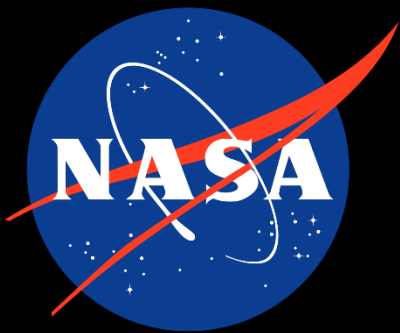




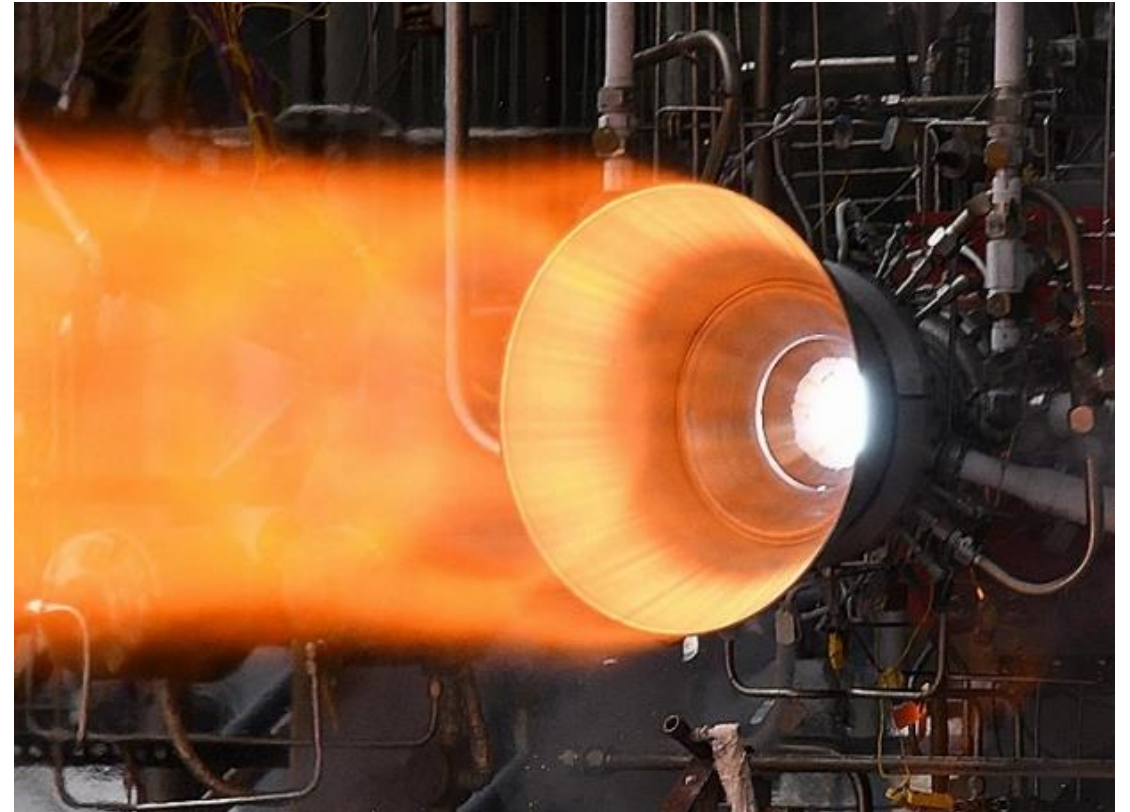
EXPLORE MOON *to* MARS

# Overview of Directed Energy Deposition for Liquid Rocket Engines

**Paul Gradl**  
NASA Marshall Space Flight Center  
March 8, 2021

Presentation to:  
Penn State University  
ExCCL/START Weekly Educational Meeting

- 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 Overviews
- 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

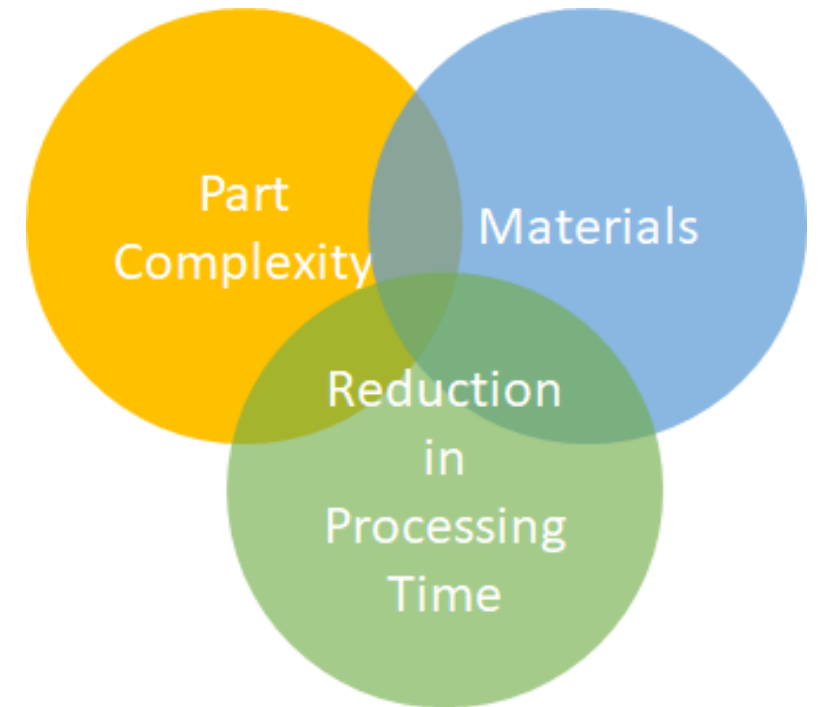
- AM = Additive Manufacturing
- DED = Directed Energy Deposition
- LP-DED = Laser Powder DED
- LW-DED = Laser Wire DED
- AW-DED = Arc Wire DED
- EB-DED = Electron Beam DED
- L-PBF = Laser Powder Bed Fusion
  
- Metal Additive Manufacturing - Build, print, grow, AM, *fabricate*...



# Why use AM? (Rocket Engines)



- Metal Additive Manufacturing 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

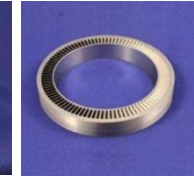
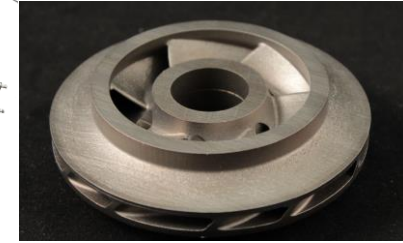
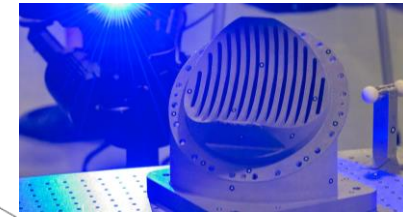




# Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

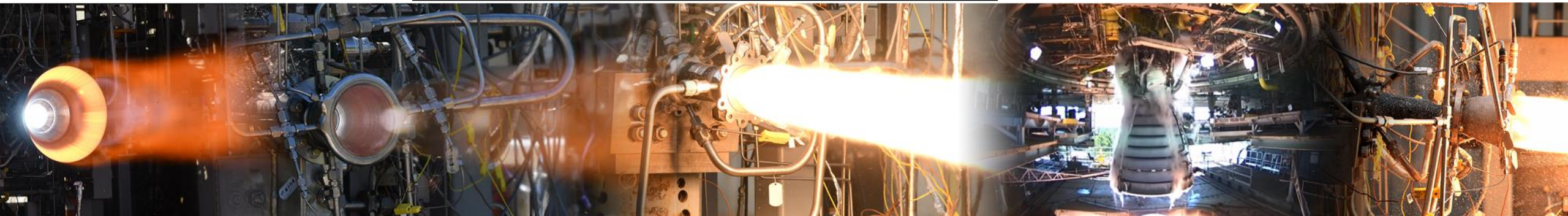


Directed  
Energy  
Deposition



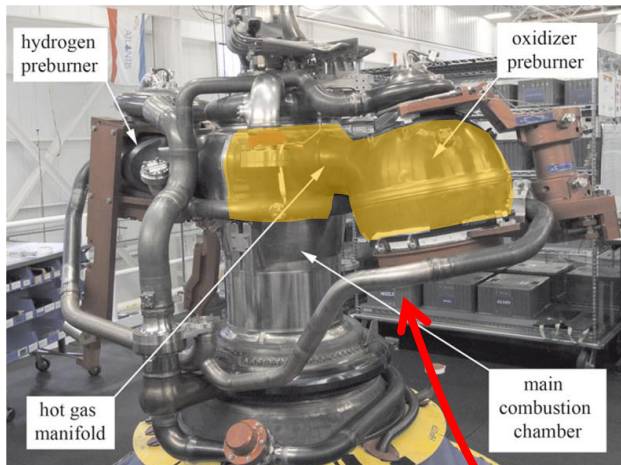
L-PBF of complex components,  
new alloy developments for  
harsh environment

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



## Traditional Manufacturing

**Forged => Machined**



## L-PBF Development



**>90 days using L-PBF (Large Platform)**

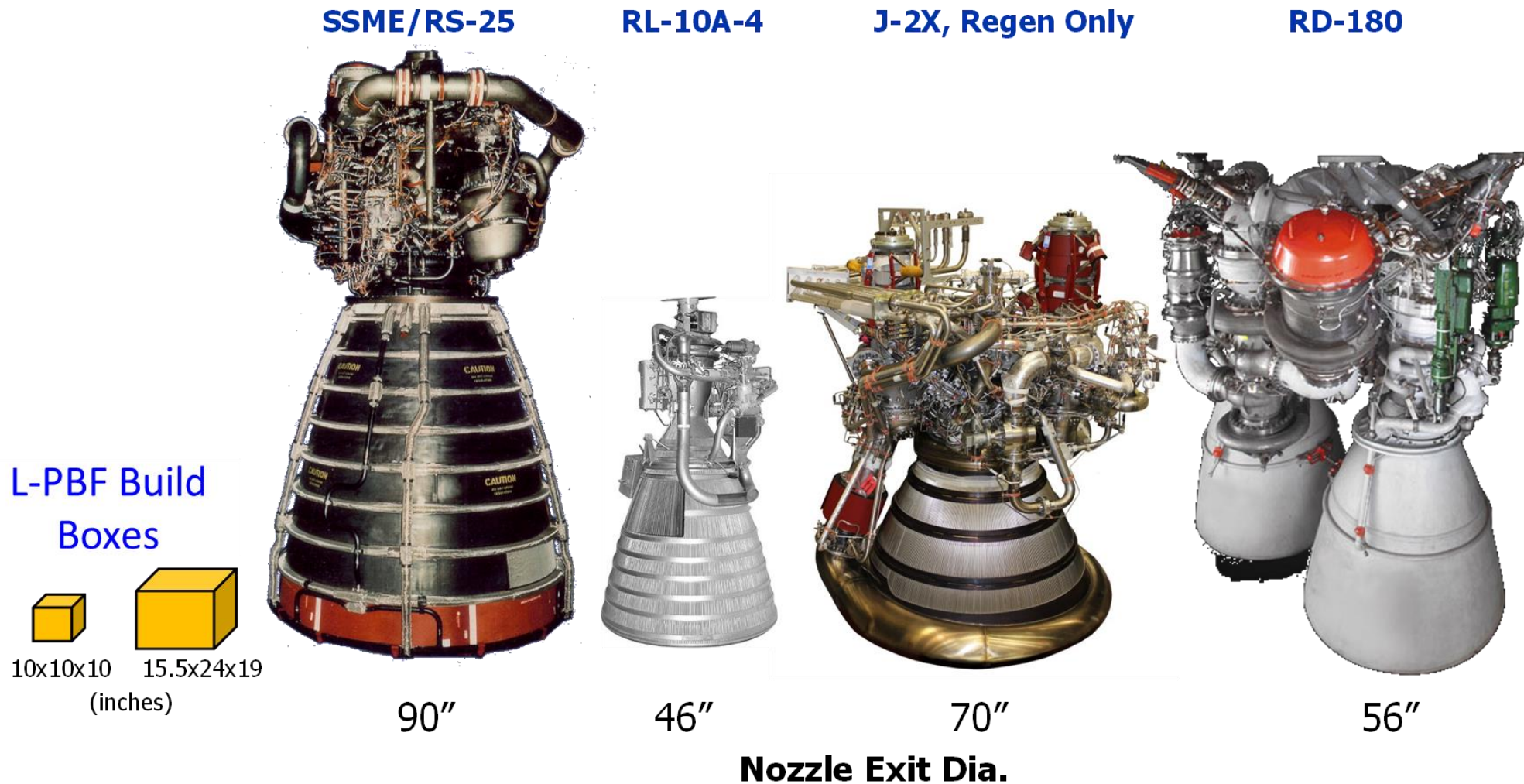


## DED Development



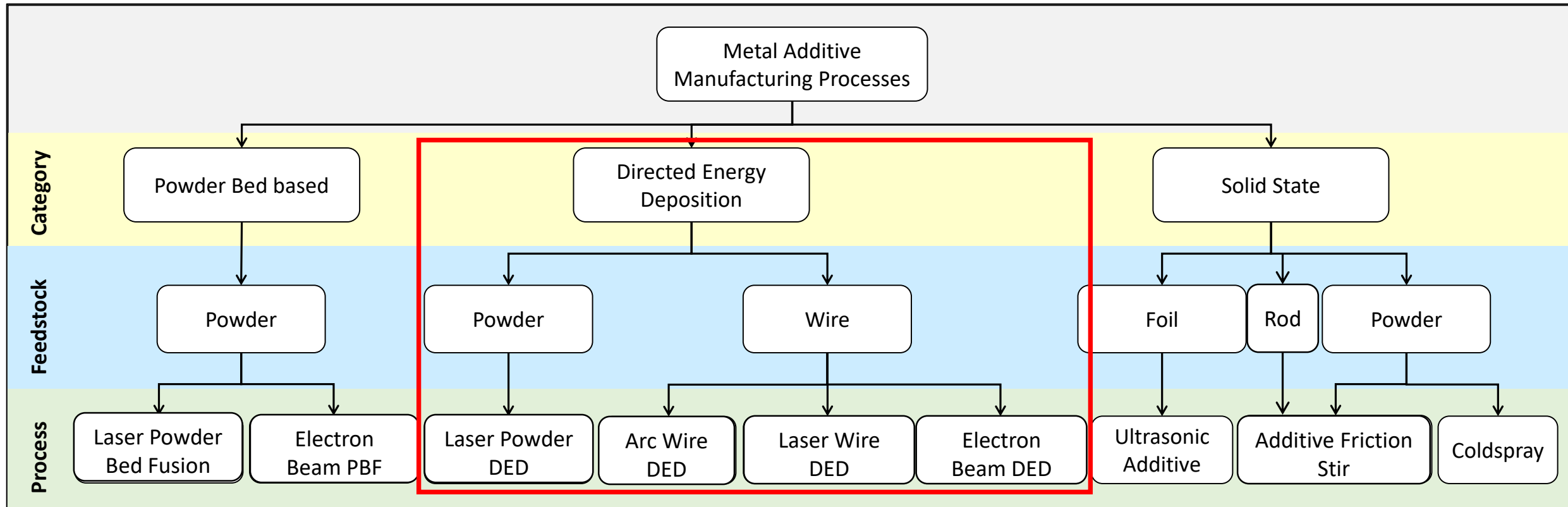
**<14 days deposition  
using LP-DED**

# The need for large scale AM...





# Metal AM Technologies - Overview



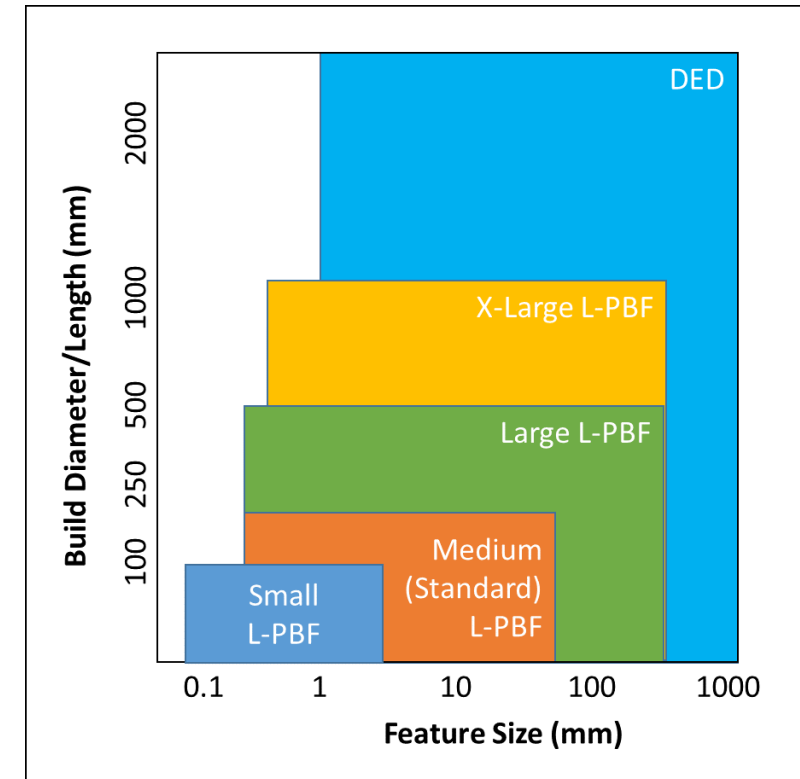
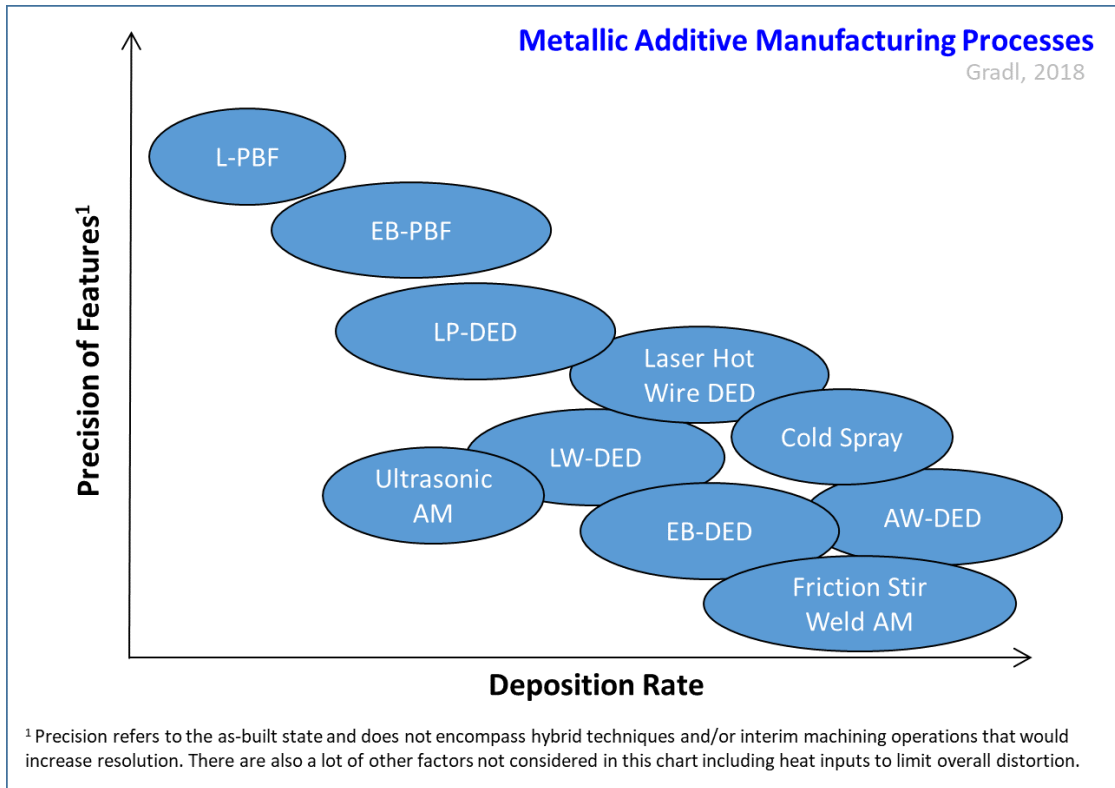
\*Does not include all metal AM processes

## Based on Ref:

- Gradl, P.R., Mireles, O., Andrews, N. "Introduction to Additive Manufacturing for Propulsion Systems. [10.13140/RG.2.2.13113.93285](https://doi.org/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).



# 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:

- Honore, M. "Structural strengthening of Rocket Nozzle Extensions by Means of Laser Metal Depositioning". In Support of Volvo Channel Wall Nozzle. Force Technology. MTI Mtg Laserfusing Presentation. 1 February, 2013.
- O'Neill, W., Cockburn, A., et al. "Supersonic Laser Deposition of Ti and Ti64 Alloys". 5<sup>th</sup> International Symposium on High Power Fibre Laser and their Applications/14<sup>th</sup> International Conference on Laser Optics. July 1, 2010. St. Petersburg, Russia.
- Paul R. Gradl. "Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles", 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Propulsion and Energy Forum, (AIAA 2016-4771)
- Gradl, P.R., Mireles, O., Andrews, N. "Introduction to Additive Manufacturing for Propulsion Systems. [10.13140/RG.2.2.13113.93285](https://doi.org/10.13140/RG.2.2.13113.93285)



# 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

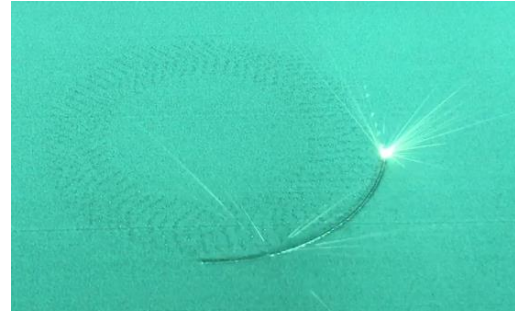


# Comparison of L-PBF and DED



**Different methods for different components!**

## Laser Powder Bed Fusion (L-PBF)



## Directed Energy Deposition (DED)



|                                          |                                                                        |                                                                   |
|------------------------------------------|------------------------------------------------------------------------|-------------------------------------------------------------------|
| <b>Feature Resolution / Complexity</b>   | High resolution of features<br>Wall thicknesses and holes <0.010"      | Medium resolution of features<br>Walls >0.040" and limited holes  |
| <b>Deposition Rate</b>                   | Low build rates<br><0.3 lb/hr                                          | High Build rates<br>lbs per hour (some systems >20lb/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><15.6" dia (400mm) or 16"x24"x19" | 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                  |



# 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

GRCo-84  
GRCo-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  
 $\gamma$ -TiAl  
Ti-6-2-4-2

## Co-Base

CoCr  
Stellite 6,  
21, 31

## Bimetallic

GRCo-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*)



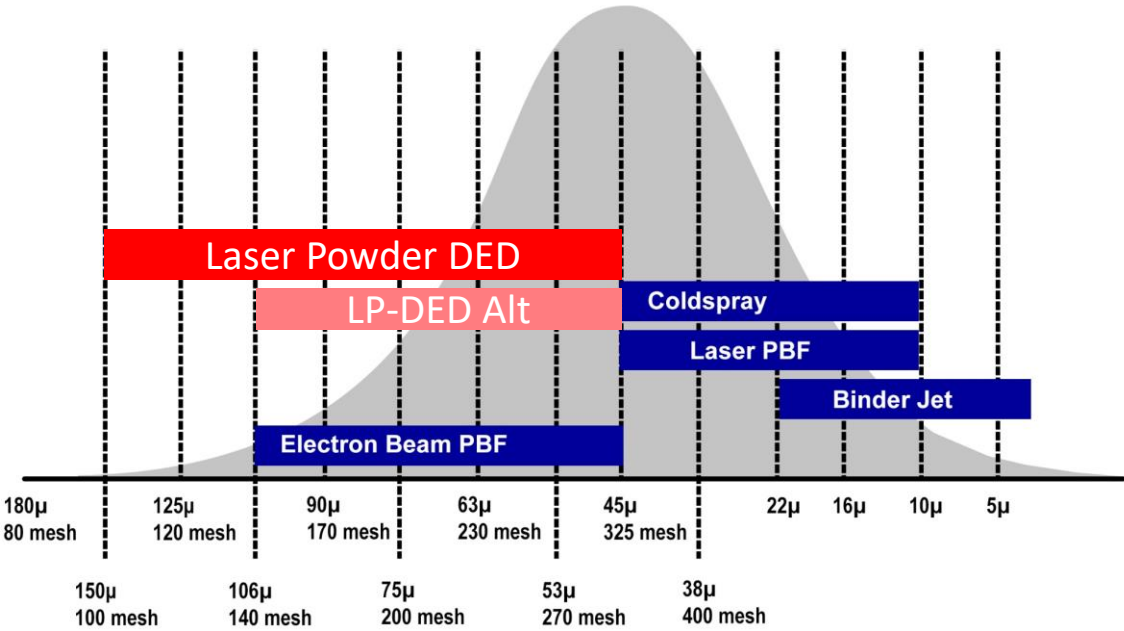
# Feedstock Material for DED



## Feedstock can be Powder or Wire

| Process          | Type of Feedstock | Typical Feedstock Size | Stock Lead Times |
|------------------|-------------------|------------------------|------------------|
| L-PBF            | Powder            | 10-45 $\mu\text{m}$    | Short            |
| EB-PBF           | Powder            | 10-45 $\mu\text{m}$    | Short            |
| LP-DED           | Powder            | 45-105 $\mu\text{m}$   | 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 $\mu\text{m}$    | Short            |
| Binderjet        | Powder w/ Binder  | 3-22 $\mu\text{m}$     | Medium           |

\*UAM = Ultrasonic Additive Manufacturing



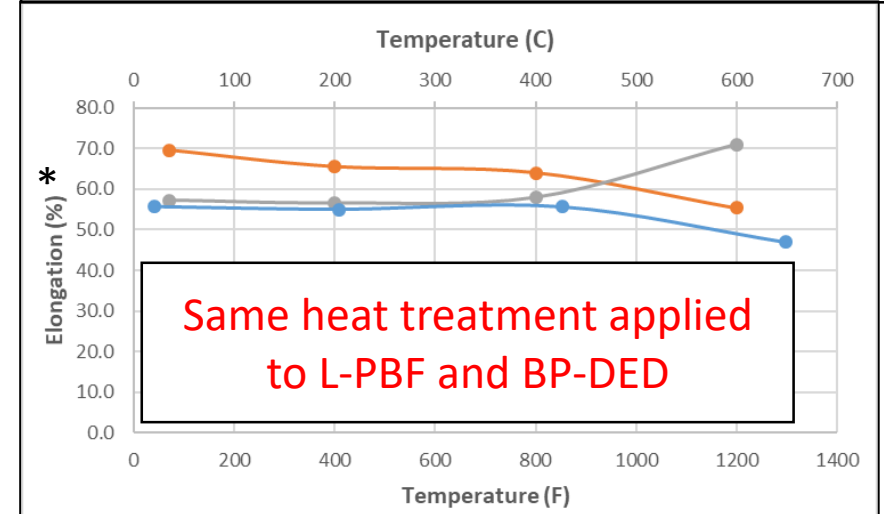
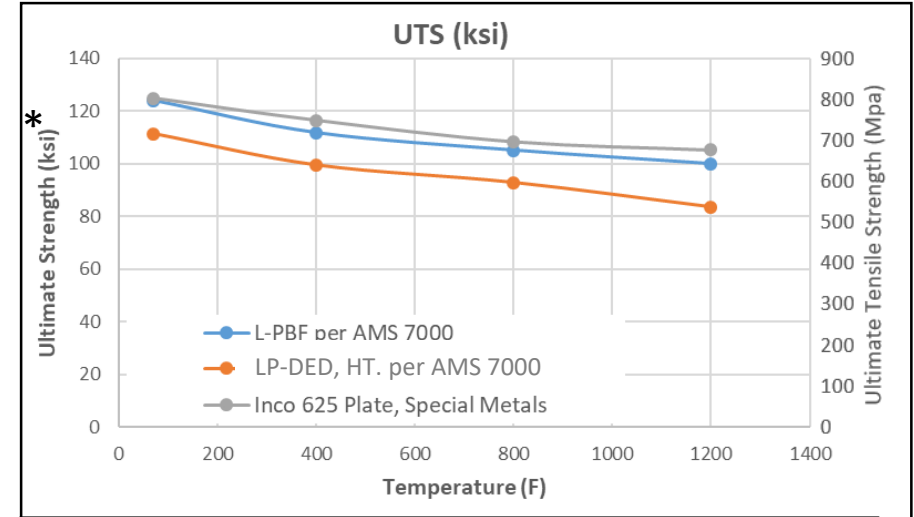


# Material Properties for Metal



- 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

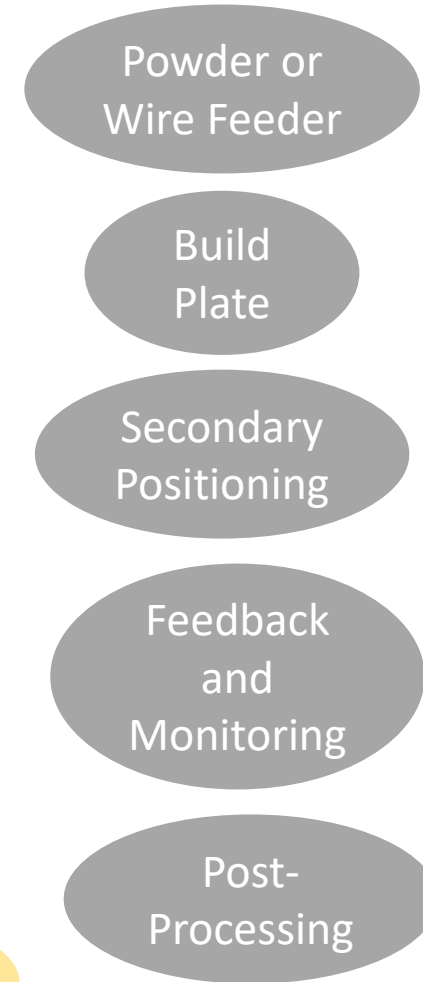
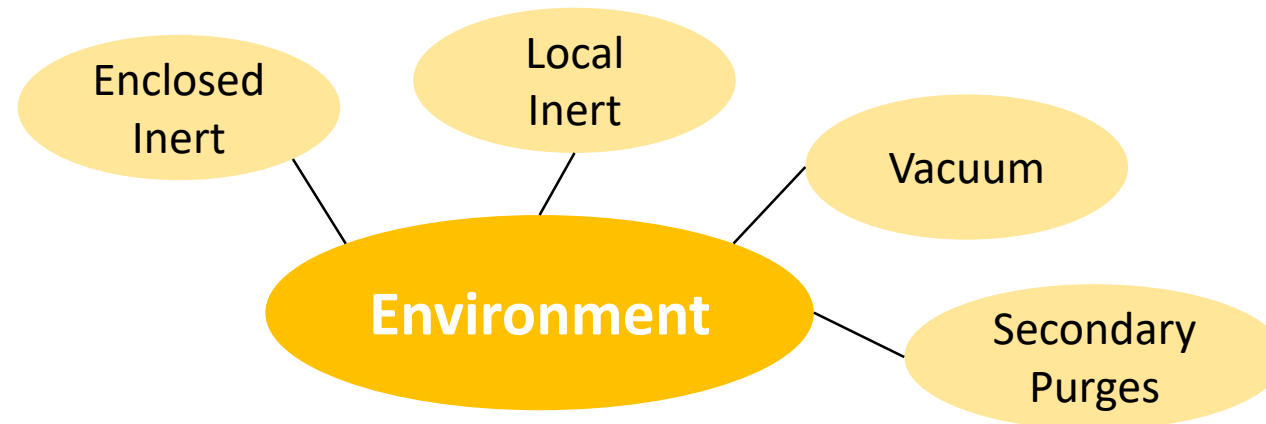
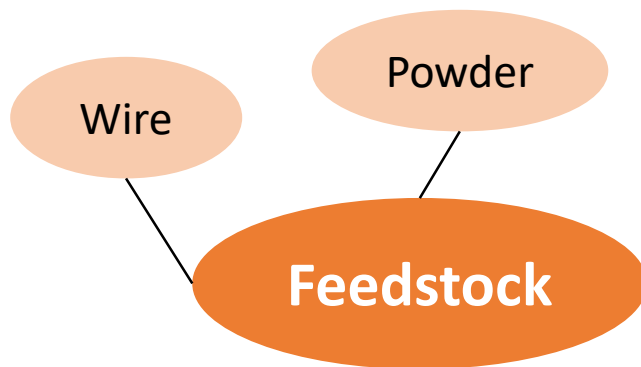
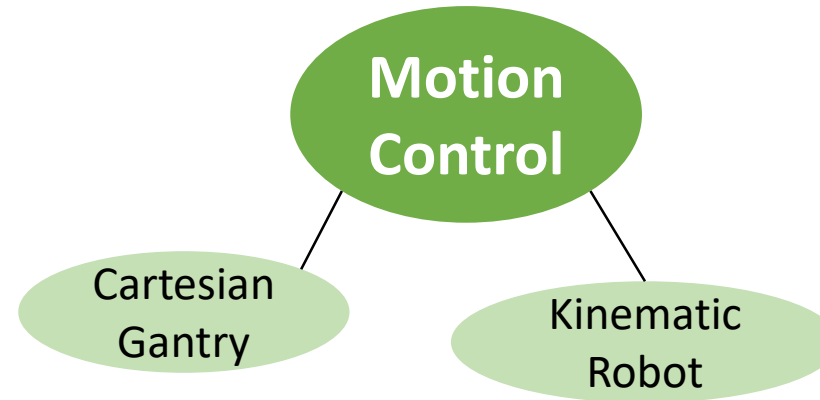
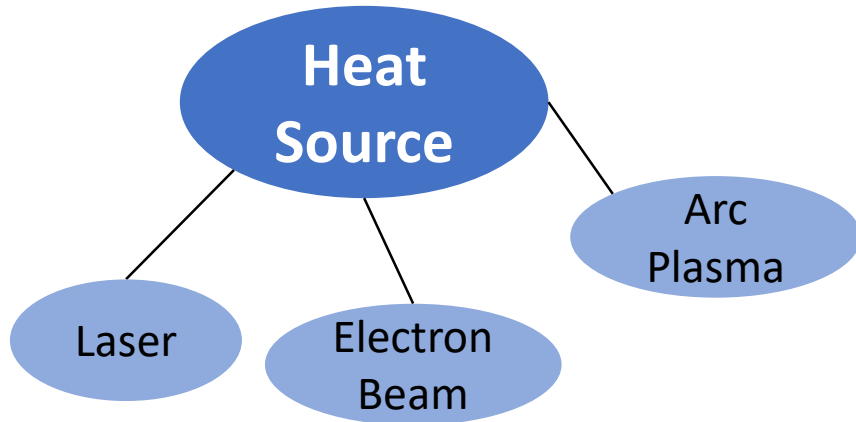
## Example of Inconel 625, L-PBF and LP-DED (Typical)



\*Not design data and provided as an example only



# Aspects of AM DED Systems

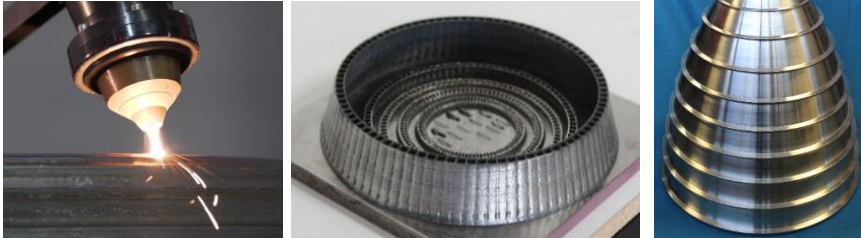


# Various DED Technologies

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.

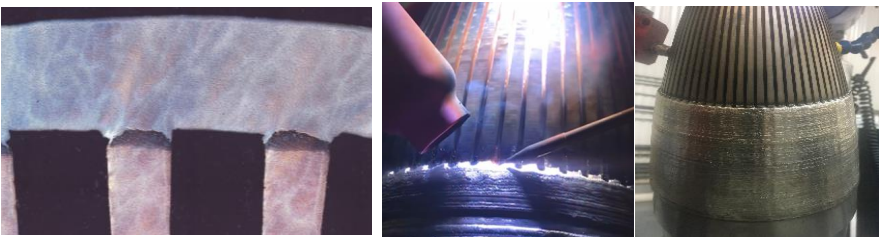
## Laser Powder DED (LP-DED)

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



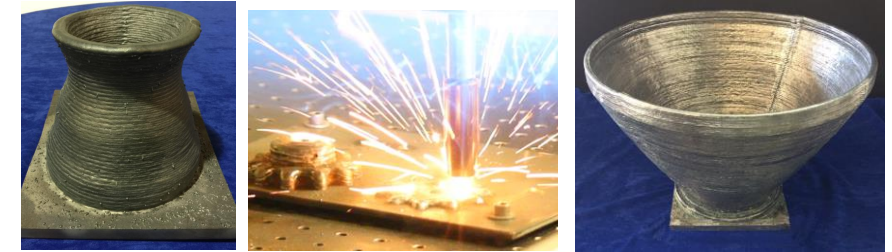
NASA L-PBF/DED



\*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

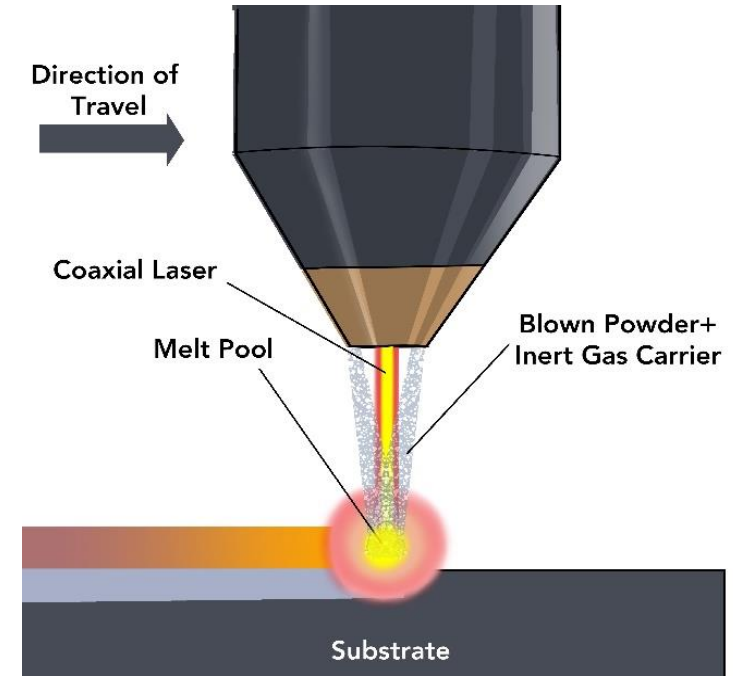


## Electron Beam DED (EB-DED)

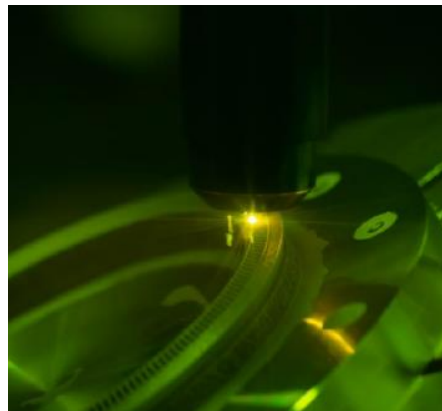
An off-axis wire-fed deposition technique using electron beam as energy source; completed in a vacuum.



- 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

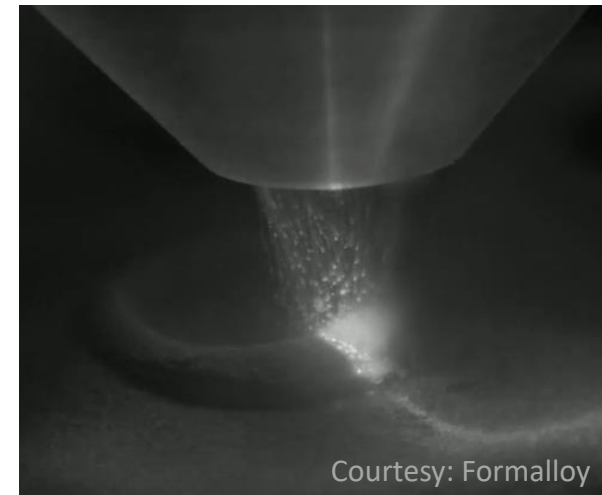
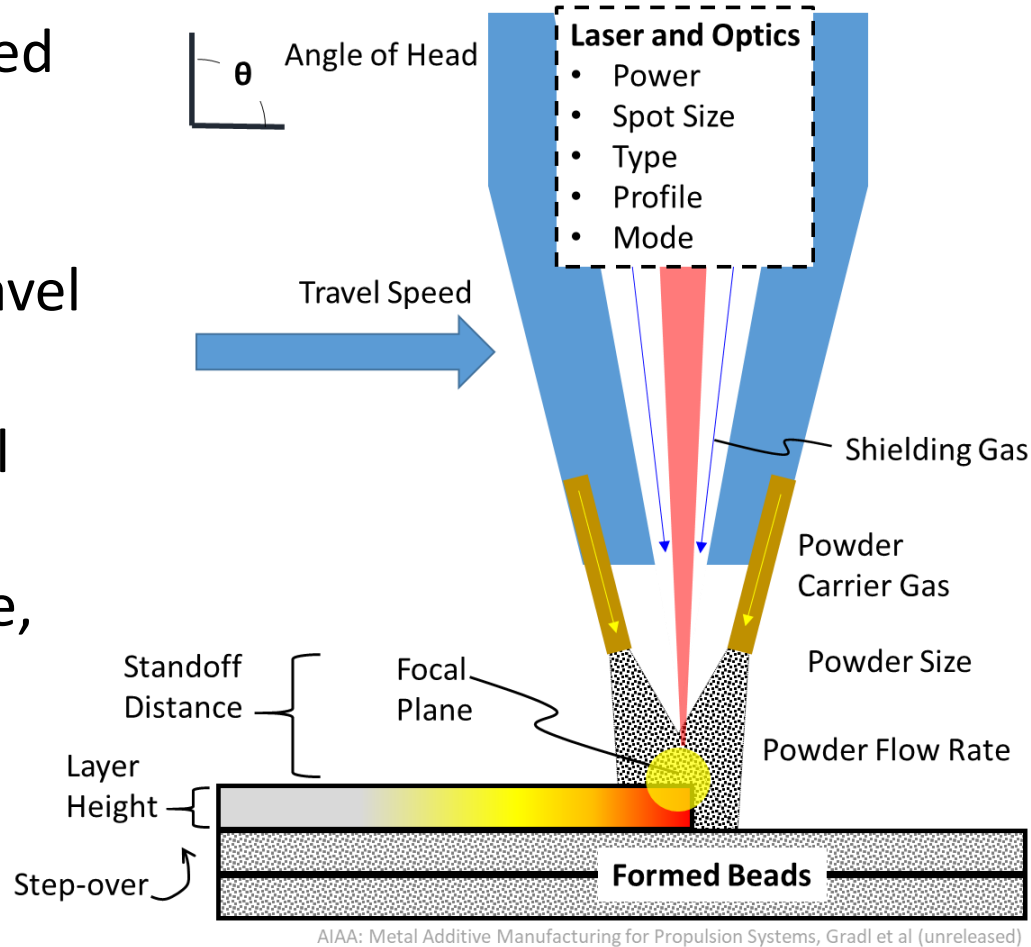


JBK-75, IN625, NASA HR-1 Manifolds



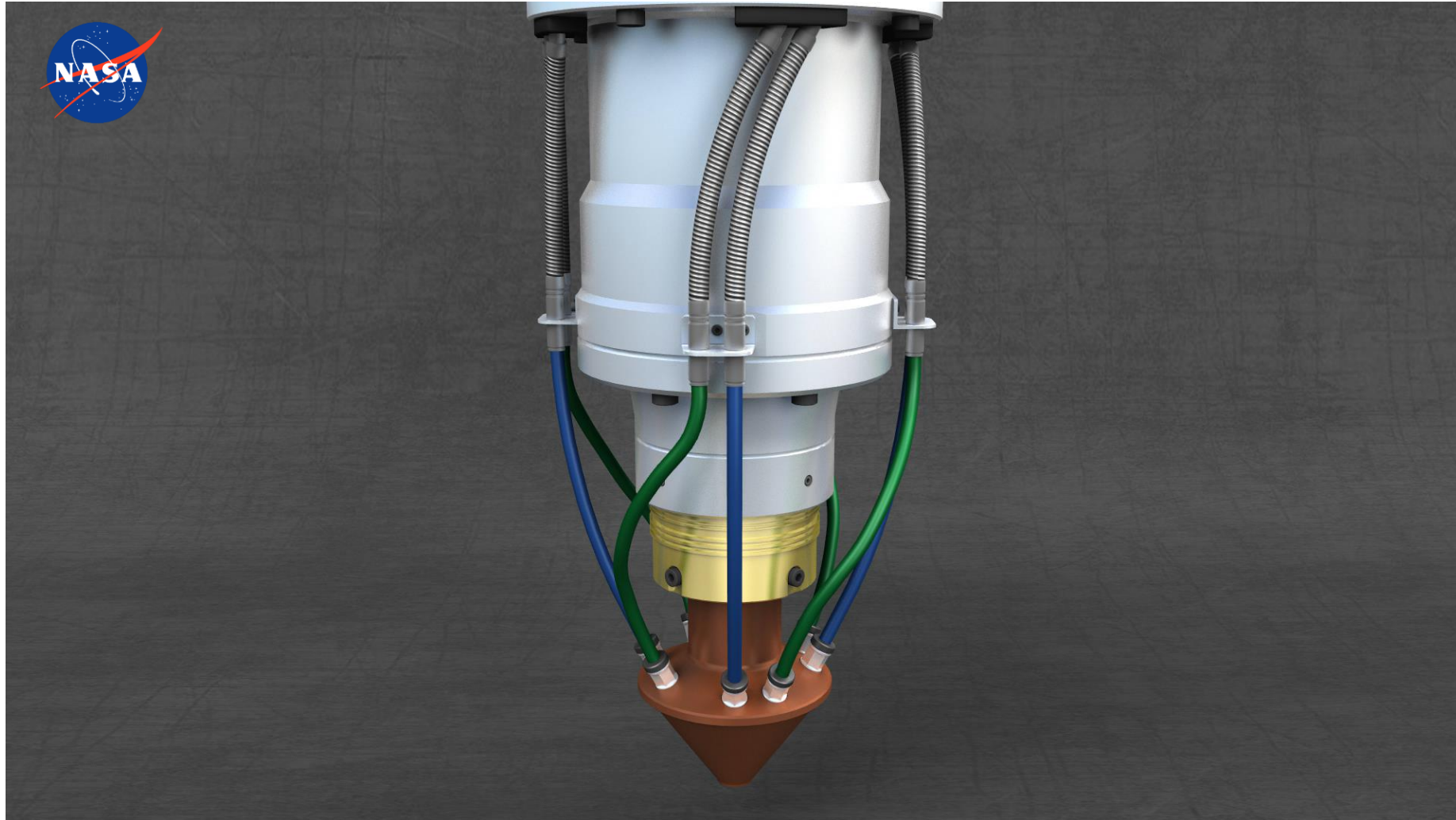
JBK-75 Integrated Channel

- 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





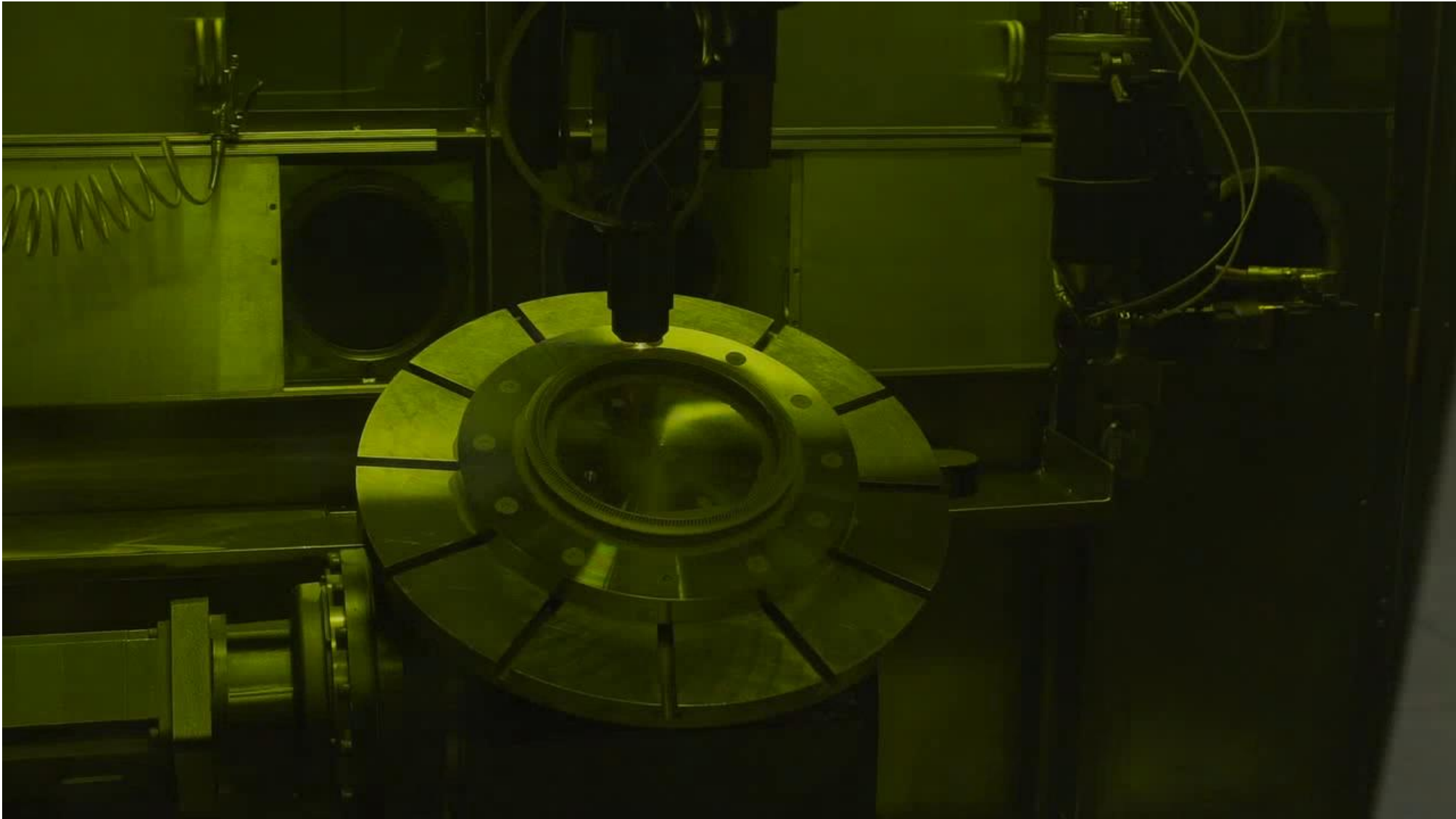
# Animation of LP-DED Process



# Example of LP-DED for large scale



# Example of LP-DED with small features

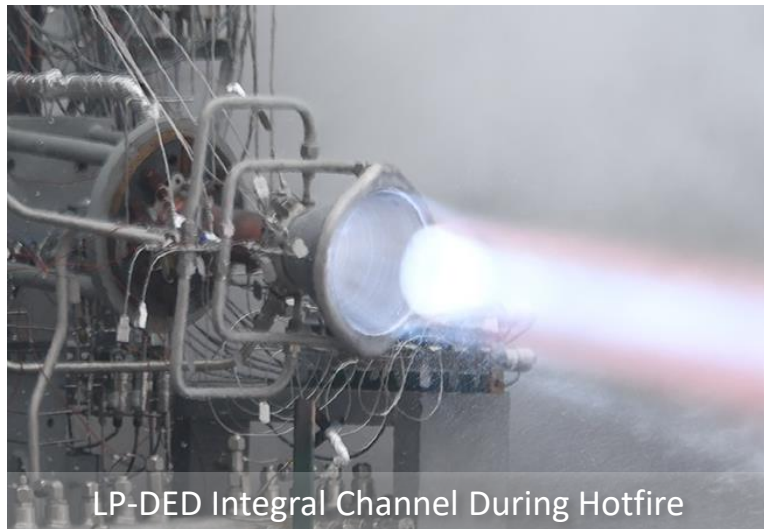


# Examples of Small Feature Large Scale LP-DED



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

Courtesy: RPM Innovations (RPMI)



LP-DED Integral Channel During Hotfire





# Component Applications using LP-DED



1/2 Scale RS25 Nozzle Liner



DM3D

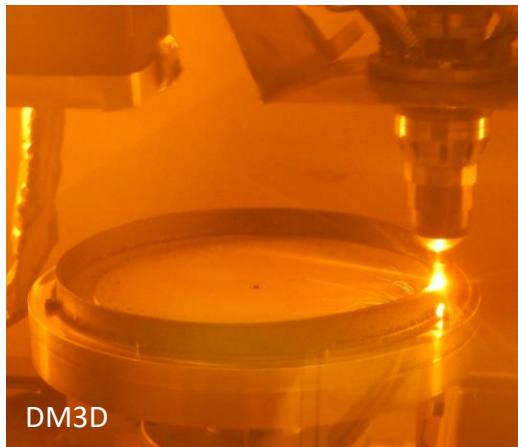


RPMI



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

RPMI



DM3D



RPMI



DM3D



RPMI



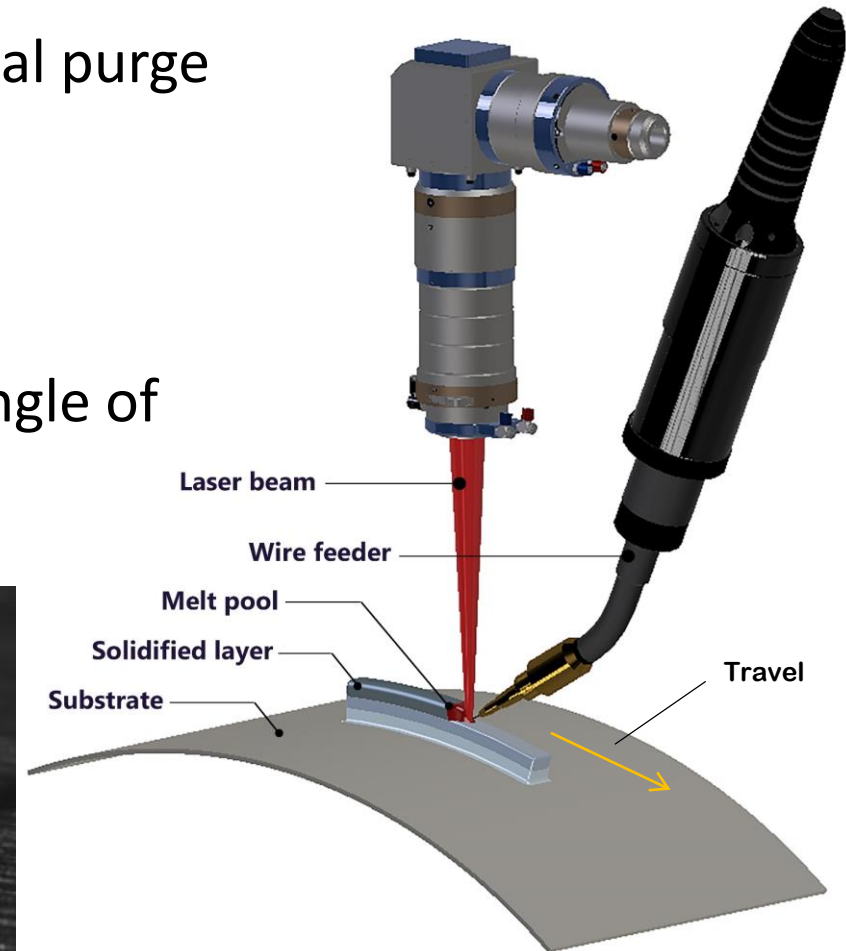
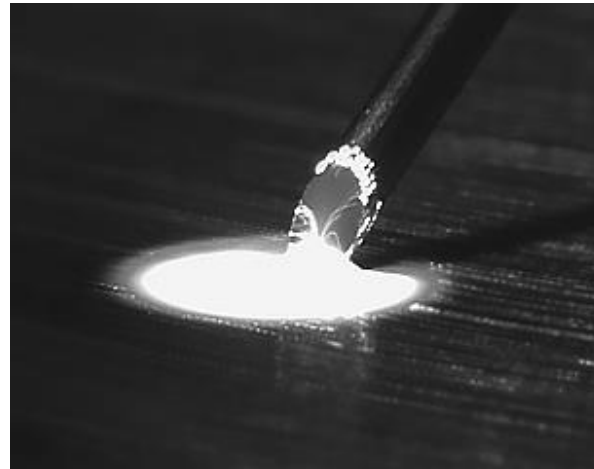
# LP-DED Large Scale Nozzle with Fine Features



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

# Laser Wire DED

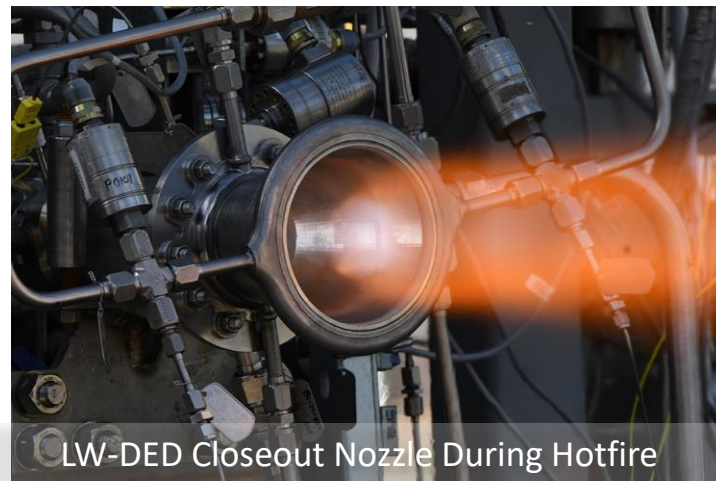
- Uses a laser energy source with a off-axis wire feed and local purge
- 100% efficiency in material usage
- High deposition rates, but balances low heat input
- Can be used on complex surfaces
- Key parameters: Laser Power, Wire feedrate, Travel rate, Angle of Head, Shielding gas flowrate



All Images Courtesy of Procada

# LW-DED Component Examples

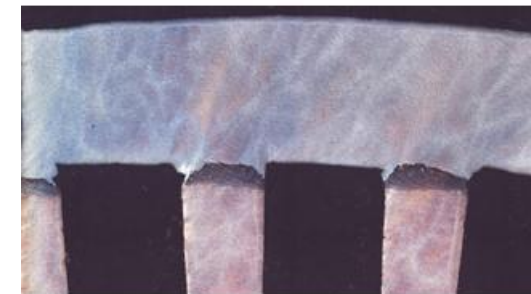
- Used on a variety of components including rocket nozzles
- Add secondary material “in-place” or freeform deposition
- Multi-alloys demonstrated



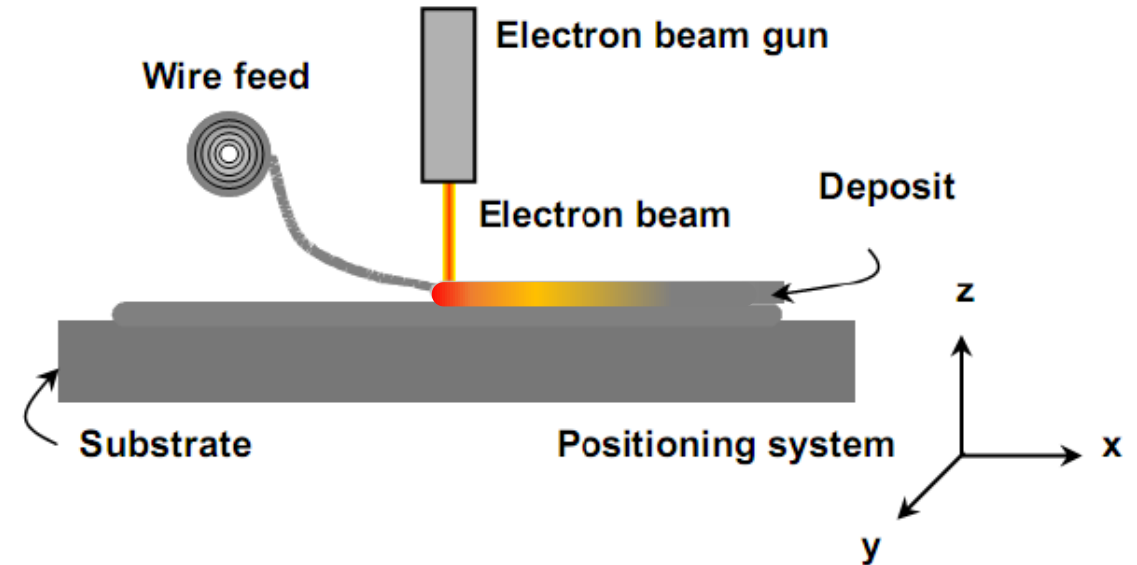
LW-DED Closeout Nozzle During Hotfire



LW-DED using multi-alloys



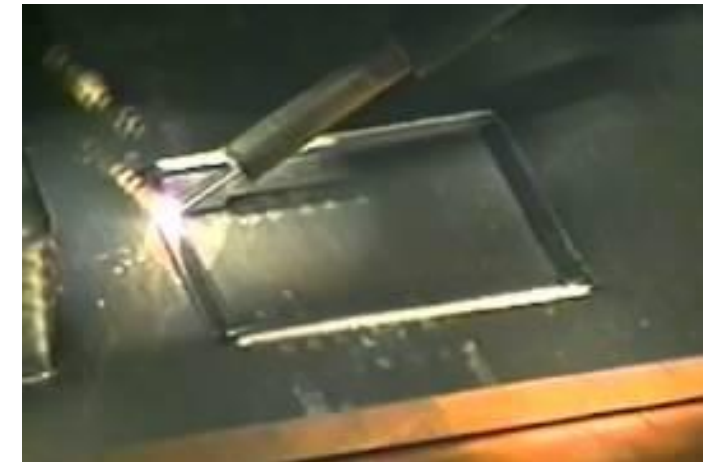
- Uses electron beam energy source with a wire feed inside vacuum chamber
- 100% efficiency in material usage
- High deposition rates
- Key parameters: Beam current and acceleration voltage, Wire Feedrate, Travel Rate, Angle of Turntable



Monolithic EB-DED Freeform

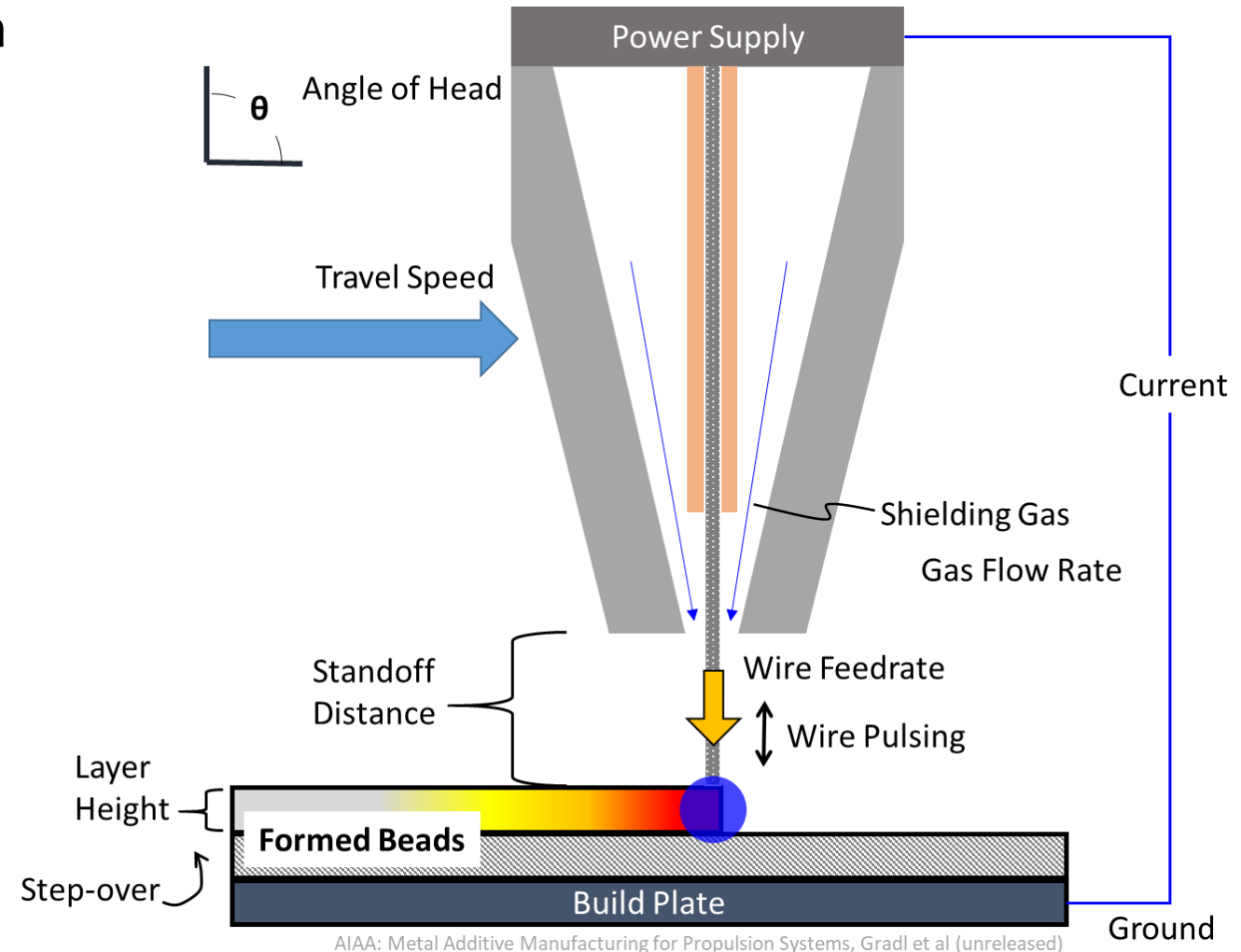


EB-DED Inco 625 Jacket on L-PBF GRCop-84 Liner



# 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



# Arc Wire DED



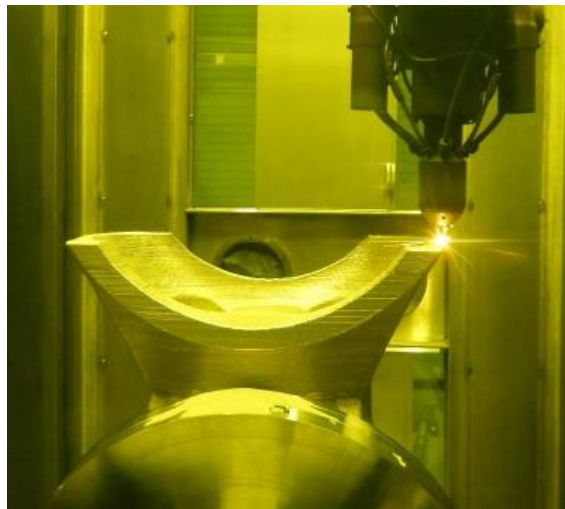
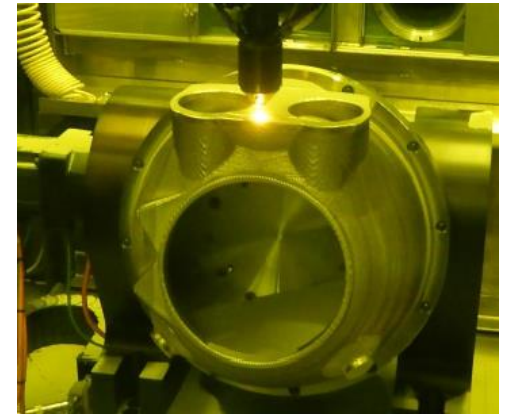
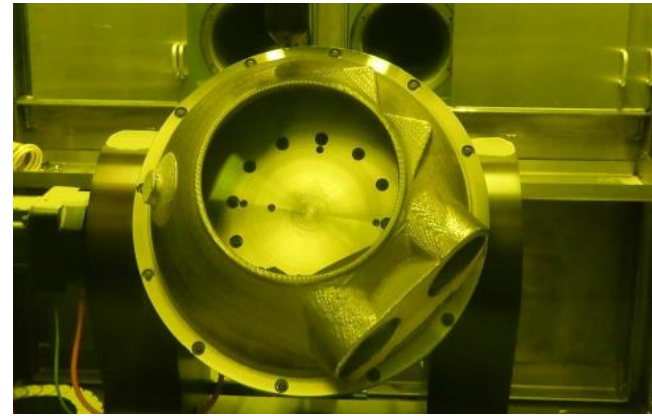
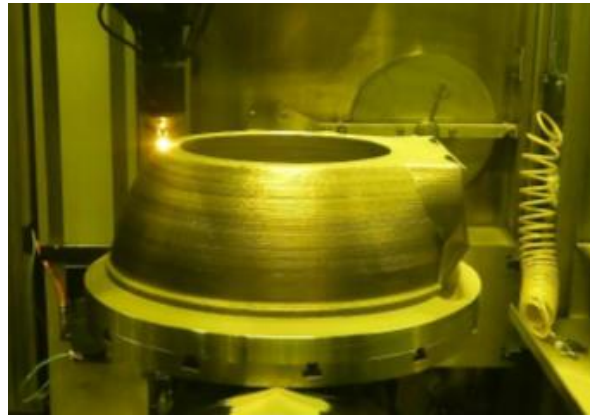
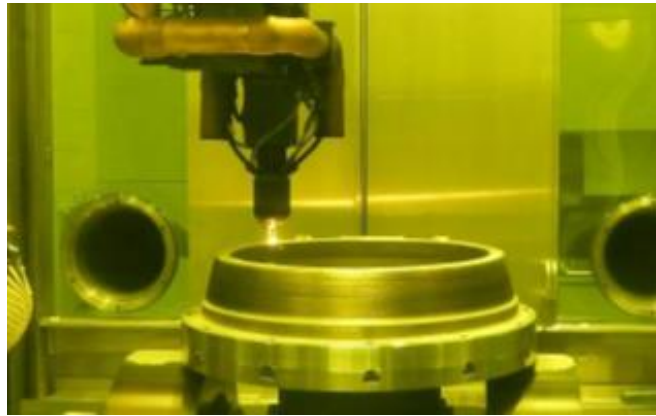
Courtesy: Keystone



# Freedom in DED design and deposition strategies



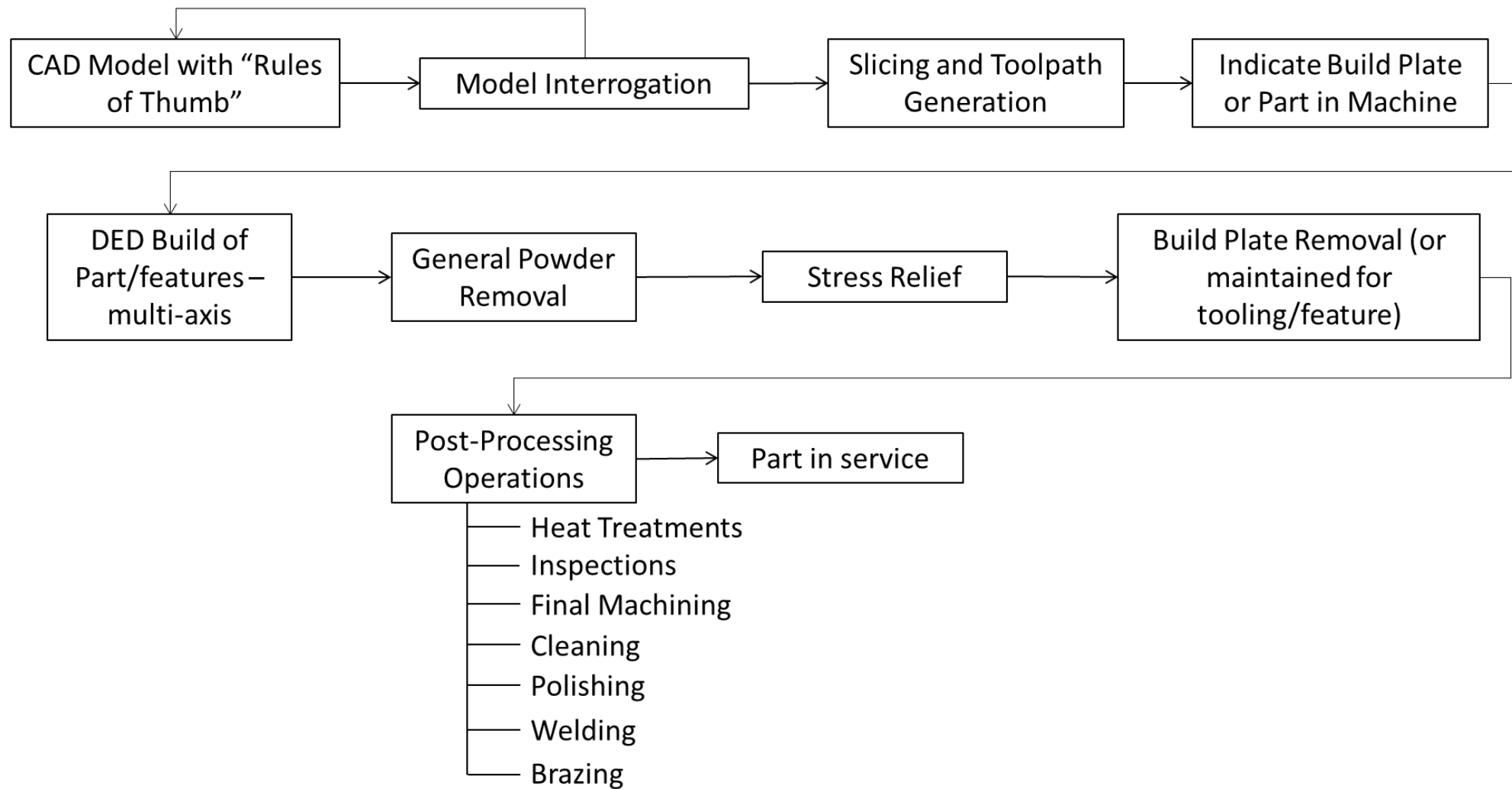
**Ability to use multiple axes for complex features fabricated locally**



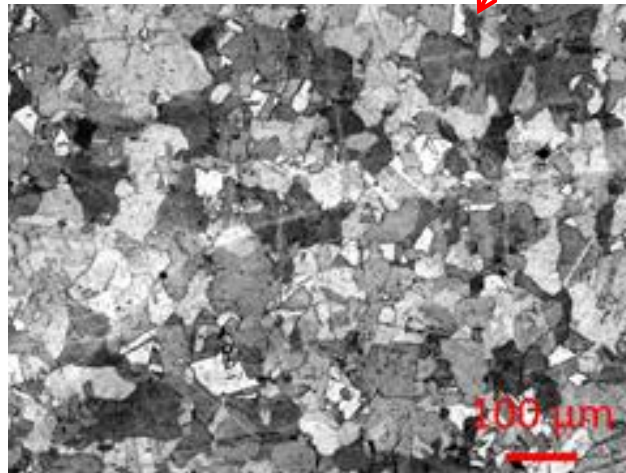
RS25 Powerhead demonstrator using LP-DED under NASA SLS Artemis Program (Courtesy: RPMI)



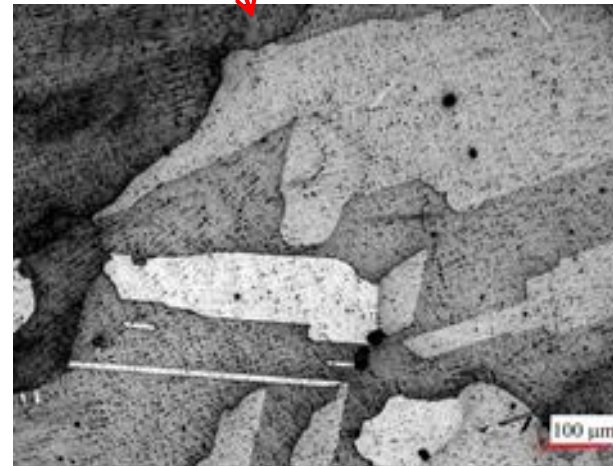
# Typical DED Process Flow



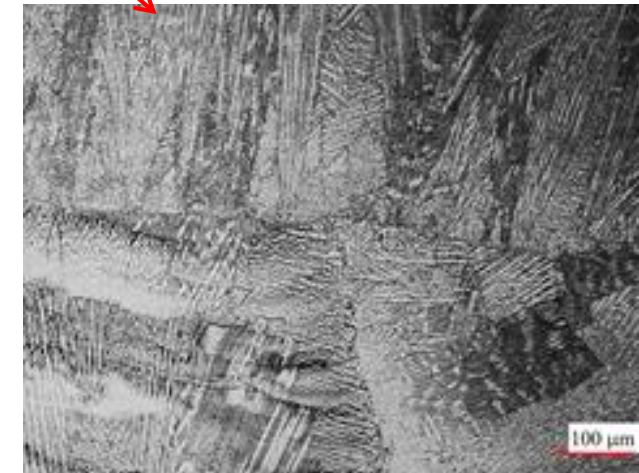
## Inconel 718



Laser Powder Bed Fusion (L-PBF)

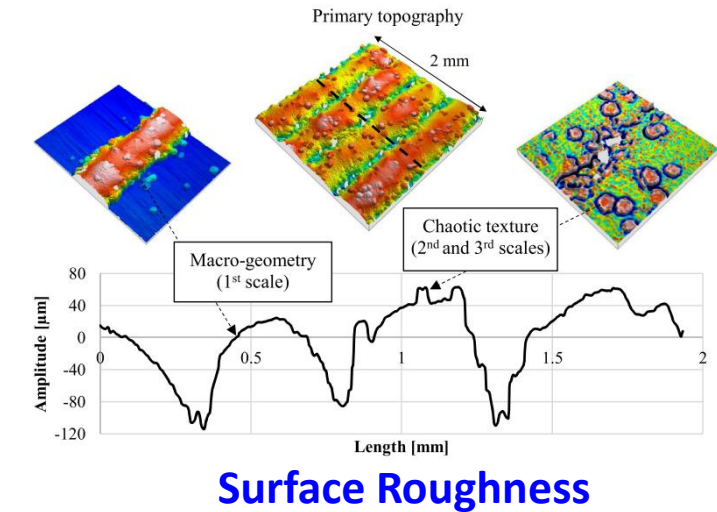


Laser Powder DED (LP-DED)

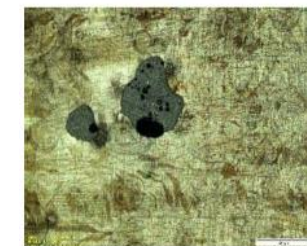
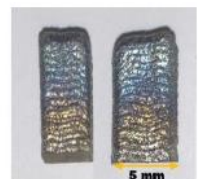
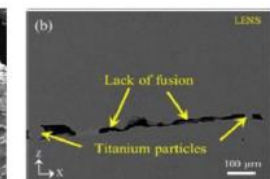
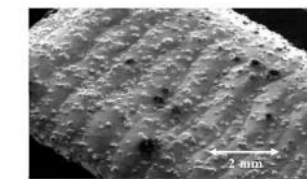
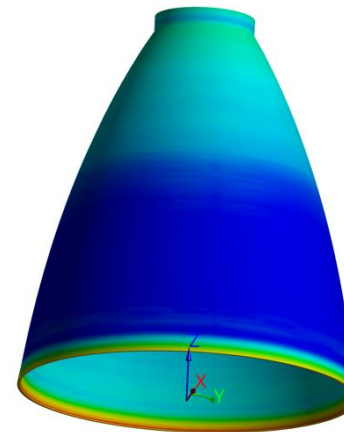
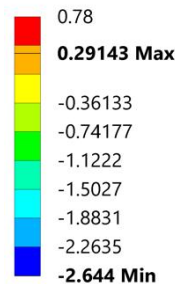


Arc Wire DED (AW-DED)

- 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



Type: Directional Deformation(X Axis)  
Unit: mm  
Coordinate System  
Time: 2.7297e+005

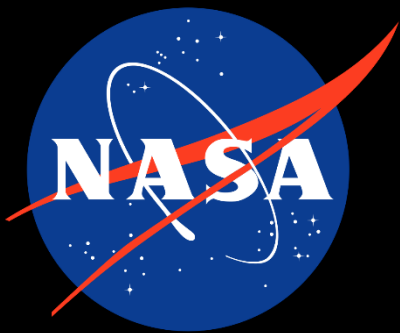




# General Summary



- DED offers a lot of flexibility for large scale and multiple material with the same build for near net shape or final shape applications
- 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
- 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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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)*

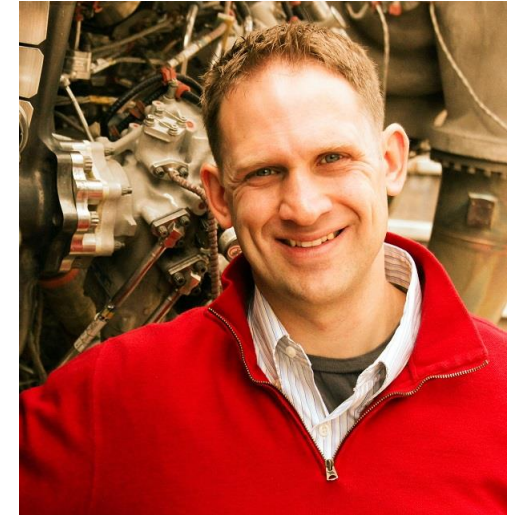


# Presenter Bio



## 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 16 years.
- Authored and co-authored over 45+ 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 as a course instructor and advisory board
- Lead editor of book *Metal Additive Manufacturing for Propulsion Applications* (AIAA, 2021)





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