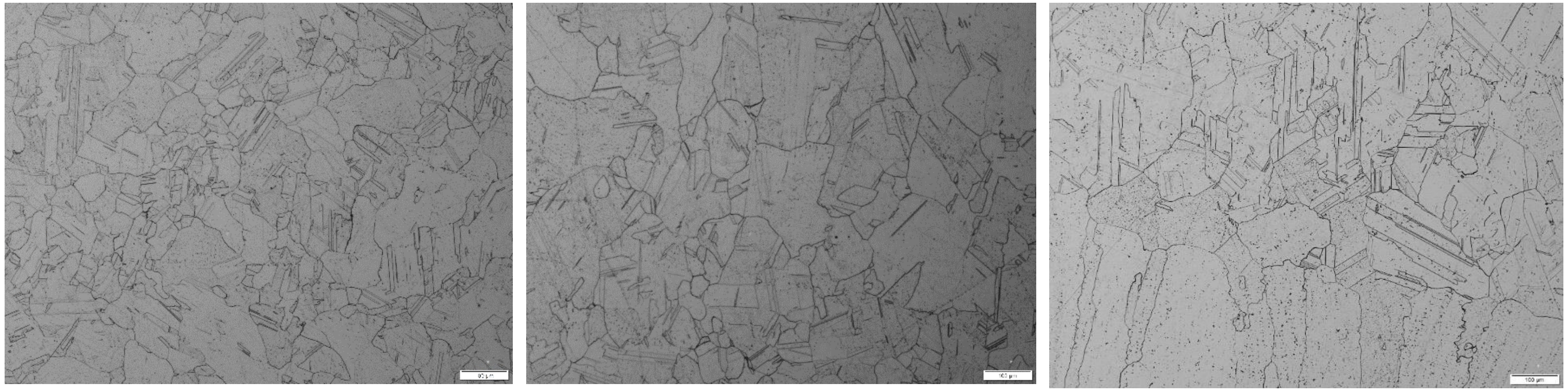
Microstructure of LP-DED – Various Spot Sizes

<u>LP-DED</u>
As-built

Build Direction

350W 1070W 2620W

<u>LP-DED</u>
Stress Relief, HIP, Annealed



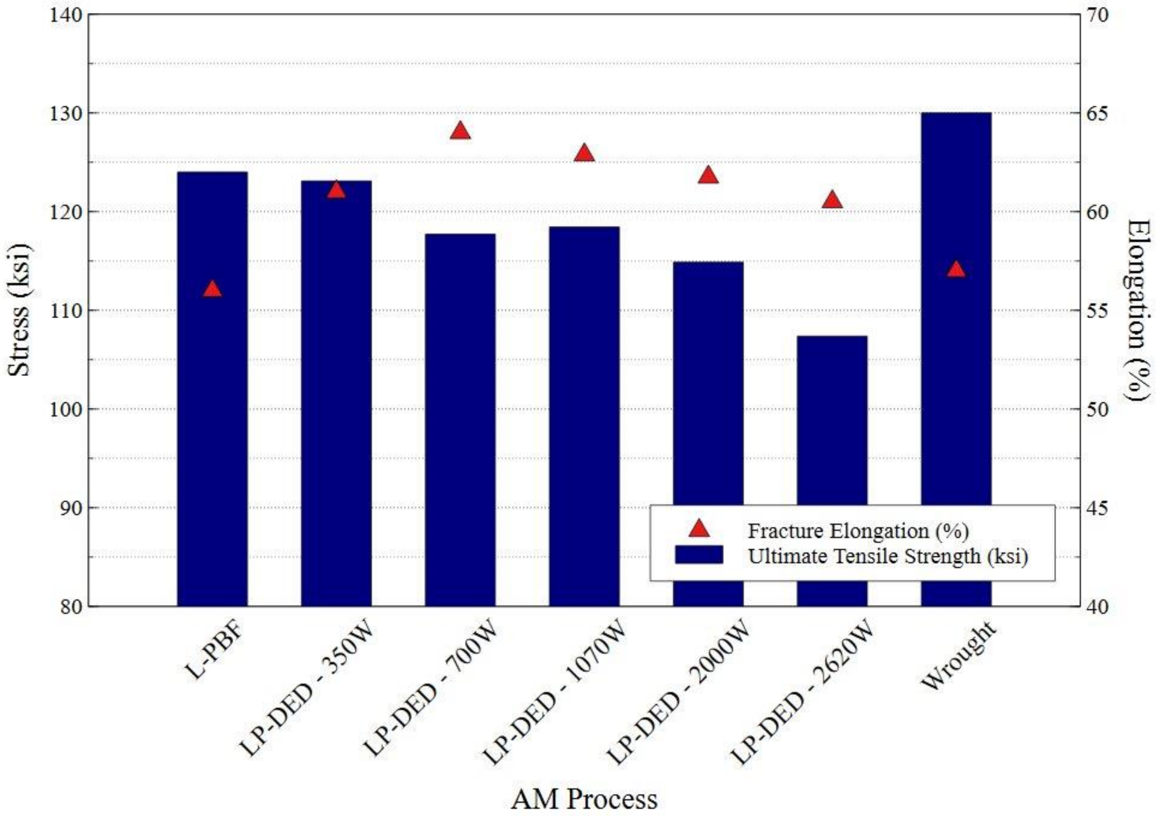
Different spot sizes and different parameters will result in different microstructure and subsequent properties

*Work based on research of Ariel Gamon/UTEP

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
- Properties should be developed after AM process is stable and parameters confirmed

Room Temperature UTS



*Not design data and provided as an example only

Typical AM Process Lifecycle

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

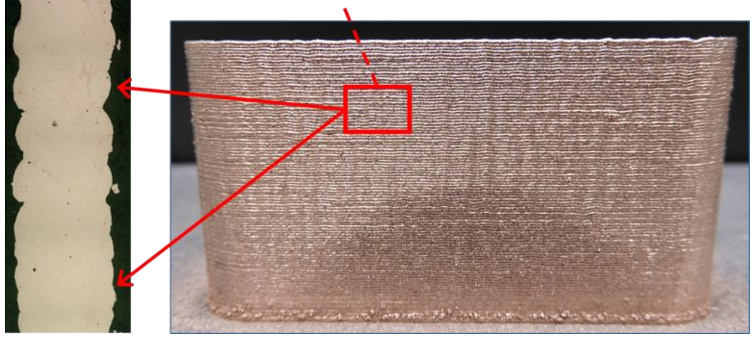
Qualification

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

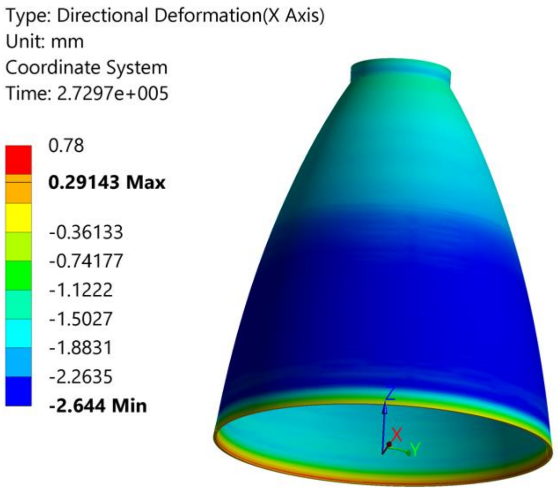
- AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl et al (unreleased)

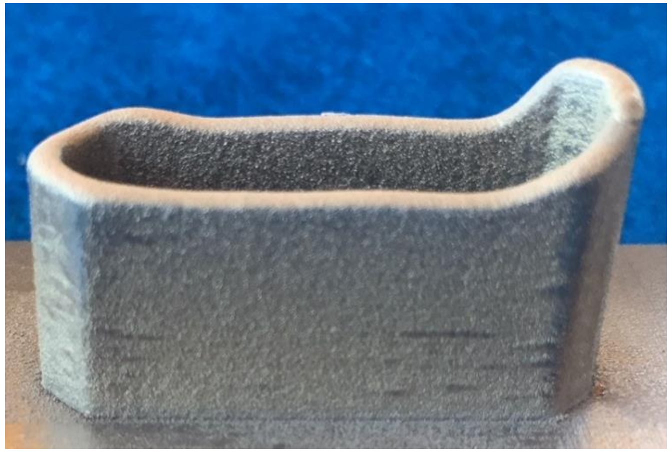
Challenges with DED

- 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



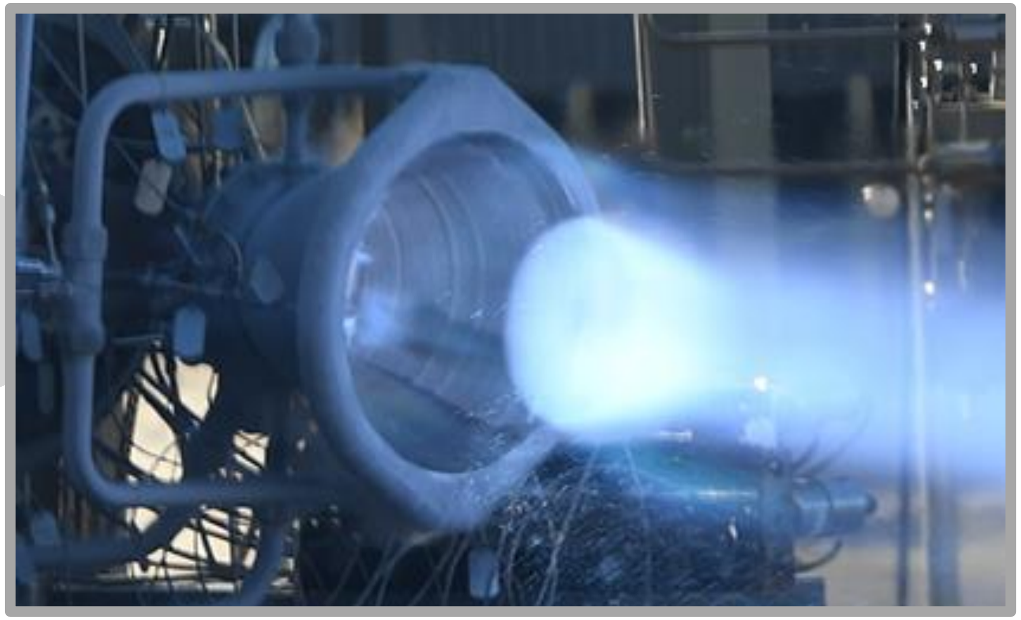


- Modeling by Kevin Wheeler / NASA Ames
- Other images based on work from: *Gradl et al "Metal Additive Manufacturing for Propulsion Applications" AIAA Book (Spring 2022)*

DED in Rocket Engine Applications

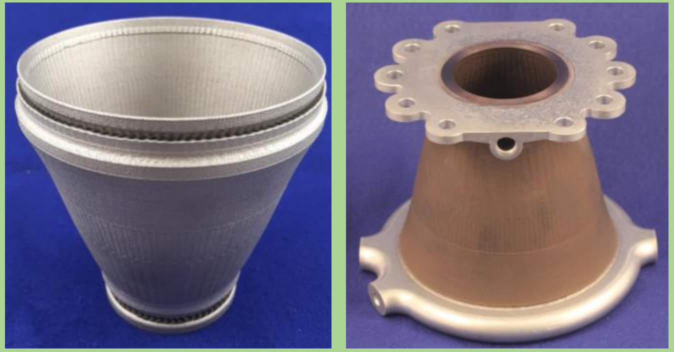
Cold spray

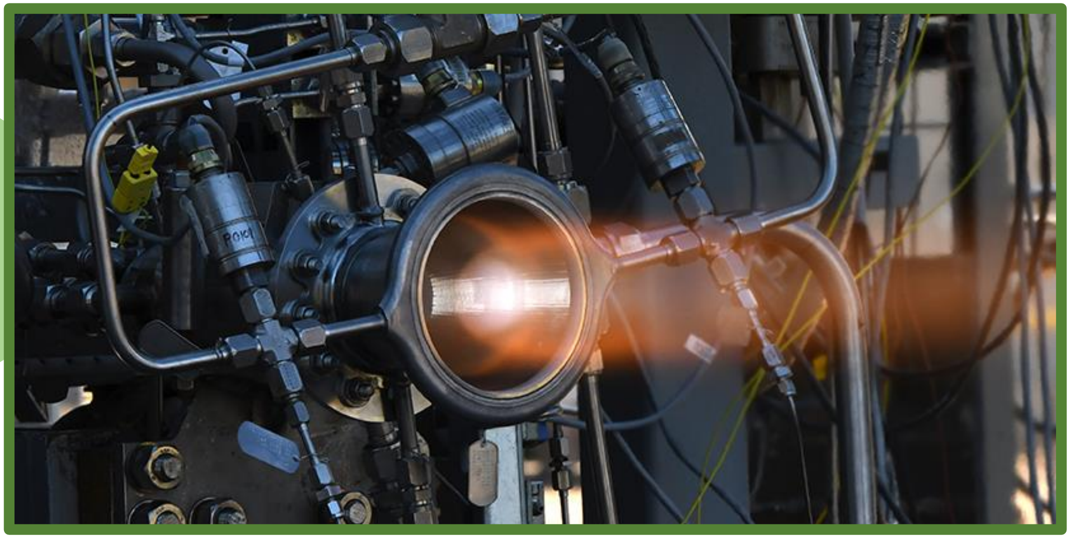
LP-DED

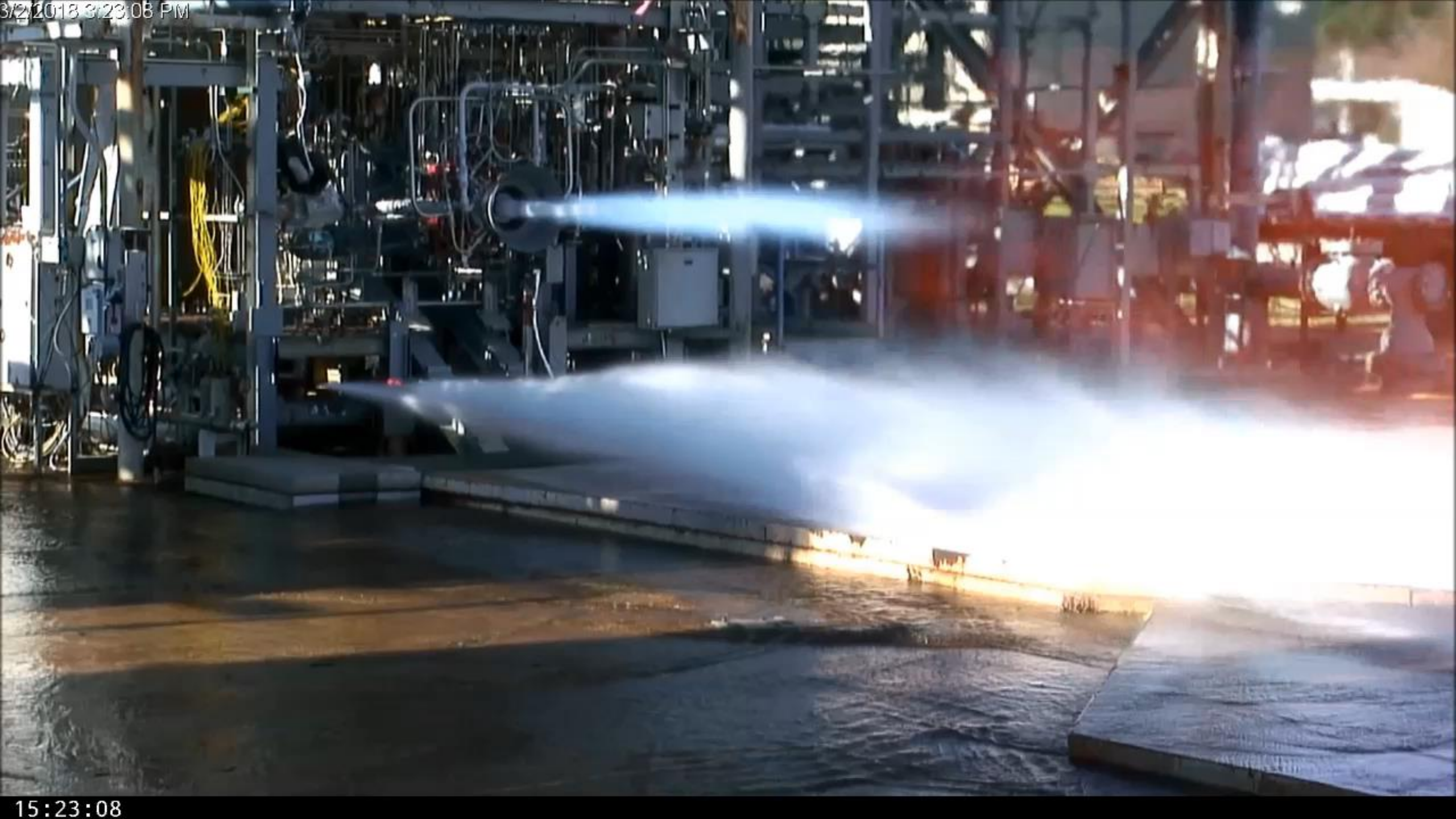


L-PBF

LP-DED



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Emerging Areas of Development for Metal AM

- 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 database of metal AM properties to allow for conceptual design – tensile, fatigue and thermophysical.
- Design complexity using lattices and thin-wall structures.
- Standards and certification of metal AM are evolving for human spaceflight.

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 the entire process – 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!
- 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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AME
Westmoreland Mechanical Testing
David Myers
Ron Beshears
James Walker
Steve Wofford
Jessica Wood
Robert Hickman
Johnny Heflin
Mike Shadoan
Keegan Jackson
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Presenter Bio

Paul Gradl

- Senior Propulsion Engineer at NASA Marshall Space Flight Center (MSFC) in the Propulsion Division, Engine Components Development and Technology Branch.
- Principal investigator and lead several projects for additive manufacturing of liquid rocket engine combustion devices and support a variety of development and flight programs over the last 18 years.
- Authored and co-authored over 70+ conference and professional papers and journal articles; holds four patents in additive.
- Associate Fellow of AIAA, serve on several committees and chairs various sessions at leading conferences on additive manufacturing.
- Active in ASTM, AIAA as a course instructor and advisory board
- Lead author and editor of book *Metal Additive Manufacturing for Propulsion Applications* (AIAA, 2021)

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