



CENTER of
EXCELLENCE
Research to Standards

ADDITIVE MANUFACTURING

AM Webinar Series 2020

AM Processes Part 2: Principles of Directed Energy Deposition

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December 8, 2020

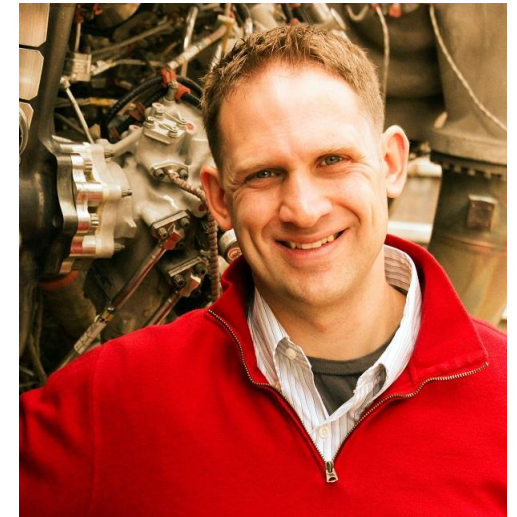


ASTM INTERNATIONAL



Paul Gradl

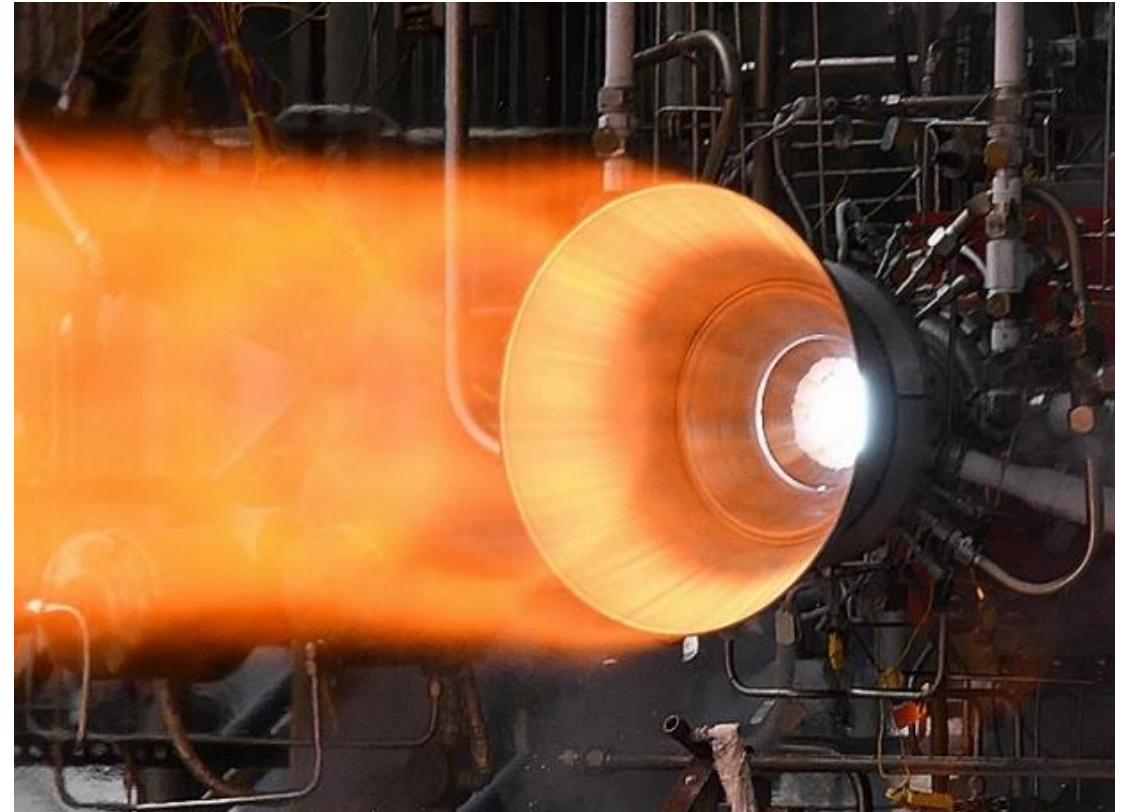
- Senior Propulsion Engineer at NASA Marshall Space Flight Center (MSFC) in the Propulsion Division, Engine Components Development and Technology Branch.
- Principal investigator and lead several projects for additive manufacturing of liquid rocket engine combustion devices and support a variety of development 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)



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 Overviews
- Other Considerations
- Wrap-up



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

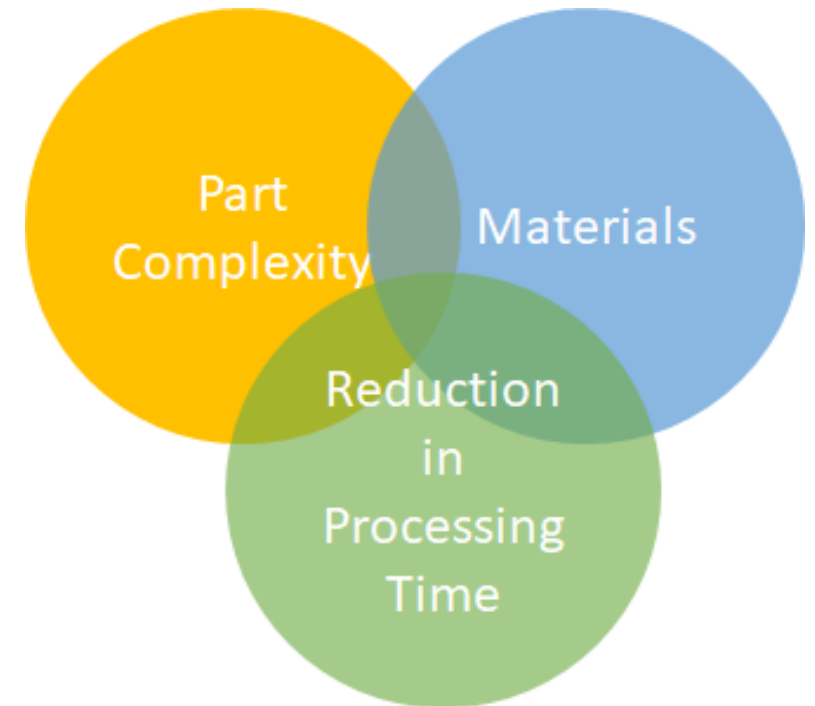
- Course will focus exclusively on metal additive manufacturing
- AM = Additive Manufacturing
- DED = Directed Energy Deposition
- LP-DED = Laser Powder DED
- LW-DED = Laser Wire DED
- AW-DED = Arc Wire DED
- EB-DED = Electron Beam DED
- L-PBF = Laser Powder Bed Fusion

- 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

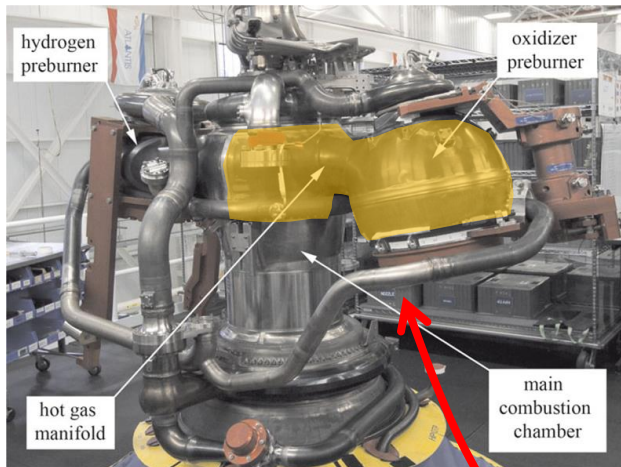


Case Study – RS25 Powerhead



Traditional Manufacturing

Forged => Machined



L-PBF Development



>90 days using L-PBF (Large Platform)

DED Development



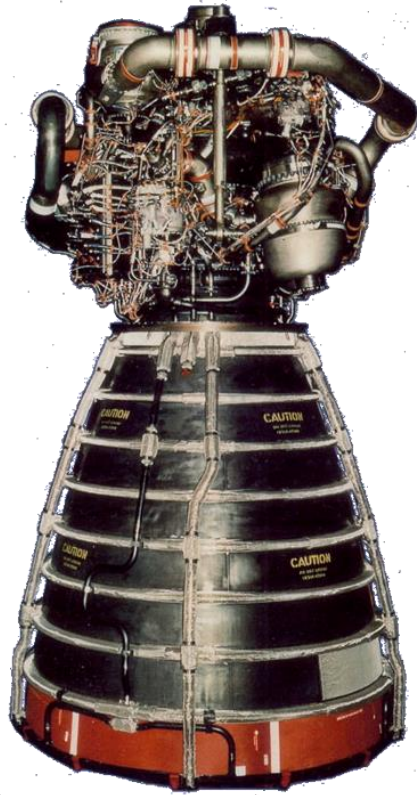
<14 days deposition using LP-DED



The need for large scale AM...



SSME/RS-25



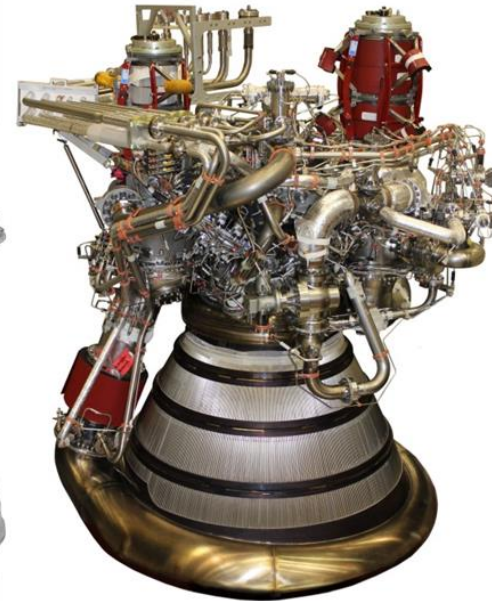
90"

RL-10A-4



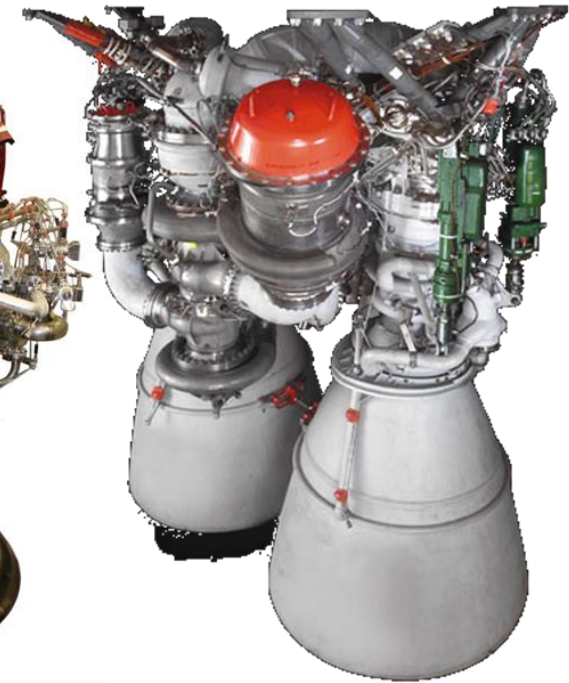
46"

J-2X, Regen Only



70"

RD-180

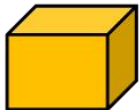


56"

L-PBF Build Boxes



10x10x10

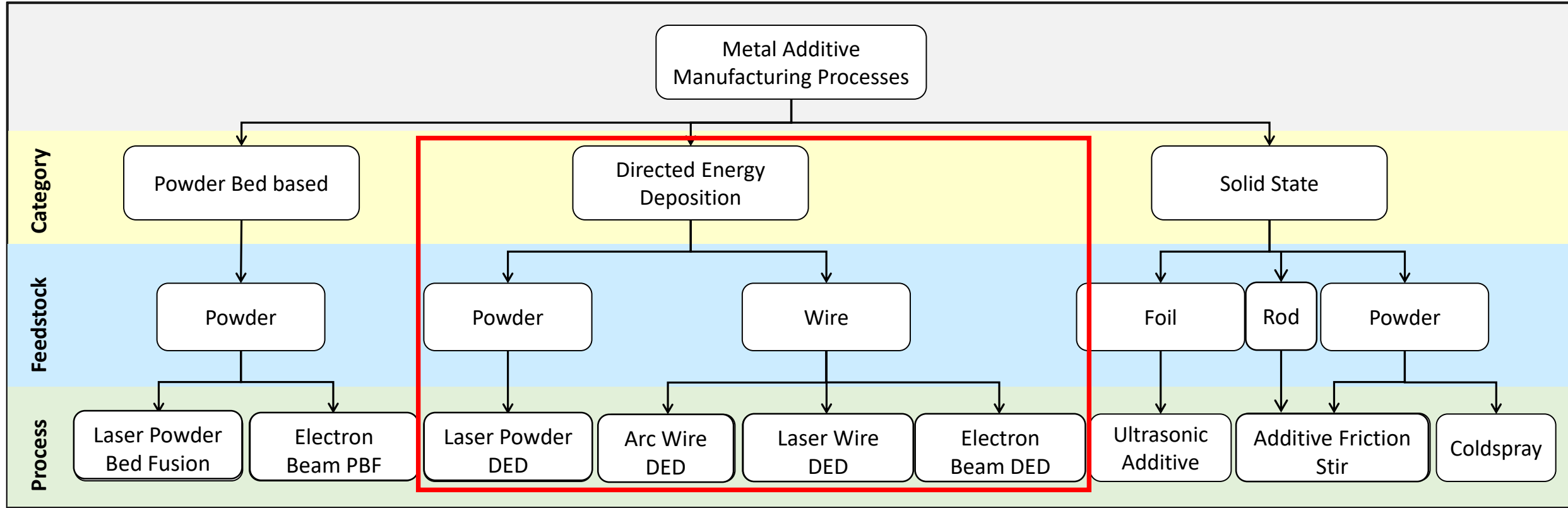


15.5x24x19

(inches)

Nozzle Exit Dia.

Metal AM Technologies - Overview

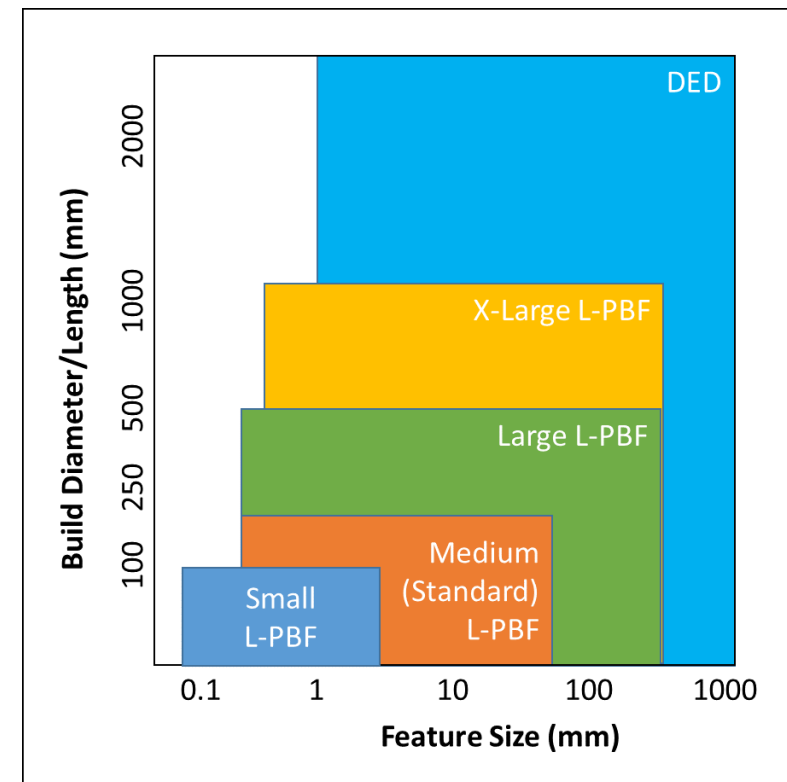
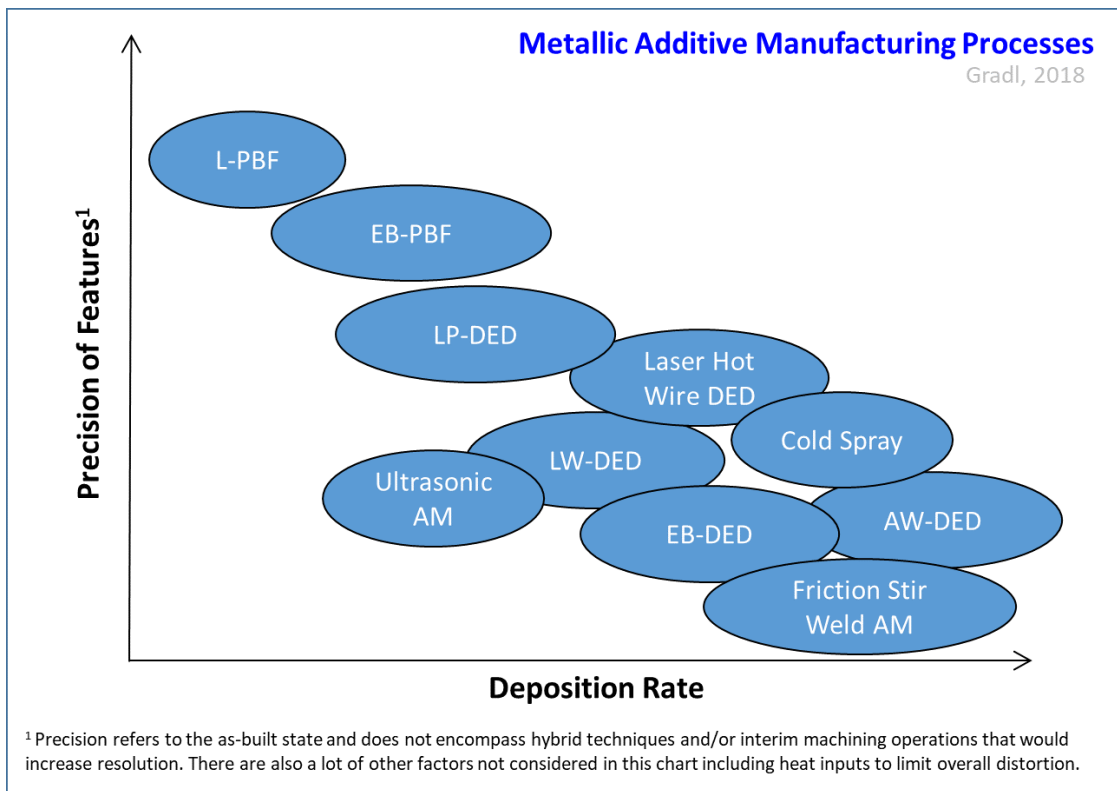


*Does not include all metal AM processes

Based on Ref:

- Gradl, P., Brandsmeier, W., Calvert, M., et al., "Additive Manufacturing Overview: Propulsion Applications, Design for and Lessons Learned. Presentation," M17-6434. 1 December (2017).
- 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



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". 5th International Symposium on High Power Fibre Laser and their Applications/14th 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)

Why DED?



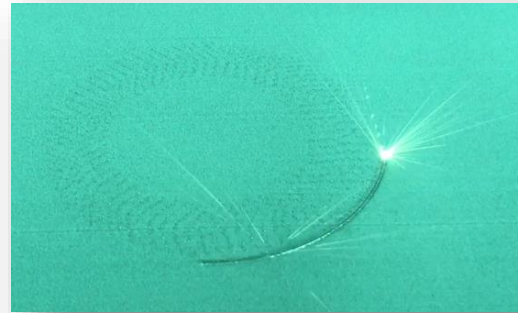
- Each Metal AM technique provides advantages and disadvantages
- DED offers advantages for various applications
 - Large Scale
 - Multi-axis
 - Use wire or powder feedstock
 - Ability to use multiple materials in same build
 - Ability to add material in a secondary operation
 - High deposition rates
 - 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 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
 γ -TiAl
Ti-6-2-4-2

Co-Base

CoCr
Stellite 6,
21, 31

Bimetallic

GRCo-84/IN625
C-18150/IN625

MMC

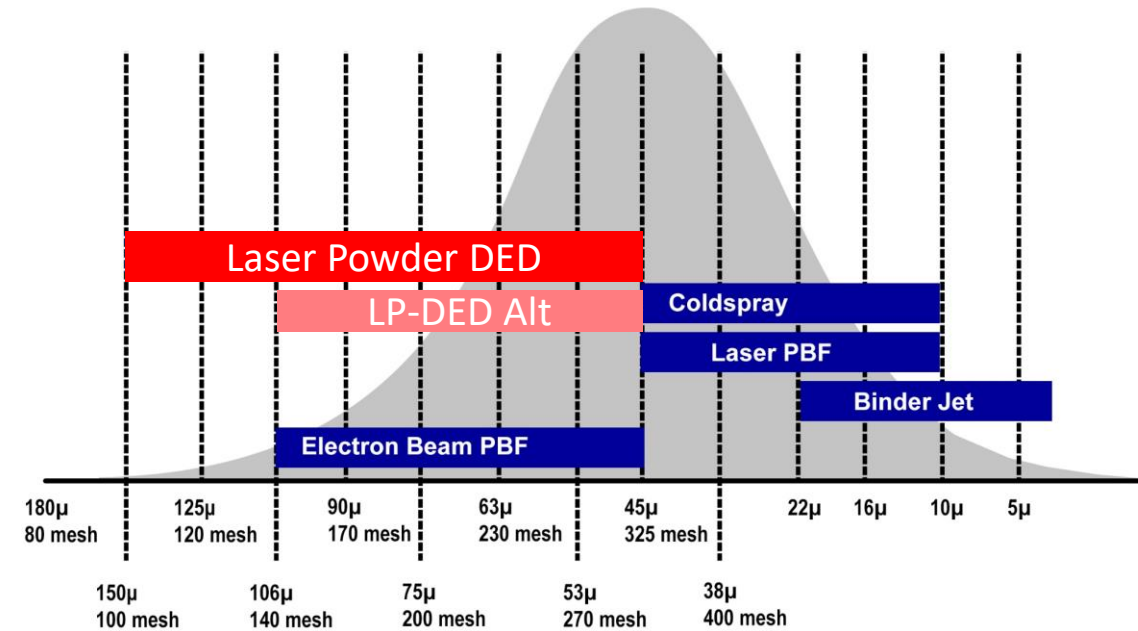
Al-base
Fe-base
Ni-base

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

Feedstock 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

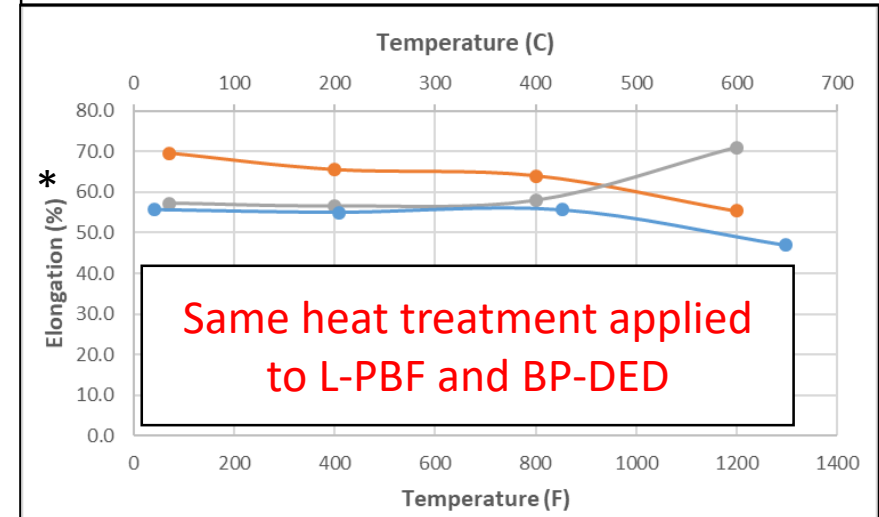
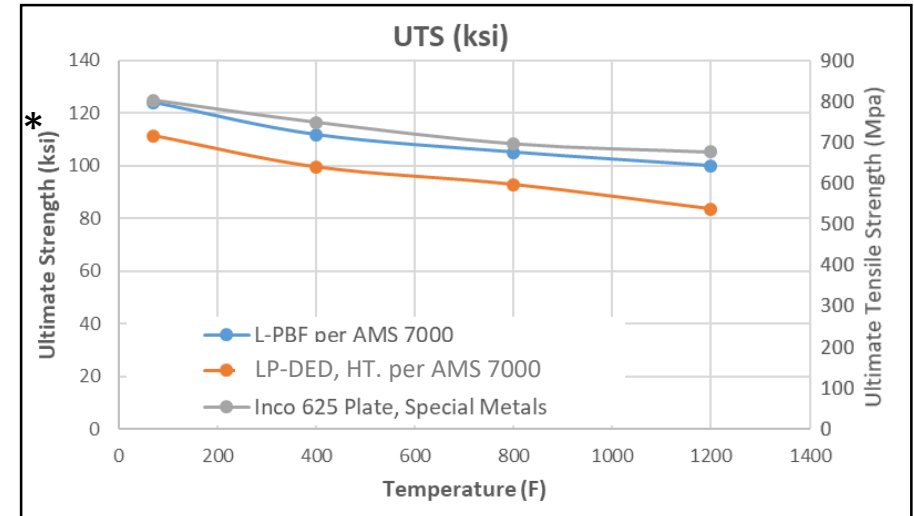


Material Properties for Metal



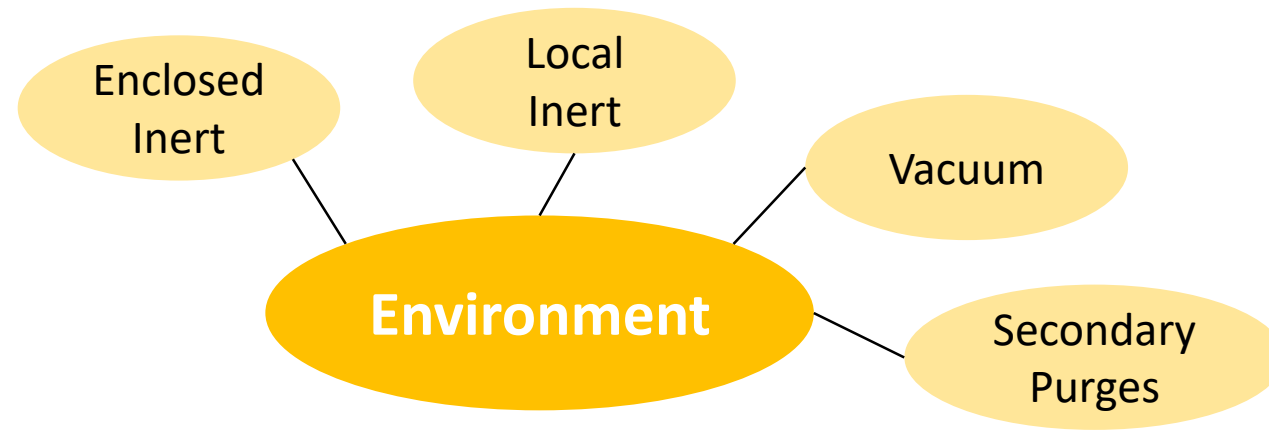
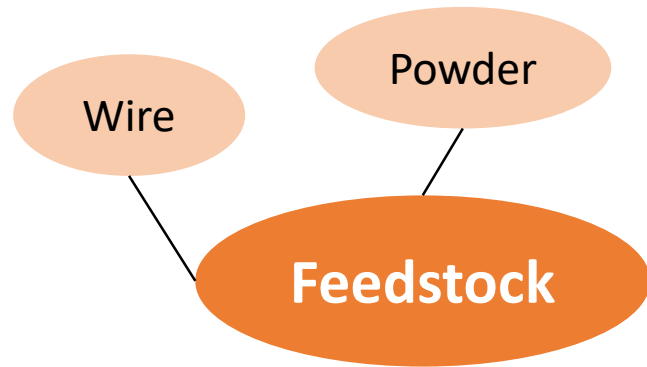
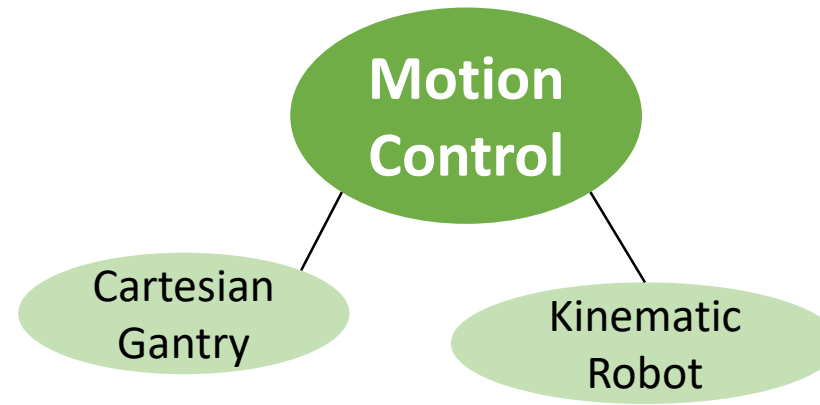
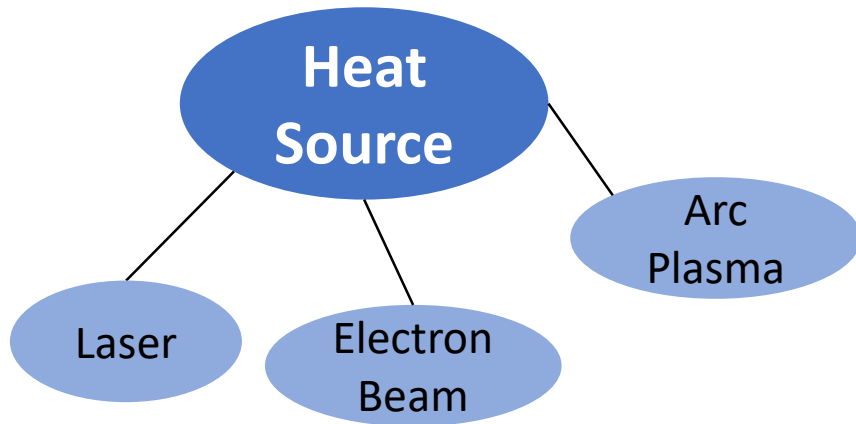
- In general, once AM processes are refined they can yield near wrought properties
- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Coldspray,....), the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build
- 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



Powder or Wire Feeder

Build Plate

Secondary Positioning

Feedback and Monitoring

Post-Processing

Various DED Technologies



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

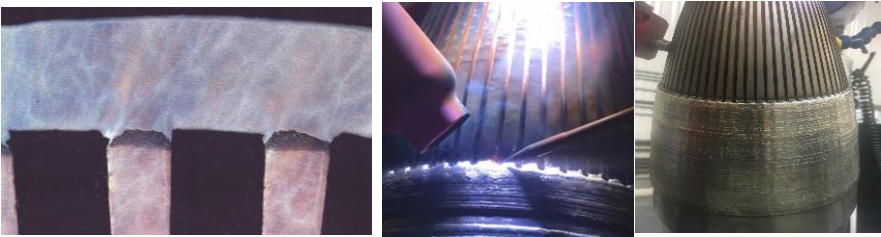
Laser Powder DED (LP-DED)

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



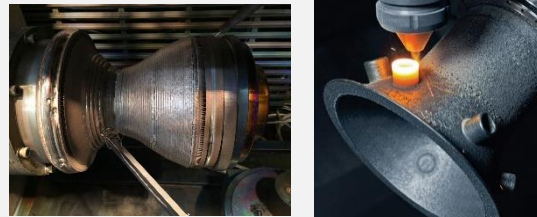
Laser Wire DED (LW-DED) / Hotwire

A melt pool is created by a laser and uses an off-axis wire-fed deposition to create freeform shapes, attached to robot system



Integrated and Hybrid DED

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



NASA L-PBF/DED



*Photos courtesy DMG Mori Seiki and DM3D

Arc Wire DED (AW-DED)

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



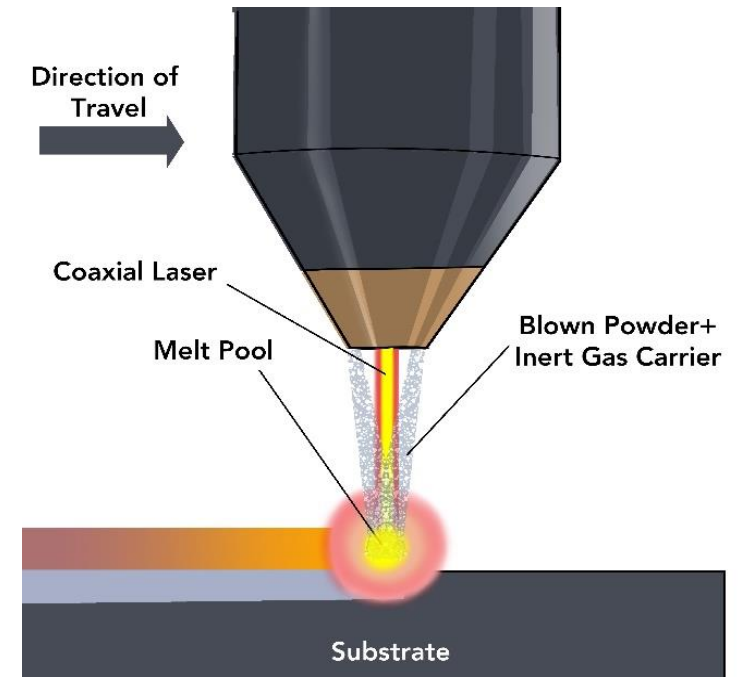
Electron Beam DED (EB-DED)

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



Laser Powder DED

- Coaxial laser energy source with surrounding nozzles that inject powder (within inert gas) fabricating freeform shapes or cladding
- **Advantages:** Large scale (only limited by gantry or robotic system), multi-alloys in same build, high deposition rate
- **Disadvantages:** Resolution of features, rougher surface than L-PBF, higher heat input



DED NASA HR-1 Liner



Integrated Channel DED Nozzle



Inco 718, 1:4 Scale



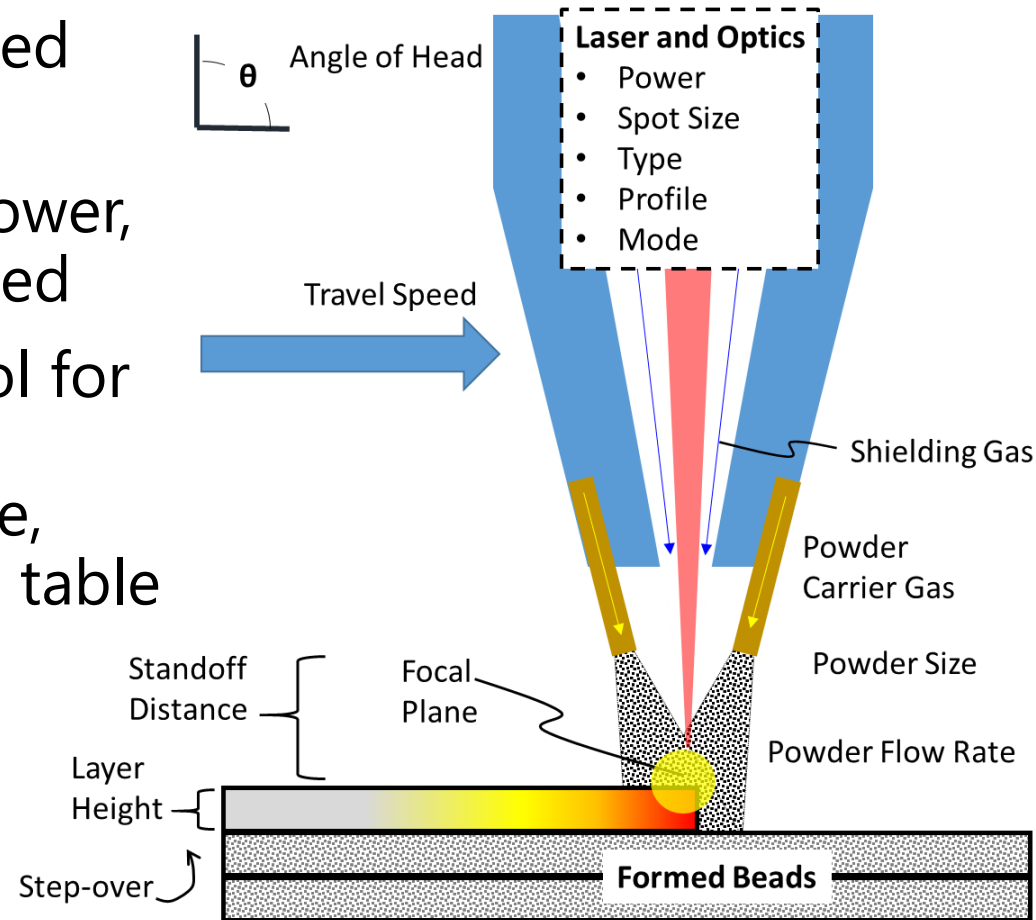
JBK-75, IN625, NASA HR-1 Manifolds



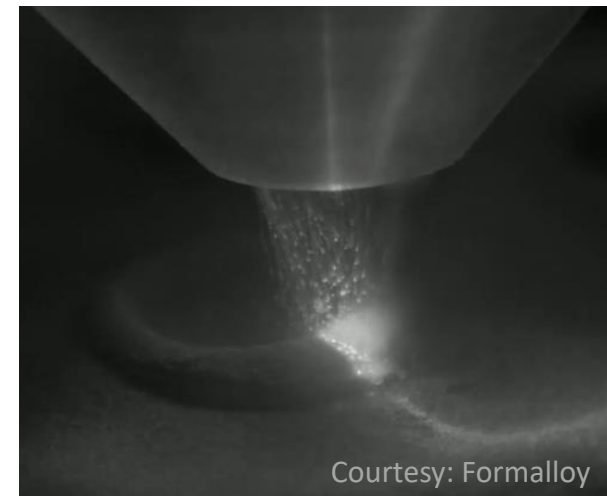
JBK-75 Integrated Channel

LP-DED Process Overview

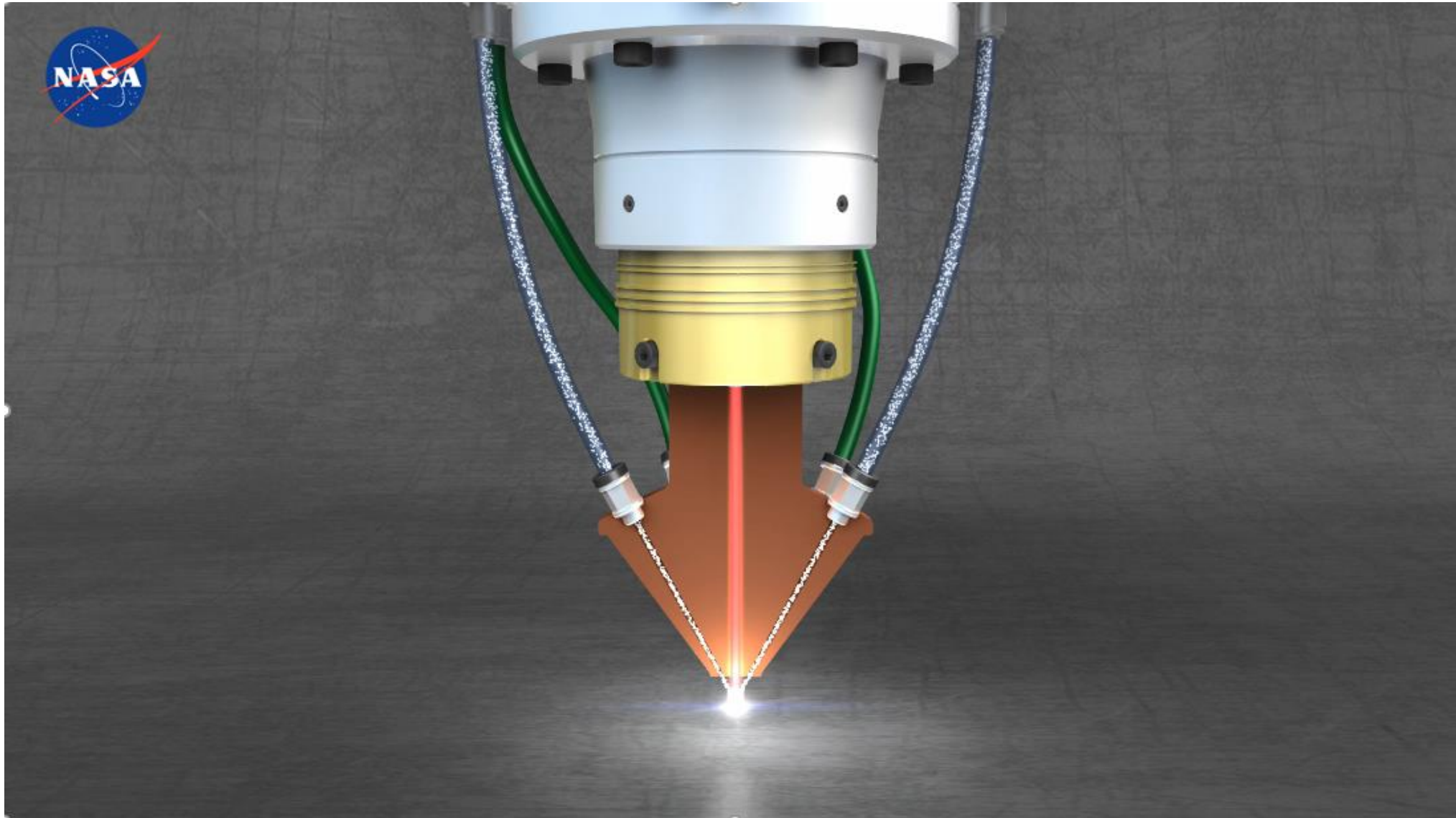
- Powder and laser beam path (sometimes optics) integrated into deposition head
- Basic parameters include power, powder feedrate, travel speed
- Additional geometry control for layer height, step over (hatching), standoff distance, angle of head and trunnion table
- Can vary spot size



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



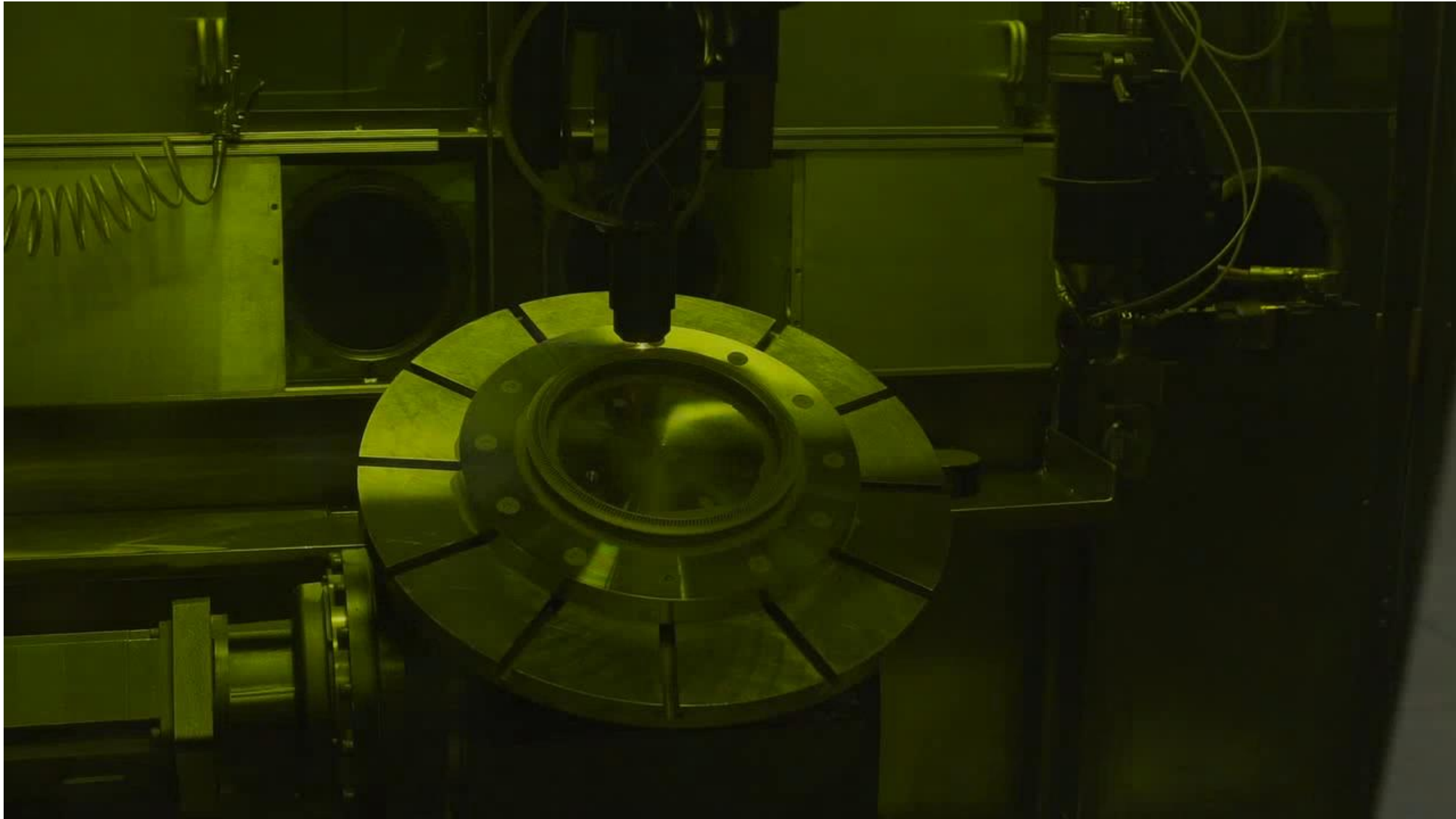
LP-DED Process Cartoon



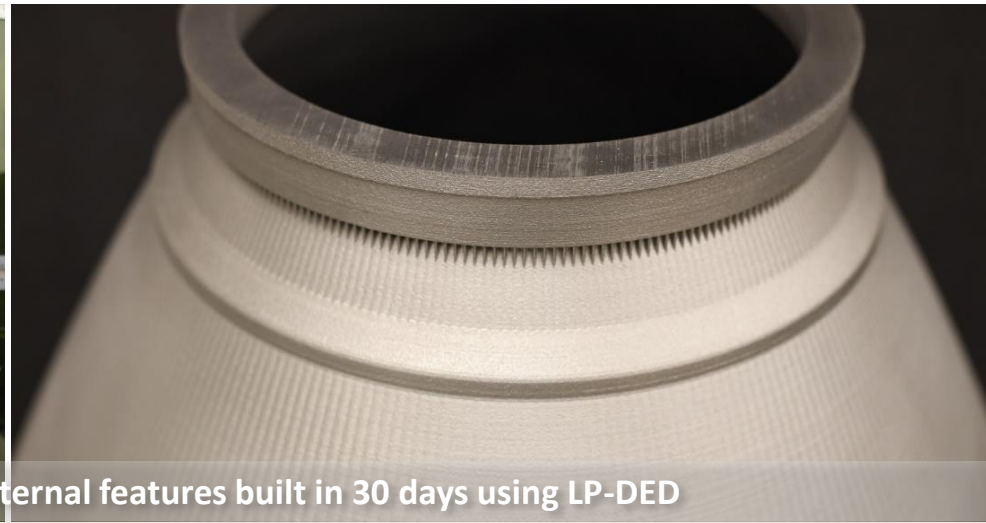
Example of LP-DED for large scale



Example of LP-DED with small features

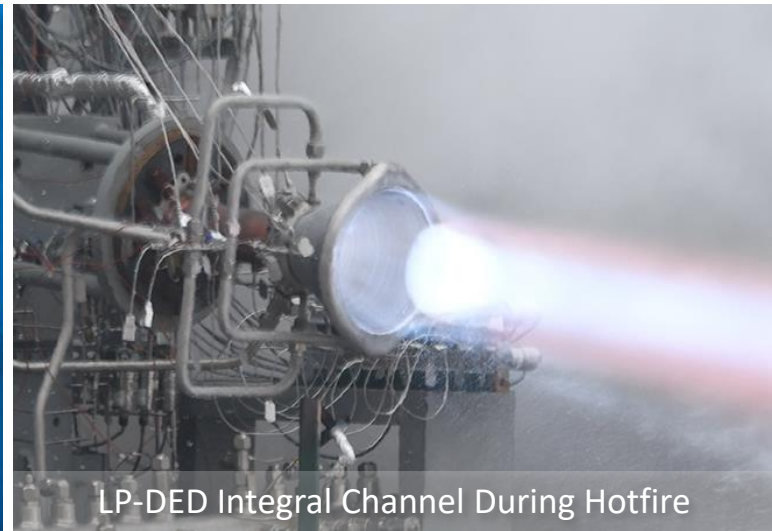


Examples of Small Feature Large Scale LP-DED



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



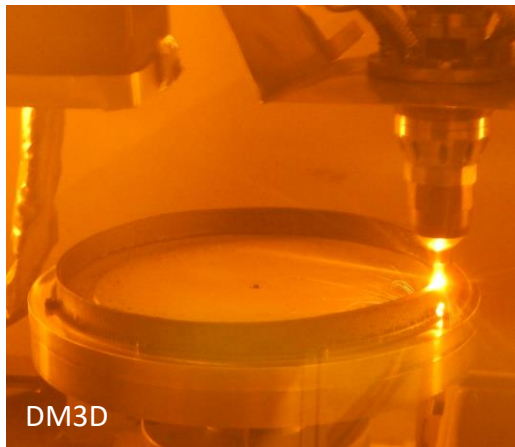
RPMI



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



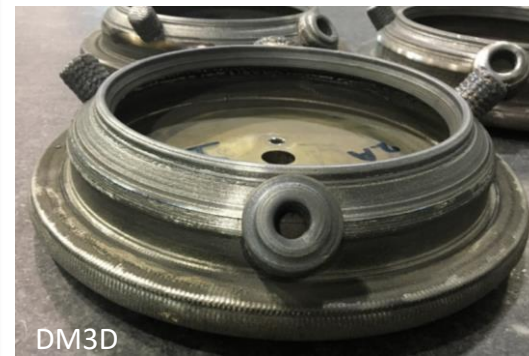
RPMI



DM3D



RPMI



DM3D



RPMI

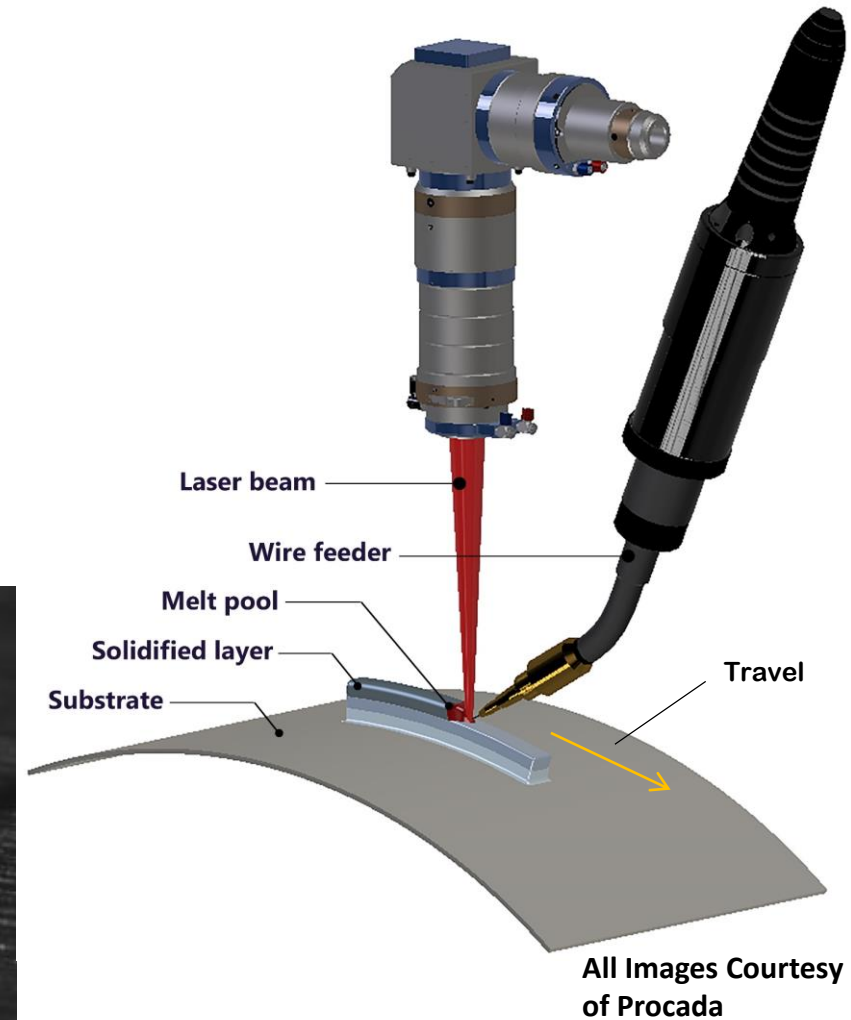
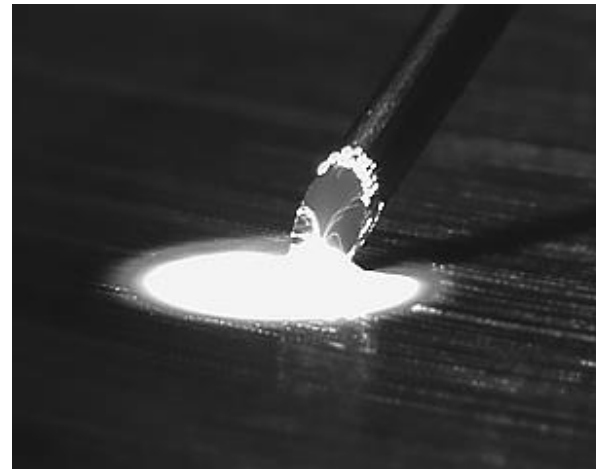
LP-DED Large Scale Nozzle with Fine Features



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

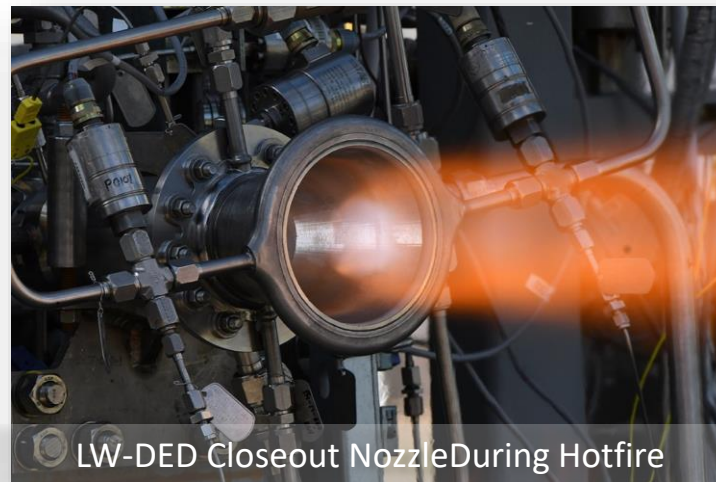
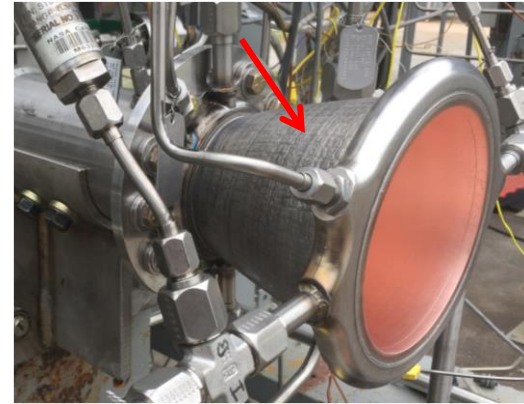
Laser Wire DED

- 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



LW-DED Component Examples

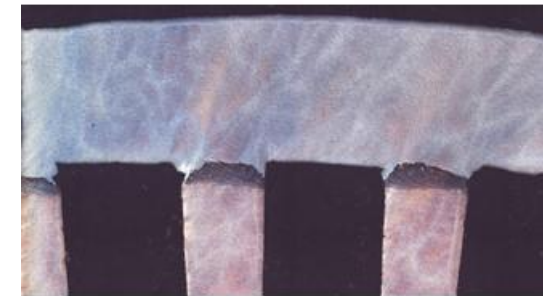
- Used on a variety of components including rocket nozzles
- Add secondary material "in-place" or freeform deposition
- Multi-alloys demonstrated



LW-DED Closeout Nozzle During Hotfire

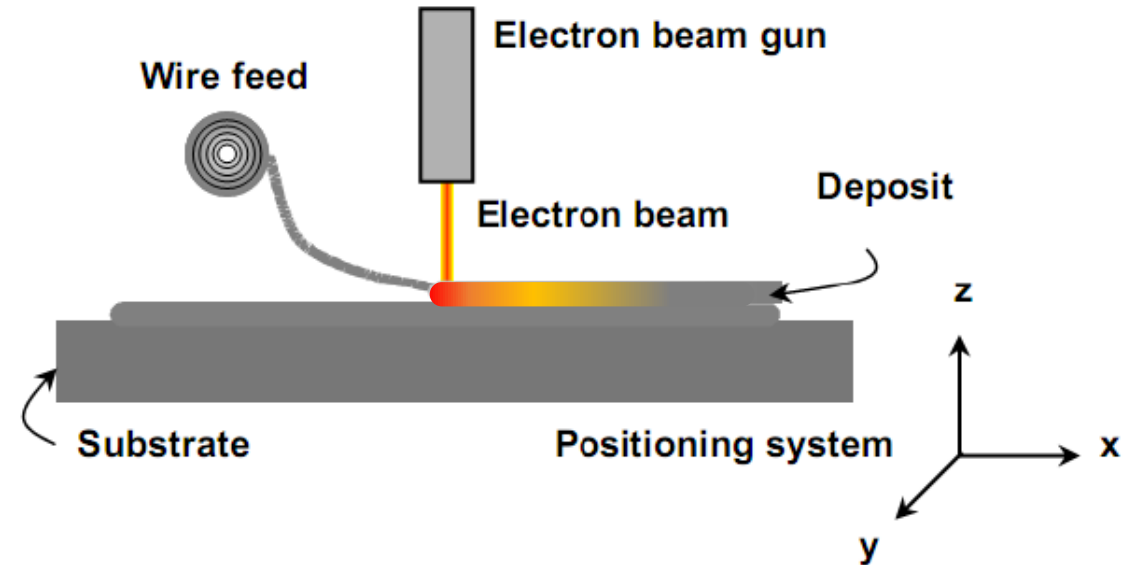


LW-DED using multi-alloys



Electron Beam DED

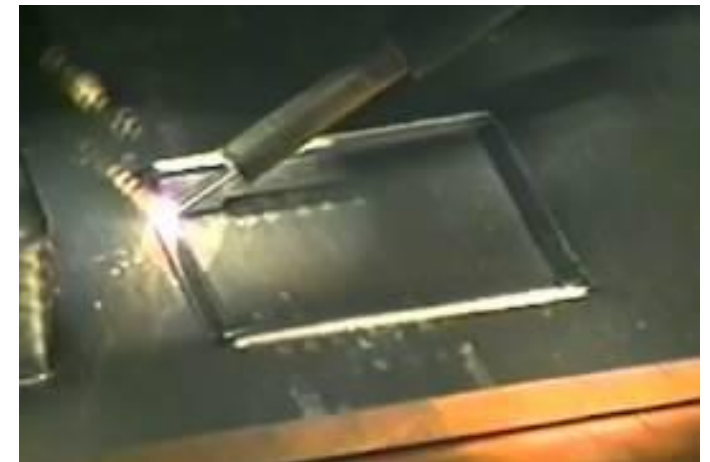
- Uses electron beam energy source with a wire feed inside vacuum chamber
- 100% efficiency in material usage
- High deposition rates
- Key parameters: Beam current and acceleration voltage, Wire Feedrate, Travel Rate, Angle of Turntable



Monolithic EB-DED Freeform

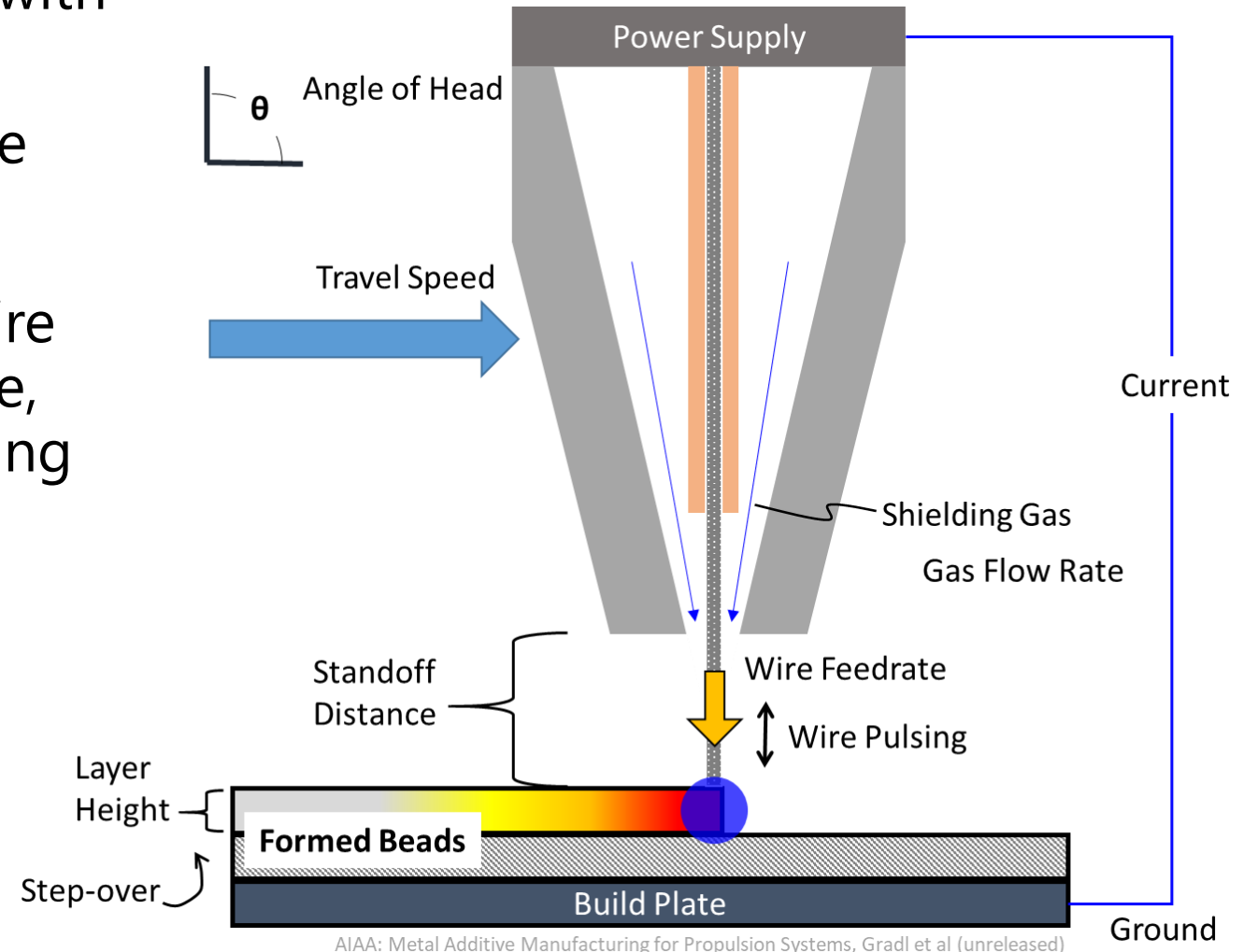


EB-DED Inco 625 Jacket on L-PBF GRCop-84 Liner



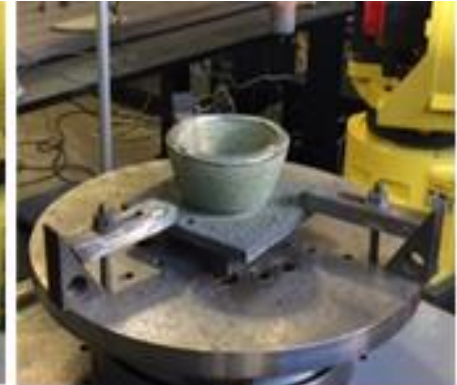
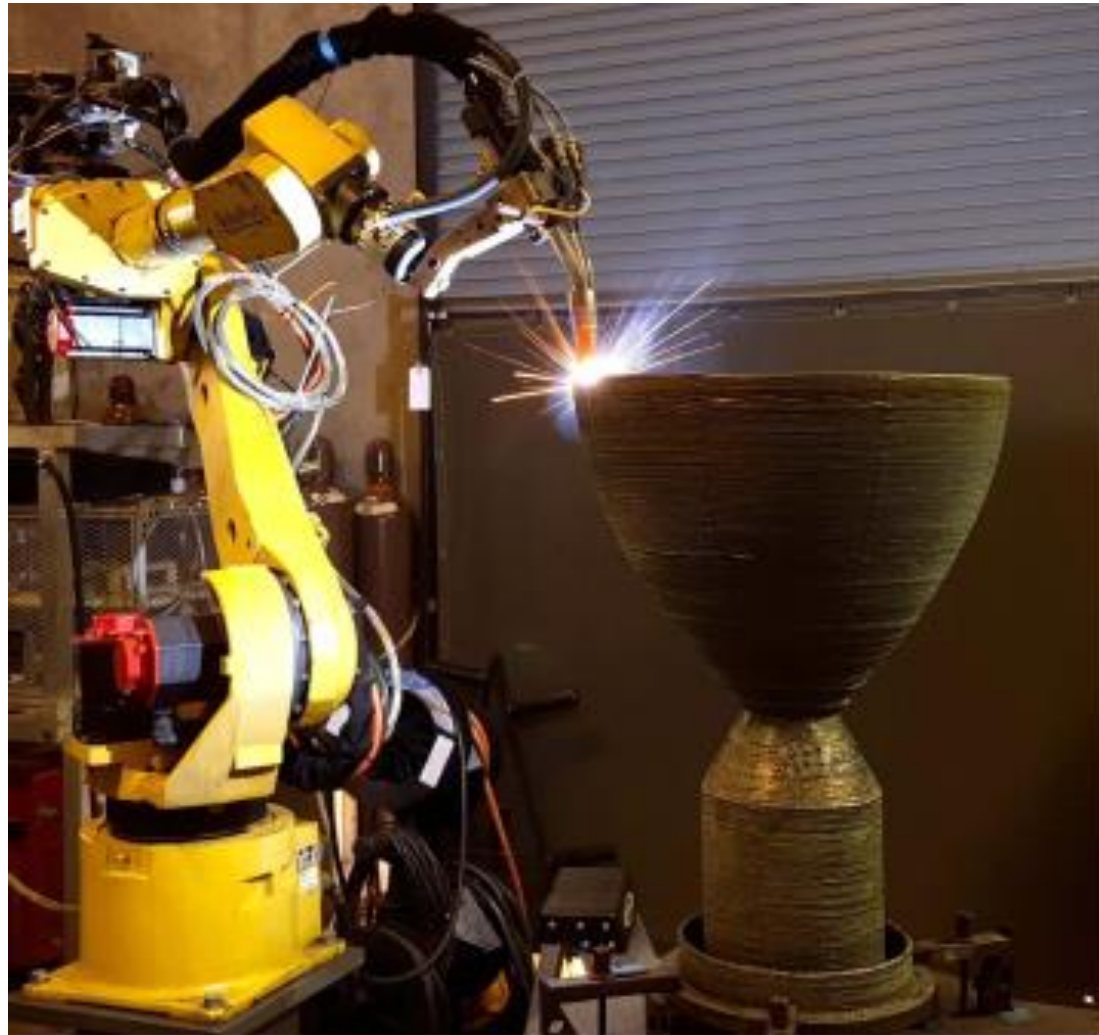
Arc Wire DED

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



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

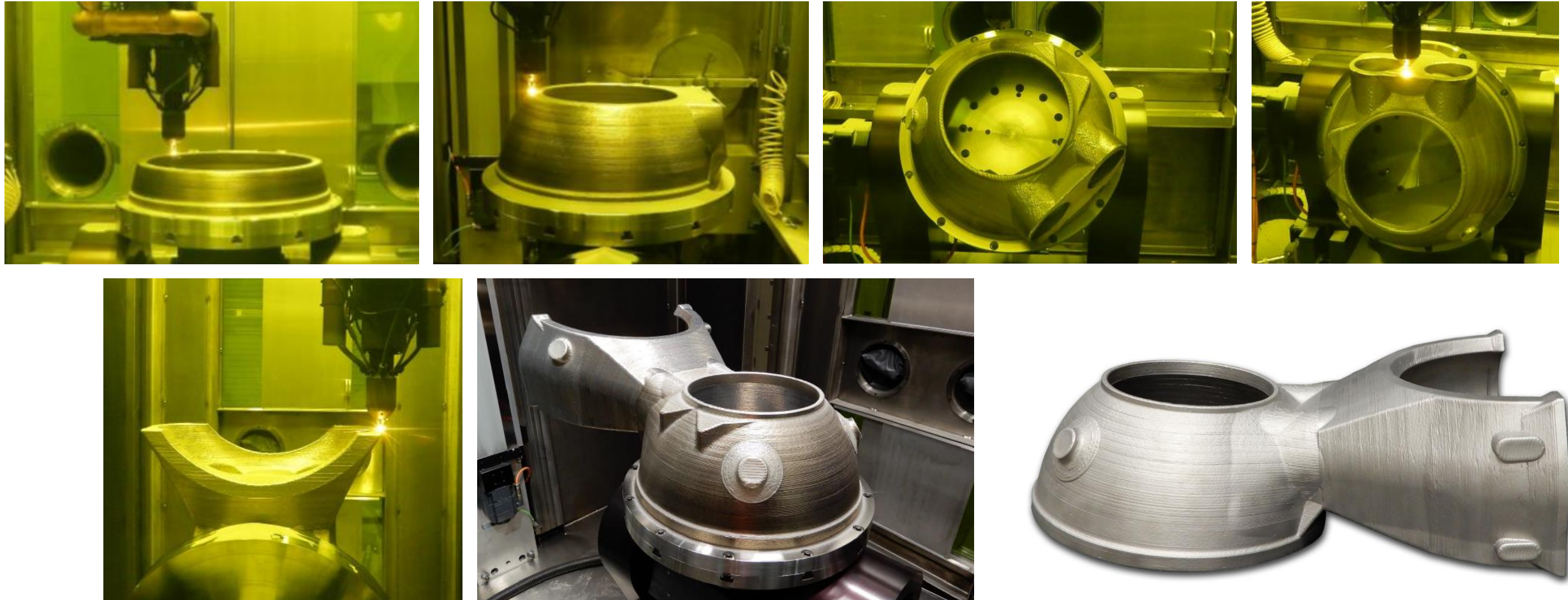
Arc Wire DED



Courtesy: Keystone

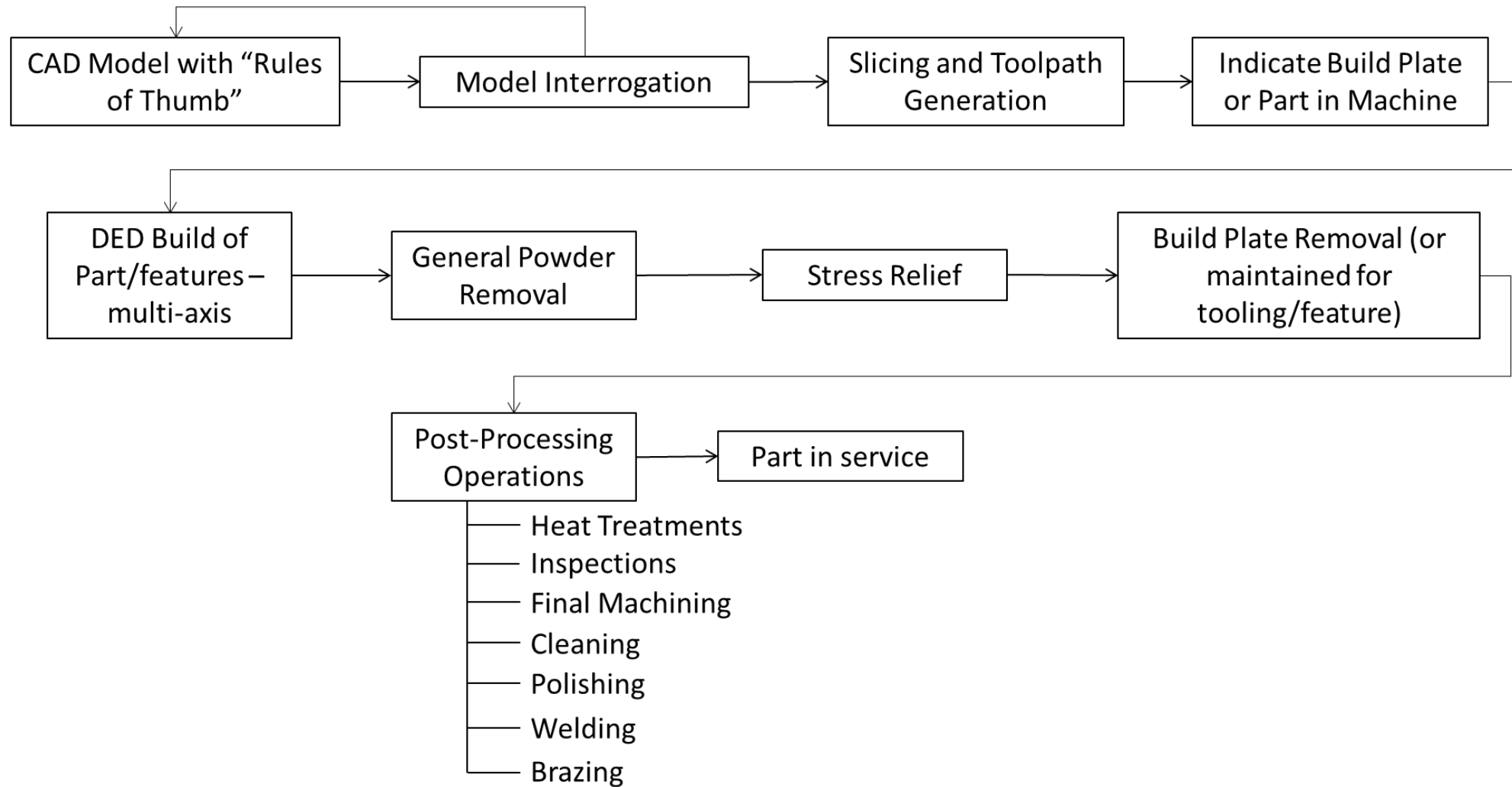
Freedom in DED design and deposition strategies

Ability to use multiple axes for complex features fabricated locally



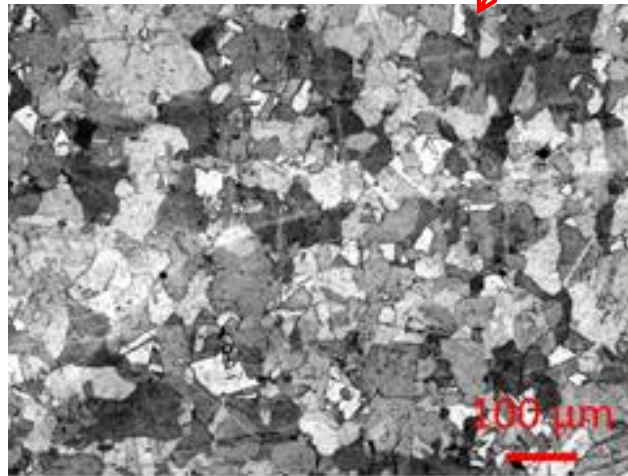
RS25 Powerhead demonstrator using LP-DED under NASA SLS Artemis Program (Courtesy: RPMI)

Typical DED Process Flow



Microstructure – Different AM Processes

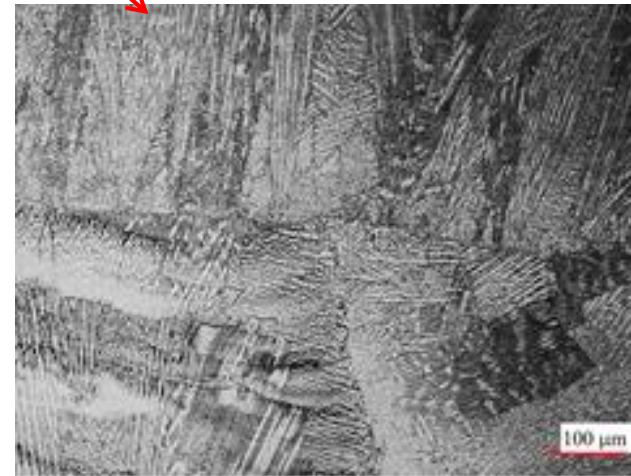
Inconel 718



Laser Powder Bed Fusion (L-PBF)



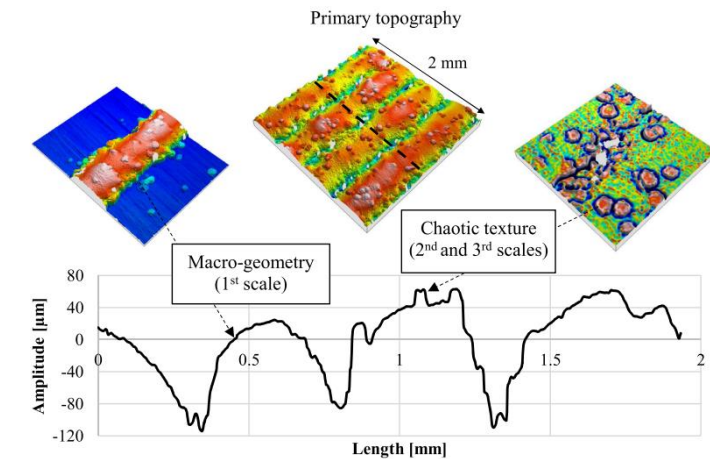
Laser Powder DED (LP-DED)



Arc Wire DED (AW-DED)

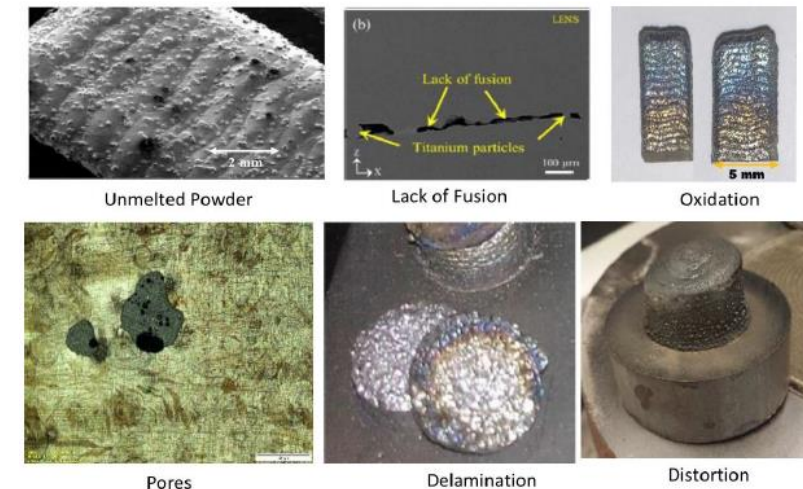
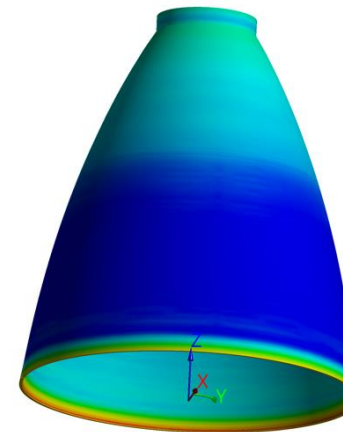
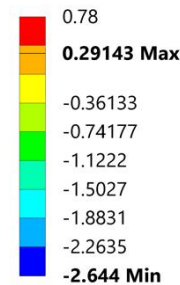
Challenges with DED

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



Surface Roughness

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



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)*

- 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



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Research to Standards

ADDITIVE MANUFACTURING

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