Making & Breaking the Rules for DED Design

Paul Gradl
NASA Marshall Space Flight Center

Laura Ely
The Barnes Global Advisors

October 31, 2022 / ASTM ICAM 2022

Selecting the correct building block

Small

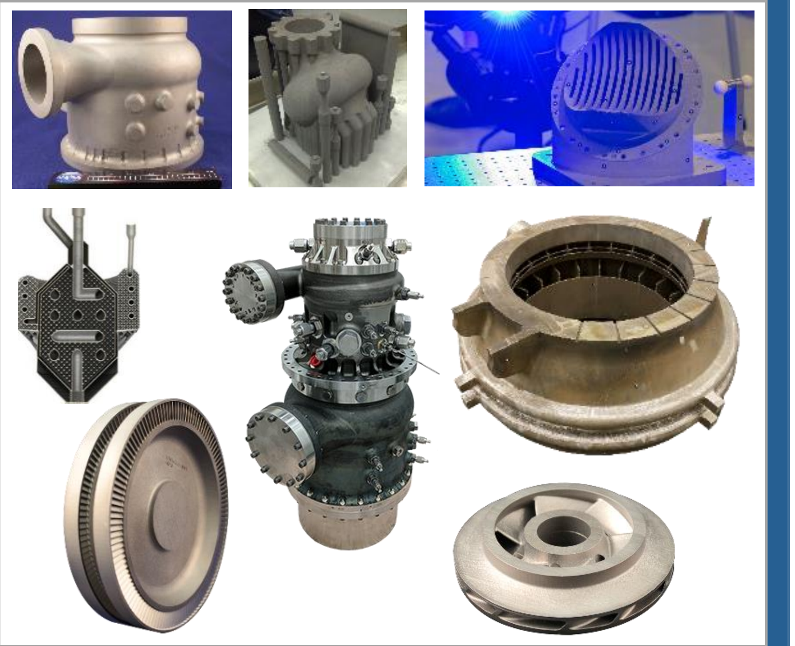
Medium

Large

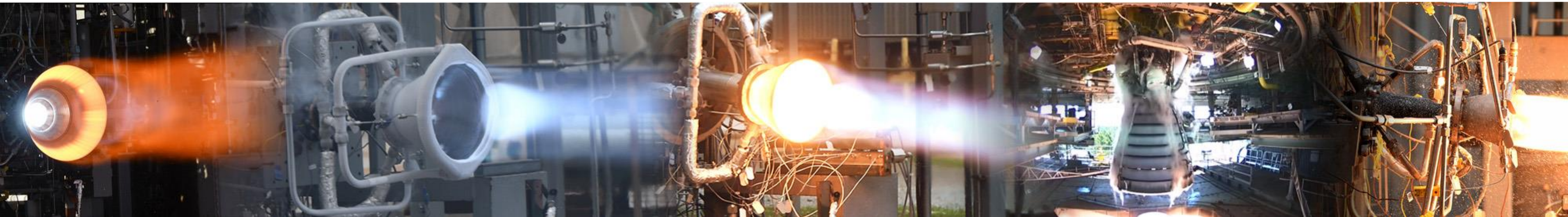
AM at NASA for Rocket Engine Applications

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

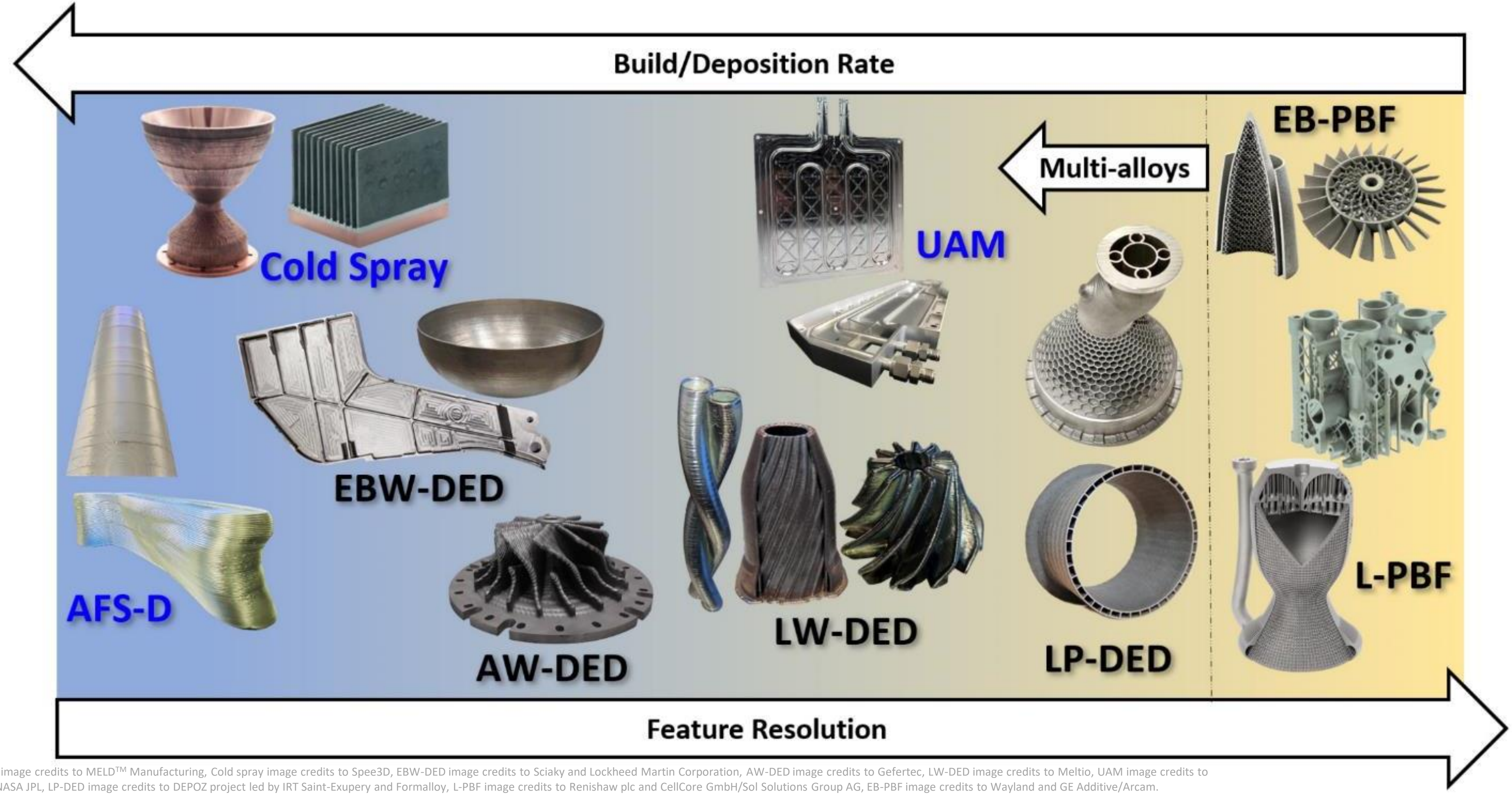
Directed Energy Deposition



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



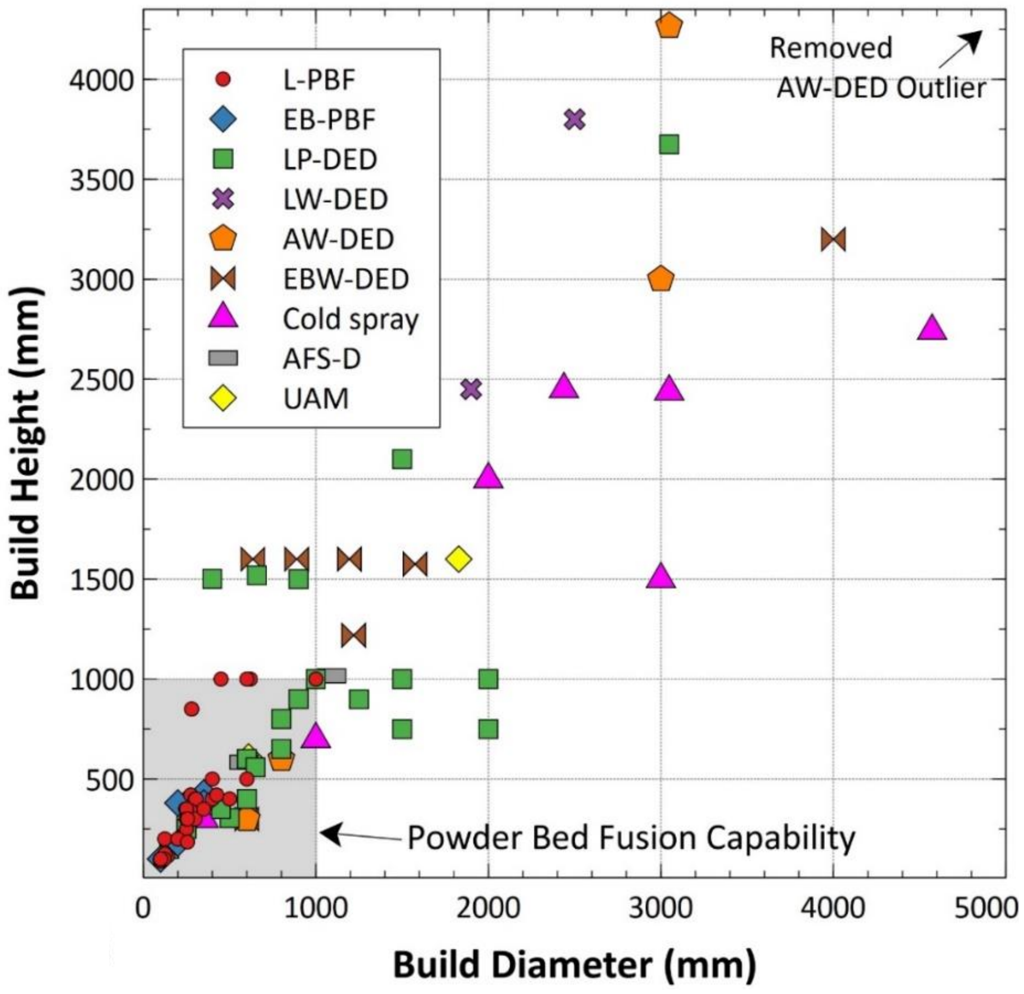
Criteria and Comparison Various Metal AM Processes



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.

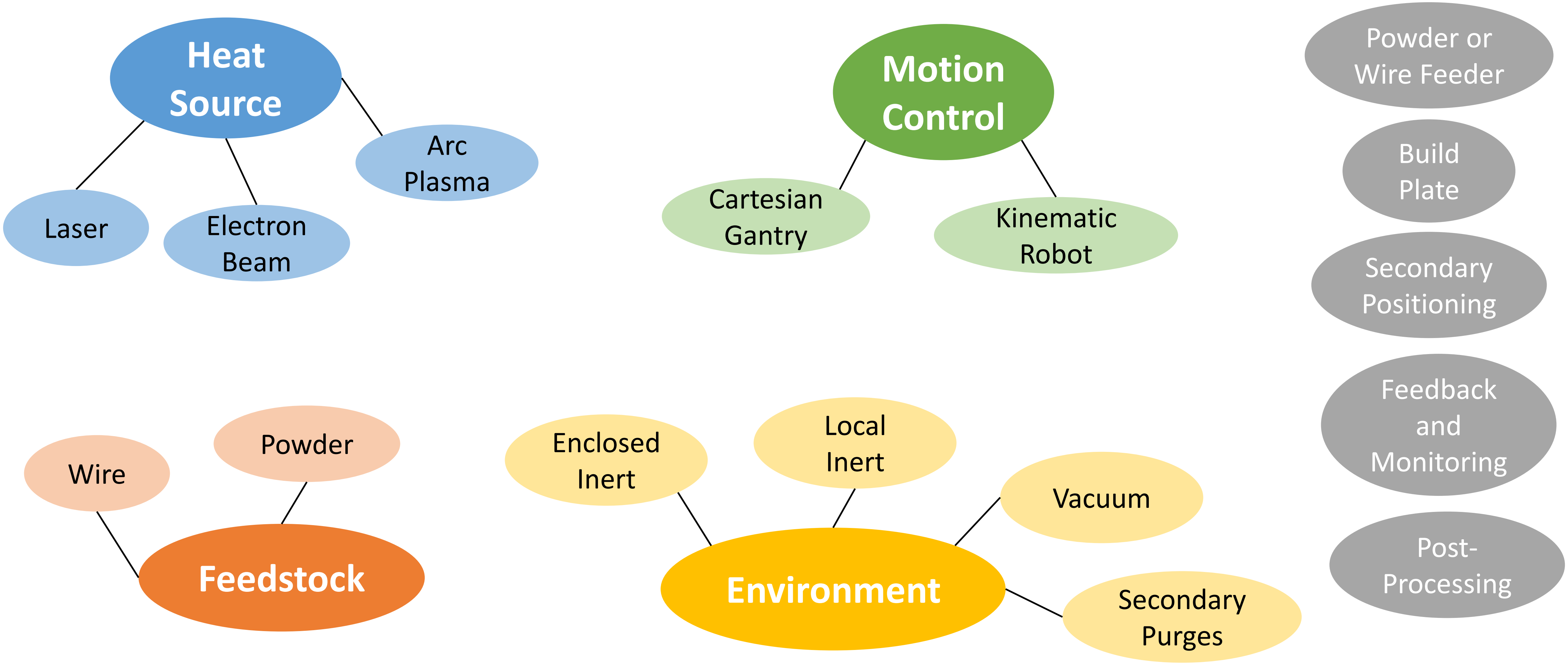
Why Directed Energy Deposition (DED)?

- DED offers advantages for various applications
  - Large Scale
  - Multi-axis build strategy
  - 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



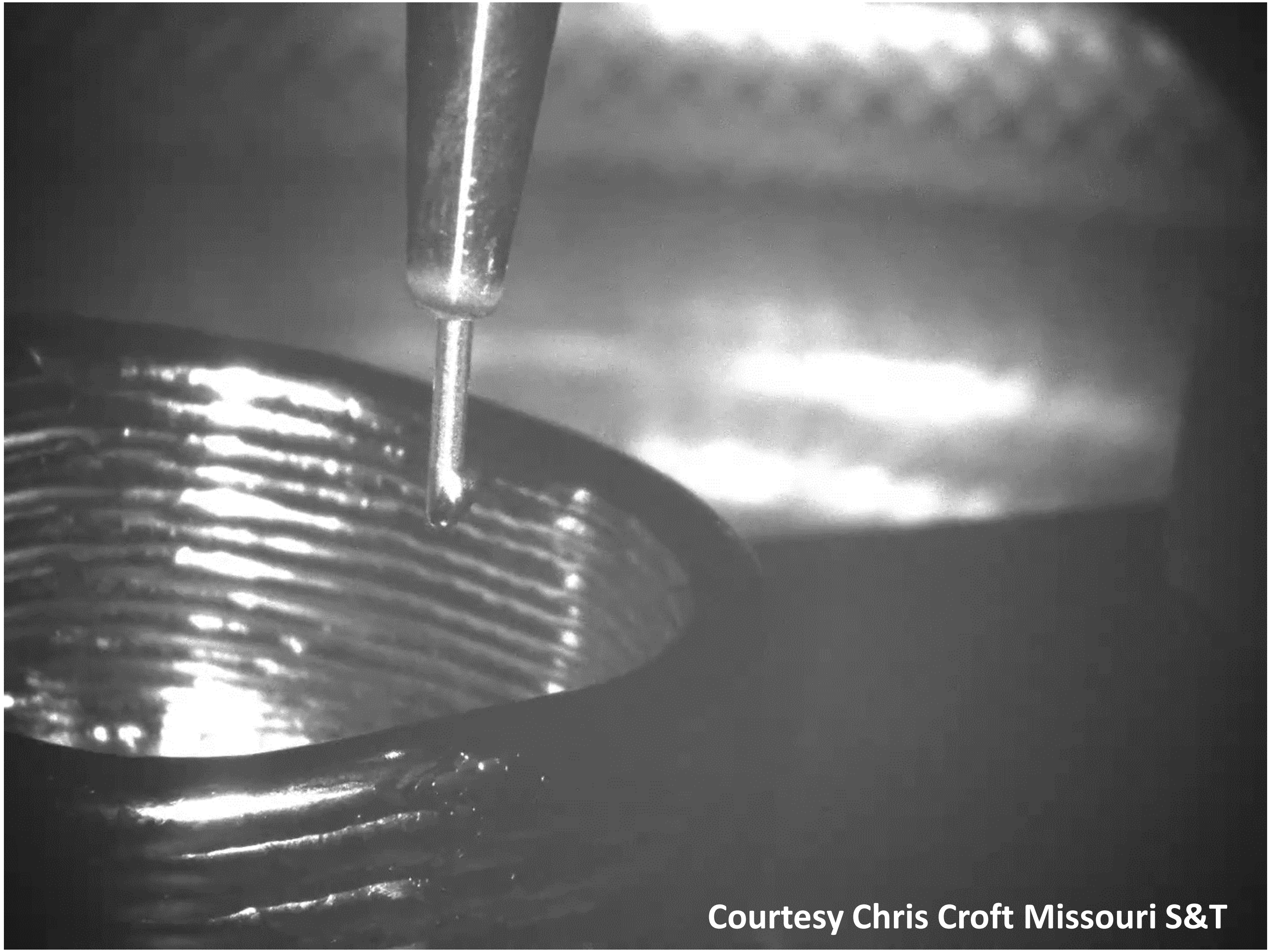
Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

Aspects of AM DED Systems

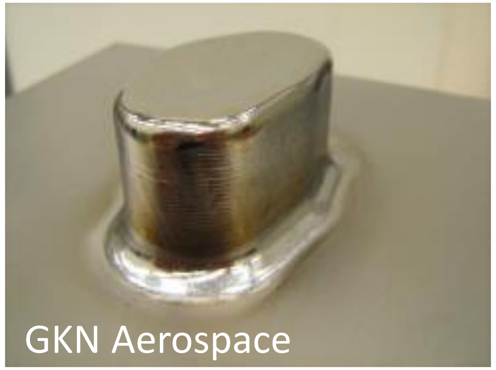


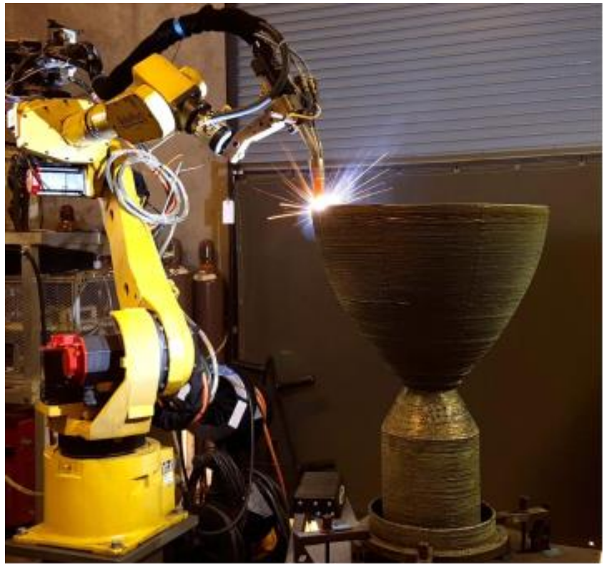
Laser Powder DED

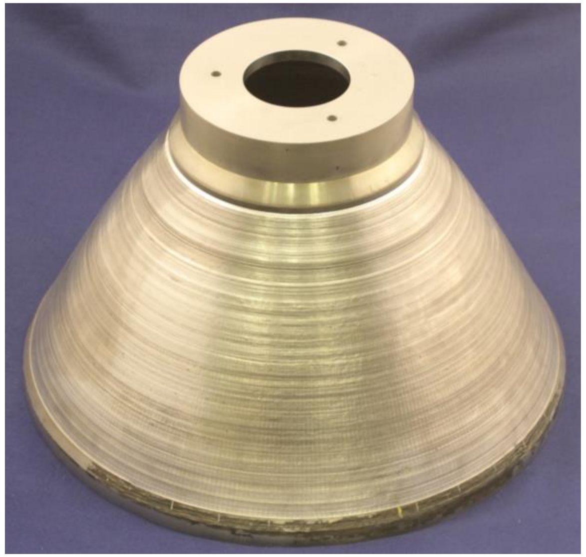
Laser Wire DED



Huge Variety of Geometries


GKN Aerospace






DM3D


RPMI


RPMI

Design for DED Considerations

Substrate
- Size, Material, Temper
- Integral or Sacrificial?

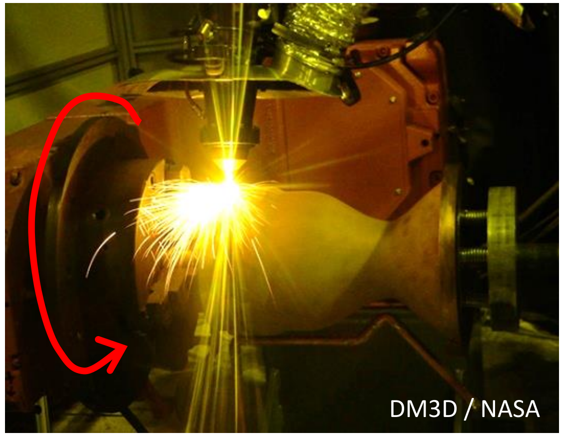
Material
- Chemistry and form
- Material feedstock effect on surface finish

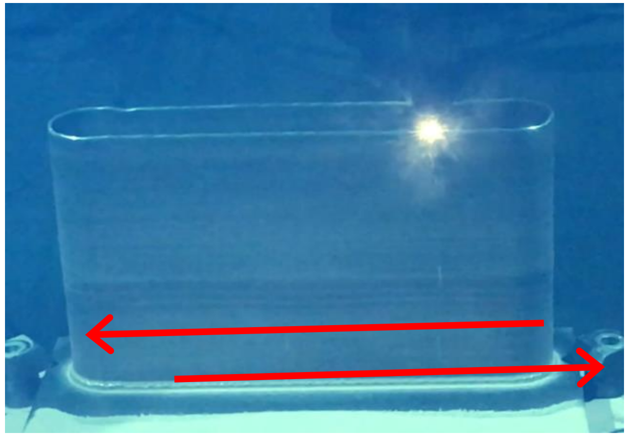
Deposition Strategy and Parameters
- Melt pool size and bead width/height
- Motion platform degrees of freedom and self-supporting angles
- Start / Stop / Transition locations and impact on properties

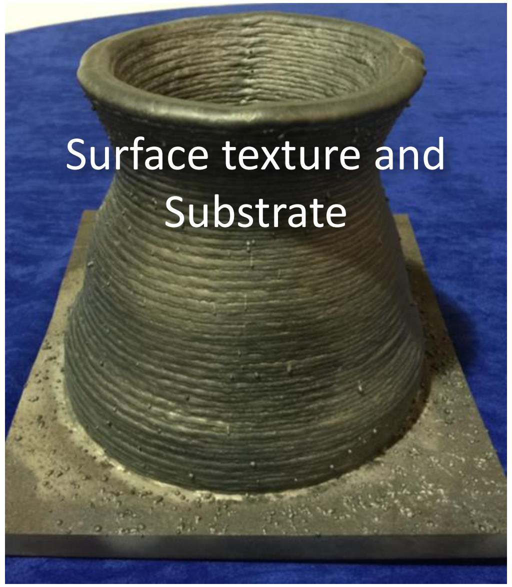
Machining
- Fixturing and datum locations

Inspection
- Surface interface with NDE and/or geometry compatibility

Example: Deposition Strategies


DM3D / NASA

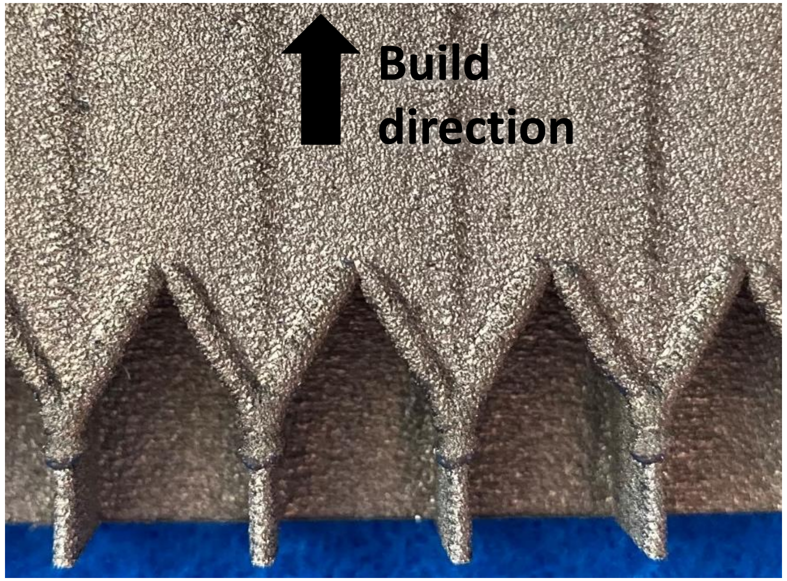




Keystone / NASA

Wall Thicknesses and Geometry Limitations

- Wall thicknesses of 1 mm are easily accomplished with LP-DED and LW-DED
- Thinner walls possible, but build angles severely limited and deposition rate reduces significantly
- Internal and complex features are feasible, but within build angle confines
  - Build angles are dependent on the build strategy – continuous motion; 3-axis, other
  - All features in 3D space must be considered including intersecting compound angles
- “Solid” support structures are used – small lattices not possible



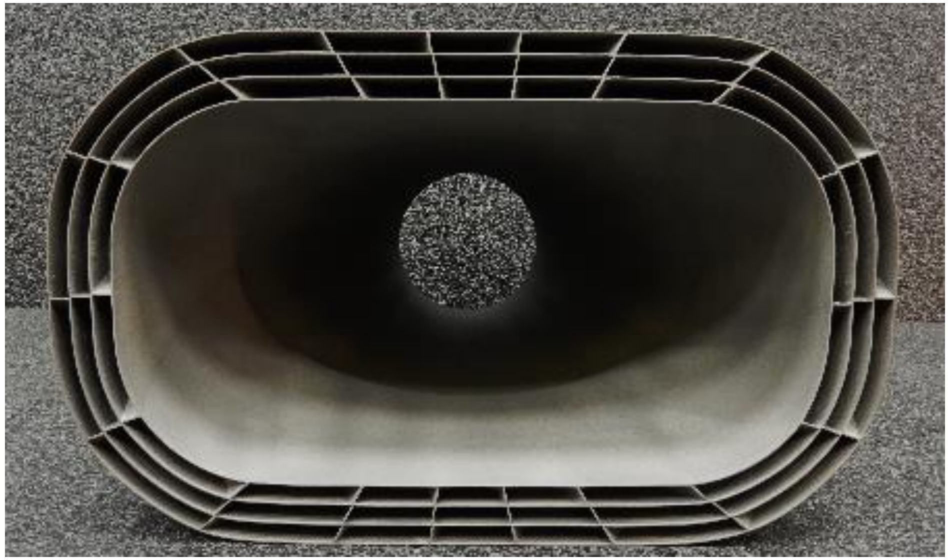


*Image courtesy of RPMI

Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

LP-DED Large Scale Nozzles

60" (1.52 m) diameter and 70" (1.78 m) height; thin-wall with <u>integral channels</u>
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.

Laser Wire DED for Large Aerostructures

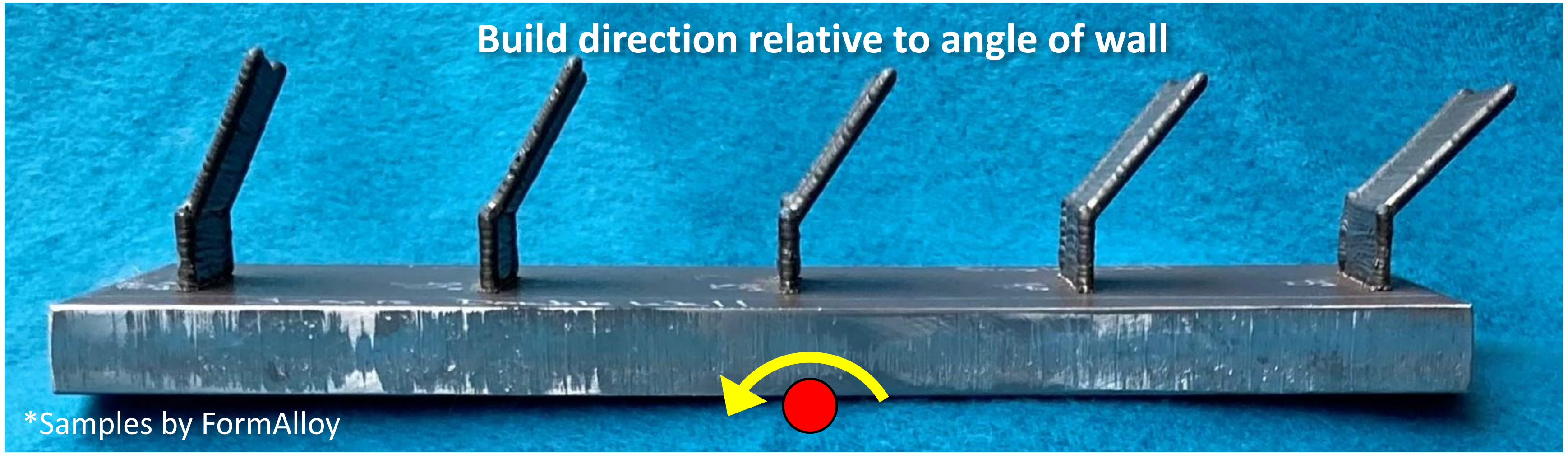
Courtesy: GKN Aerospace

Large Melt Pool LW-DED Example

- Bead width of ~10-15mm is common and is tailorable for Laser Wire DED
- Deposited wall thicknesses dependent on single or multi-bead approach
- Build strategy – Deposit features onto a flat substrate (plate or forged billet)
- Self supporting angles are possible but simpler approach is straight walls; avoid build complexity when not necessary

<u>The key is to Optimize Preform Design for Machining & Inspection</u>

Build Angles depend on strategy



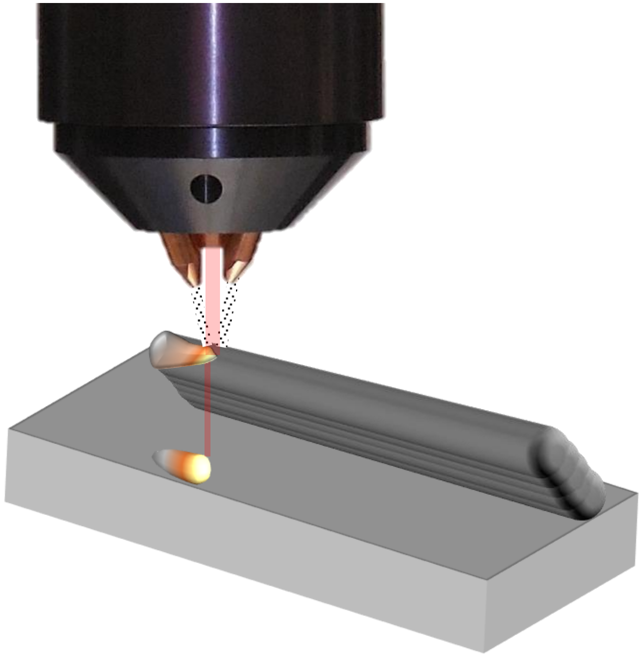


*Image courtesy of RPMI

Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

Freedom in DED design and deposition strategies

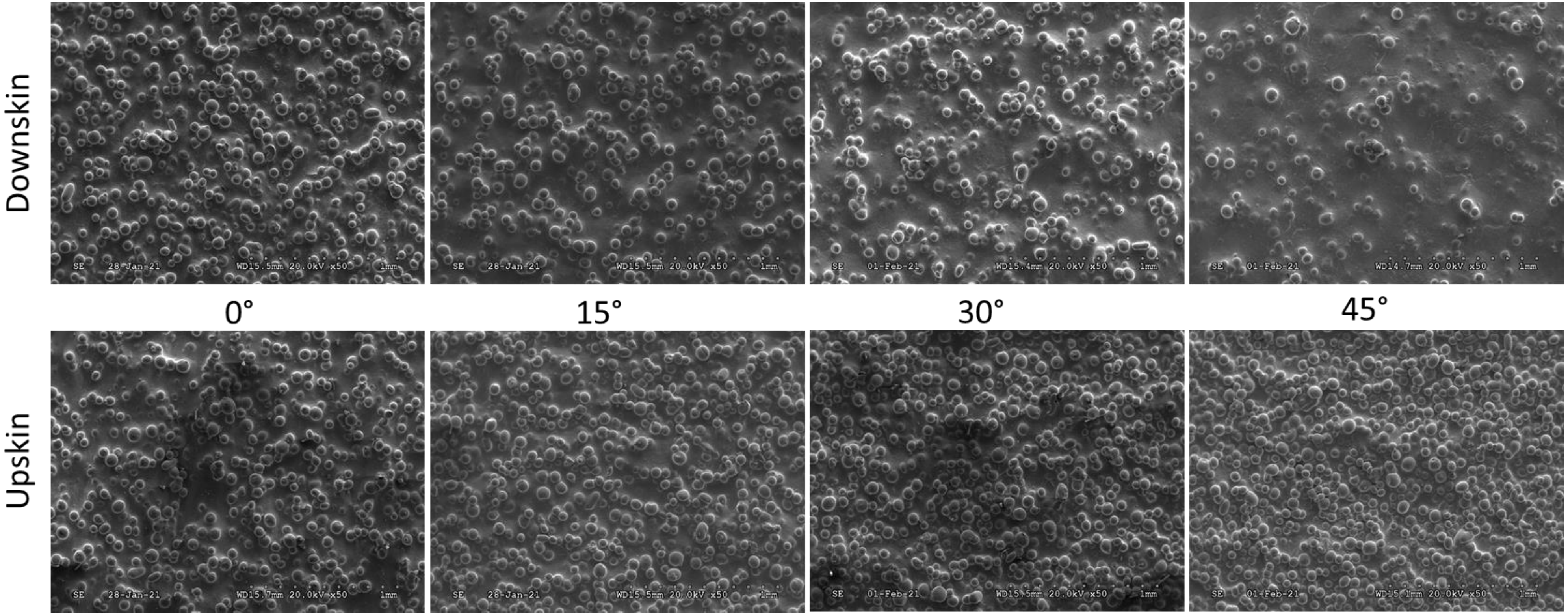
Ability to use multiple axes for complex features fabricated locally

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

Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

Example of Angle Influence on Texture for LP-DED

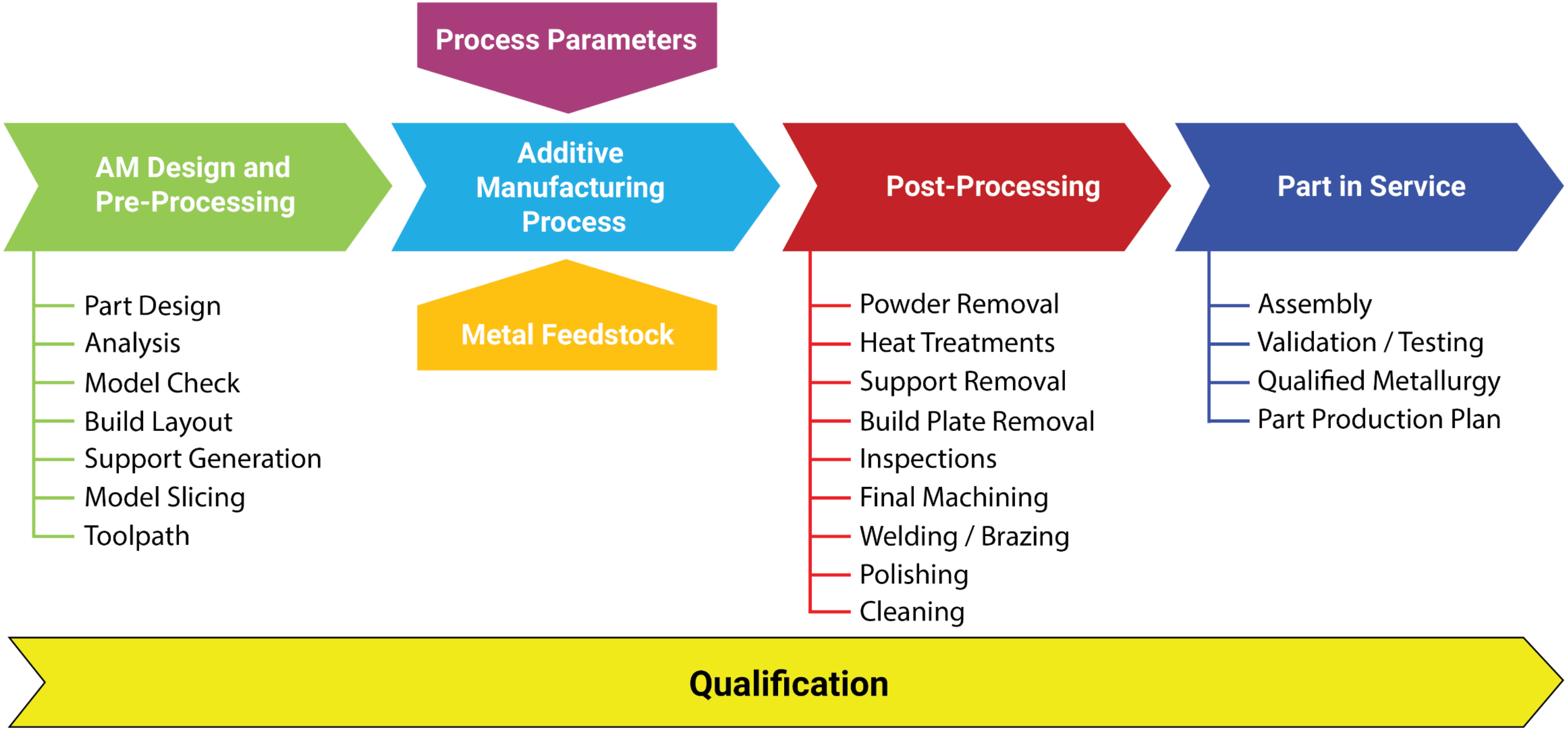
Angle relative to build direction



*Samples from RPMI

Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

Additive Manufacturing Typical Process Flow



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

Reference: 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

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

← FEATURE RESOLUTION — DEPOSITION SPEED →

Courtesy: RPM Innovations

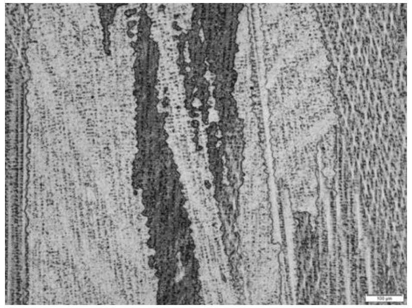
Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

Material Properties for Various AM Processes

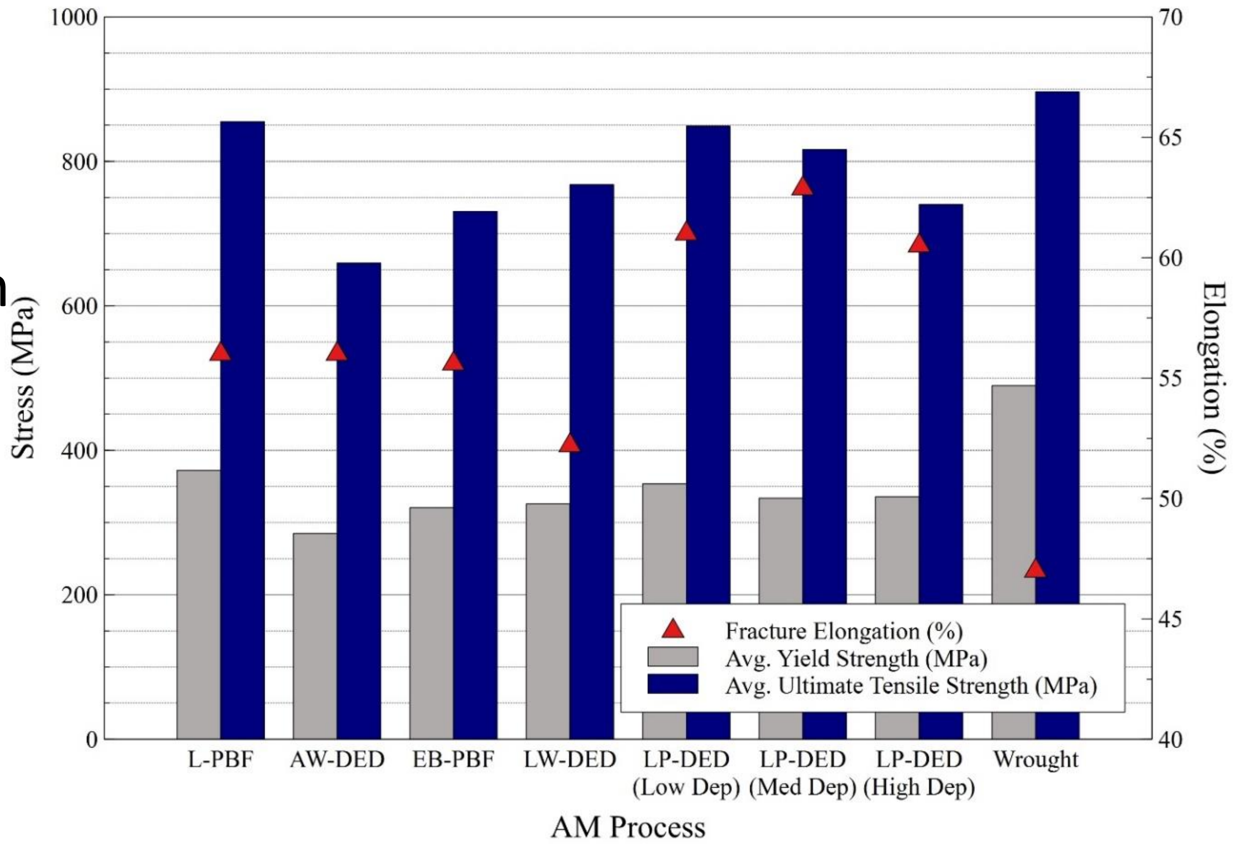
- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Cold spray….), the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build.
- Heat treatments should be developed based on the requirements and environment of the end component use.
- Process, parameters, and feedstock should all be stable before property development.


Laser Powder DED


Laser Wire DED


Arc Wire DED

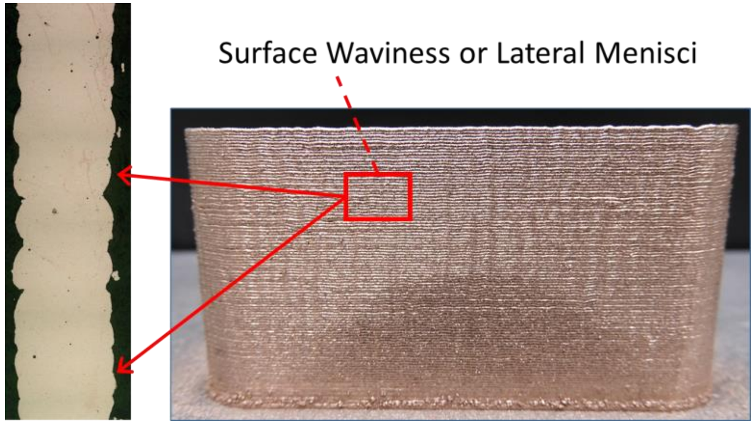
Alloy 625, Heat Treated per AMS 7000 Room Temperature UTS



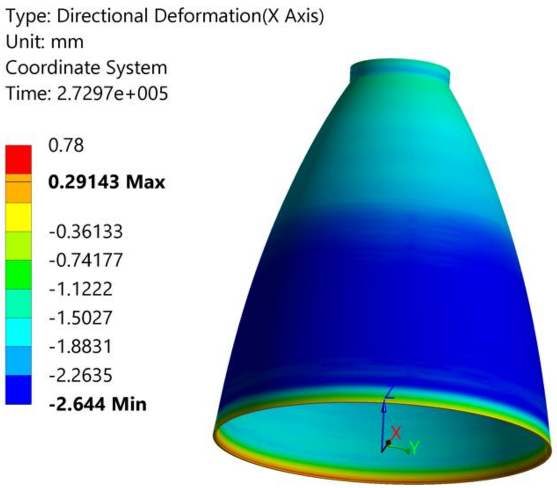
*Not design data and provided as an example only

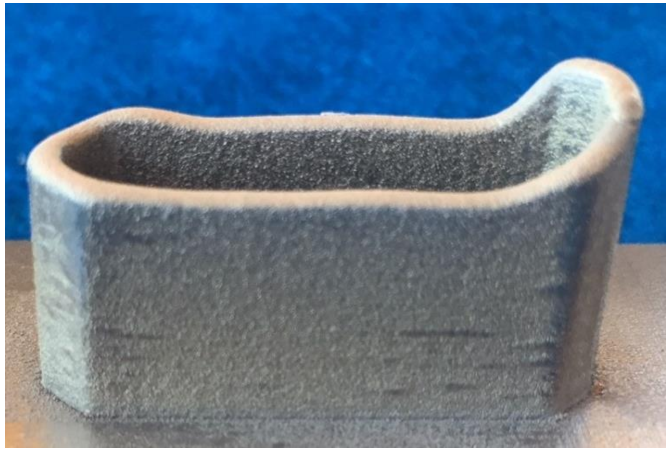
Challenges with DED

- 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

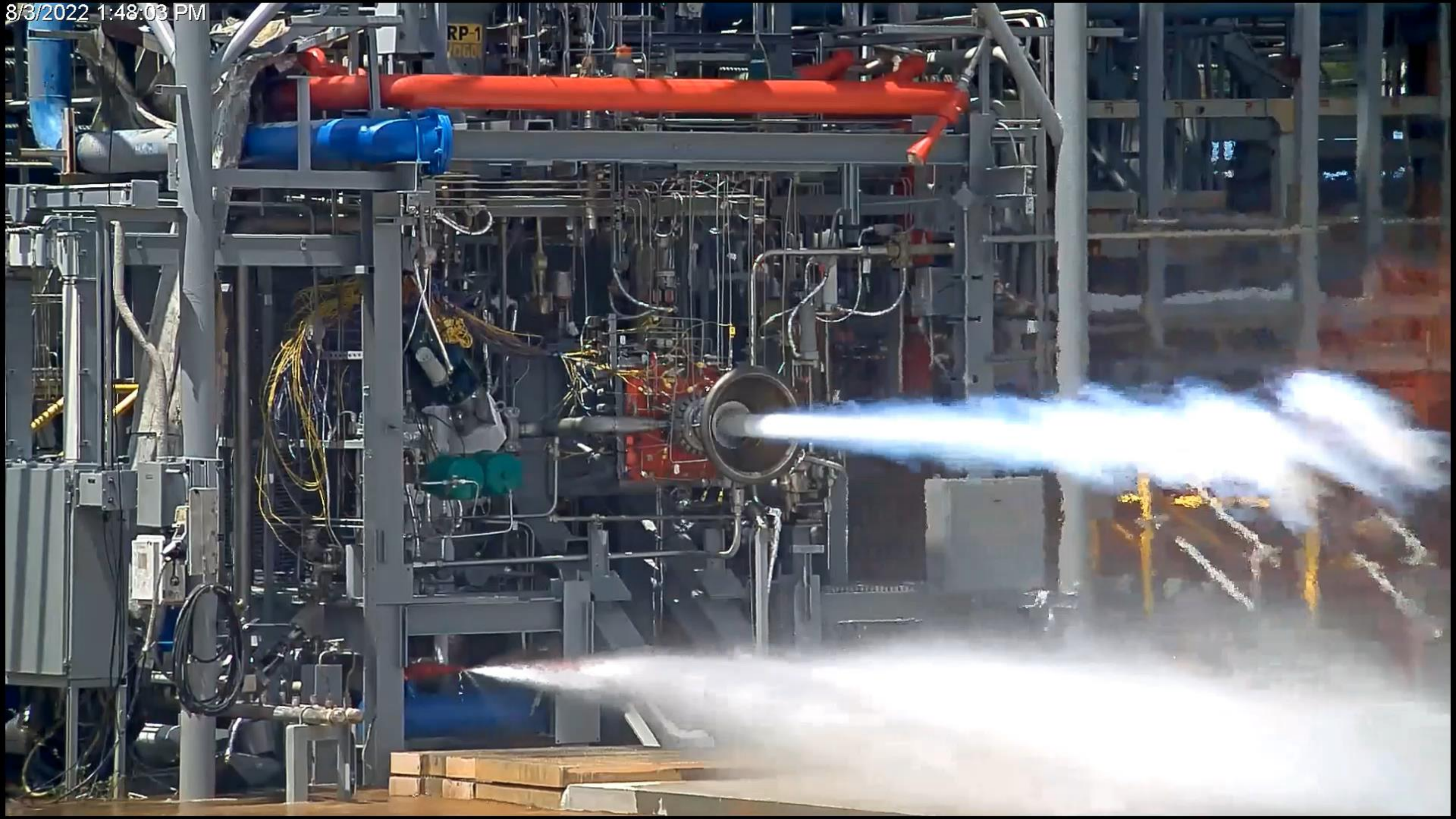


Surface Roughness



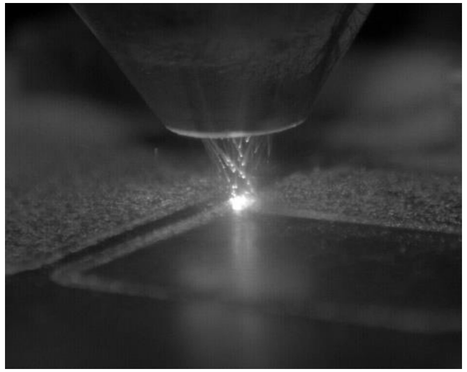


- Modeling by Kevin Wheeler / NASA Ames
- Other images based on work from: *Gradl et al "Metal Additive Manufacturing for Propulsion Applications" AIAA Book (2022)*


8/3/2022 1:48:03 PM
RP-1

General Summary

- Various DED processes exist and should be traded against requirements to provide the best technical and programmatic solution for the application.
- DED has advantages for high deposition rates but may be a detriment to feature resolution.
- Lots of options with DED for multi-alloys, build strategies, deposition rates…
- **Complete understanding of the design process, build-process, feedstock, and post-processing is critical to take full advantage of AM.**
- Additive manufacturing takes practice!
- AM is evolving and imagination is the limit.





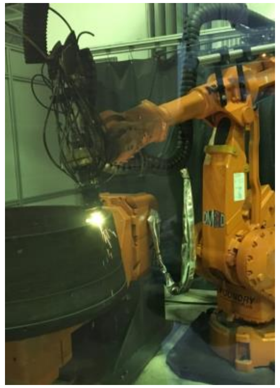


Photo: NASA/Ben Smegelsky

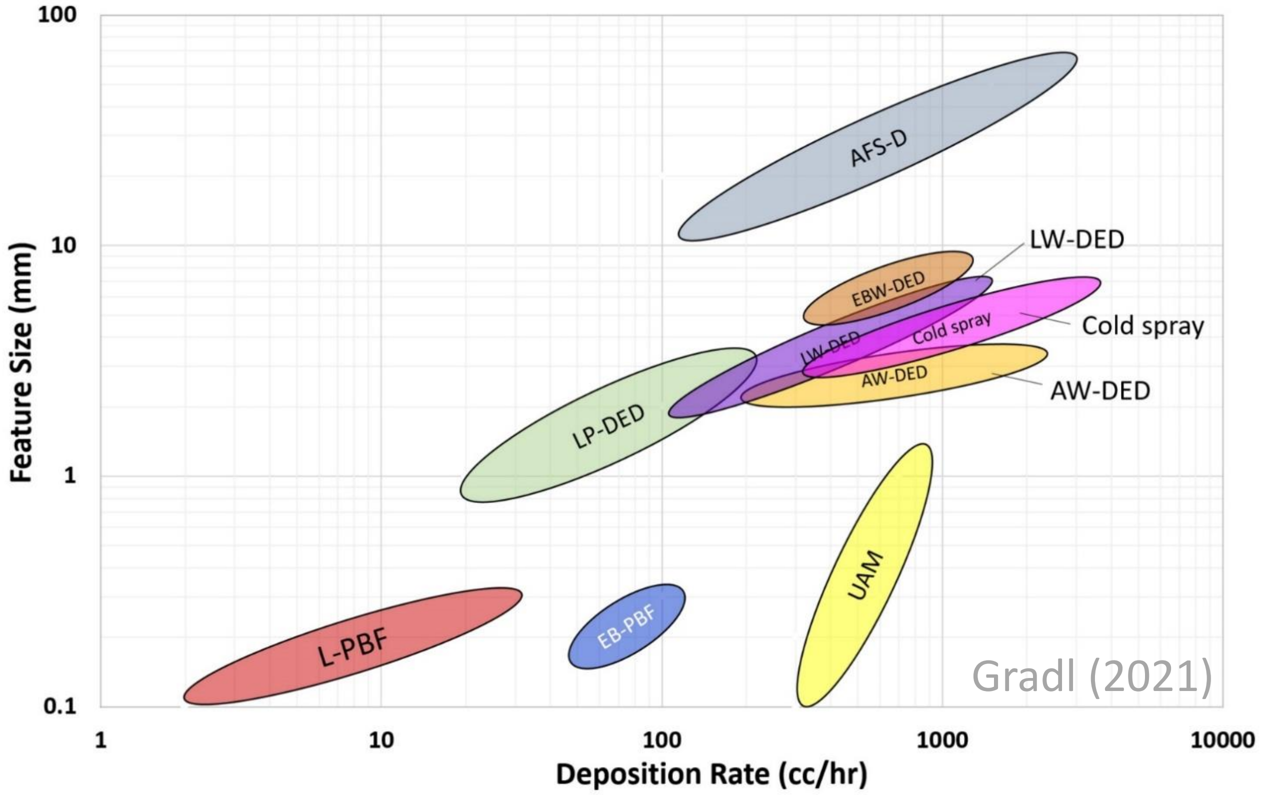
Contact:

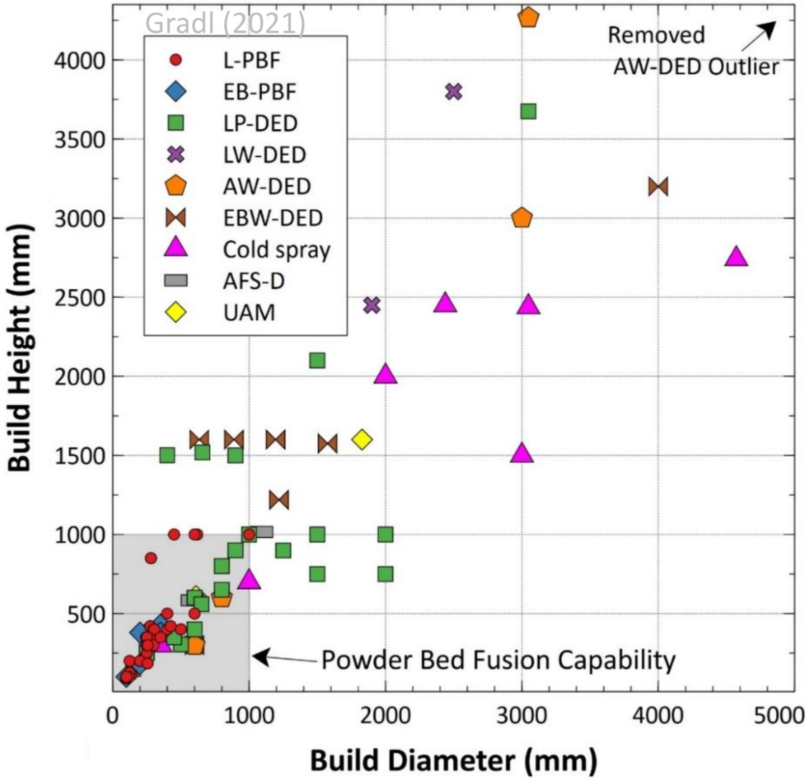
Paul Gradl
Paul.R.Gradl@nasa.gov

THE BARNES GLOBAL ADVISORS

Laura Ely
Laura@barnesglobaladvisors.com

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

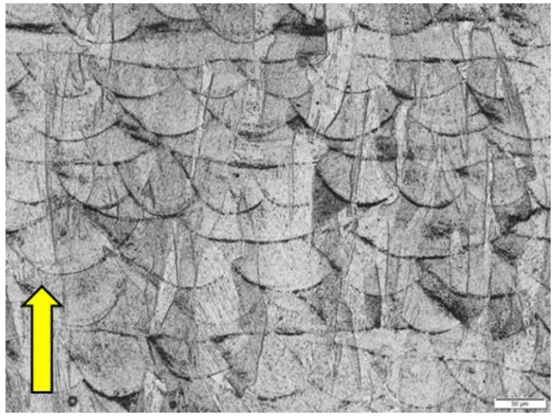
DED Design Considerations

	Substrate		Material		Deposition			
Consideration	Size, material, and temper	Use of substrate as sacrificial or integral to part	Deposition of different materials and functionally graded materials	Material form effect on surface finish	Melt pool size and bead width/height	Motion platform degrees of freedom	Start / Stop / Transition locations with different material properties	Thermal cycling and stress build up create part warpage
Impact	Insufficient heat dissipation, inability to fit final part in DED preform	Design flexibility and cost	Ability to design with location specific material performance	Some processes may require finish machining or other surface smoothing	Dictates deposition geometries, feature resolution, and number of beads required	Features may be limited by self-supporting angle	Add sacrificial deposition for Start/Stop outside of final part or locate in less critical area	Part may require intermediate stress relief during deposition or other design compensation
DfAM or MfAM	MfAM	DfAM	DfAM	MfAM	DfAM and MfAM	DfAM and MfAM	MfAM	MfAM

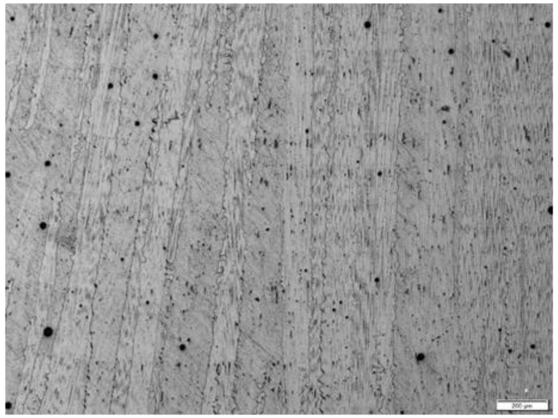
DED Design Considerations

	Machining	Non-Destructive Evaluation
Consideration	Fixturing and datum locations	Surface interface with NDE and/or geometry compatibility
Impact	Inability to machine final part from preform	Either requires more expensive NDE or inability to use that type of feature
DfAM or MfAM	MfAM	MfAM

Microstructure of Various AM Processes
Alloy 625 – As-Built

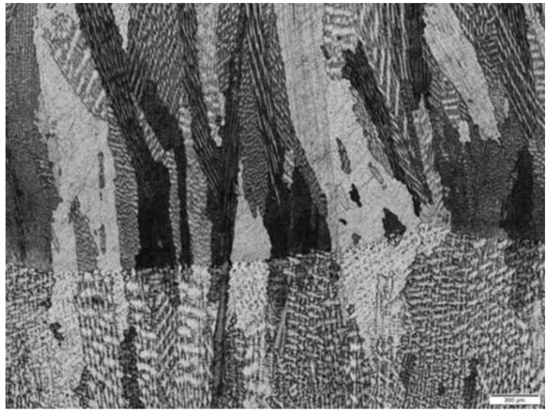


Laser Powder Bed Fusion

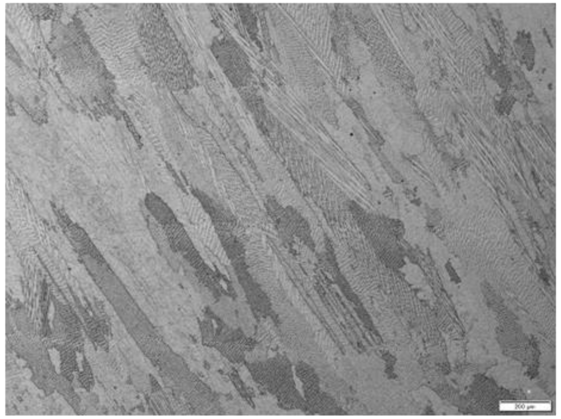


Electron Beam Powder Bed Fusion

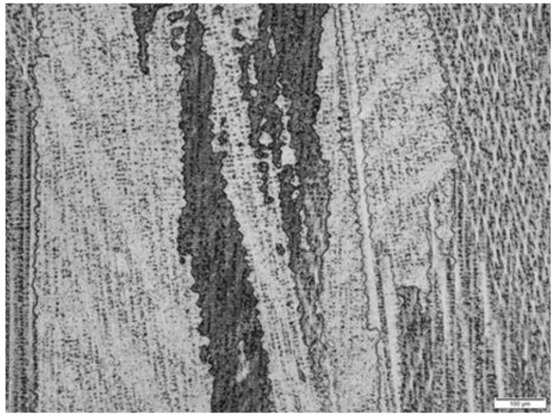
Laser Powder DED (1070 W)



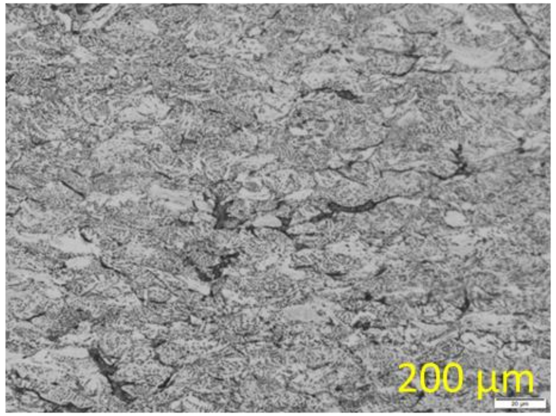
Electron Beam Wire DED



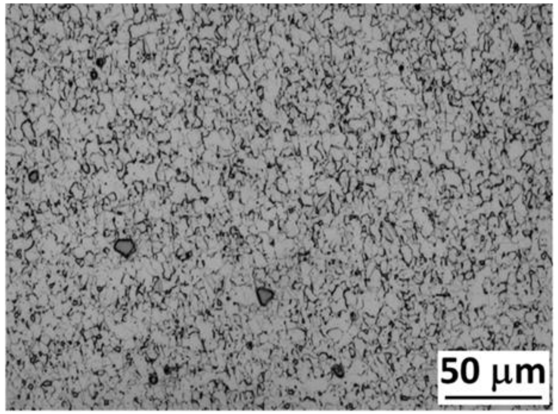
Laser Wire DED



Arc Wire DED



Cold Spray



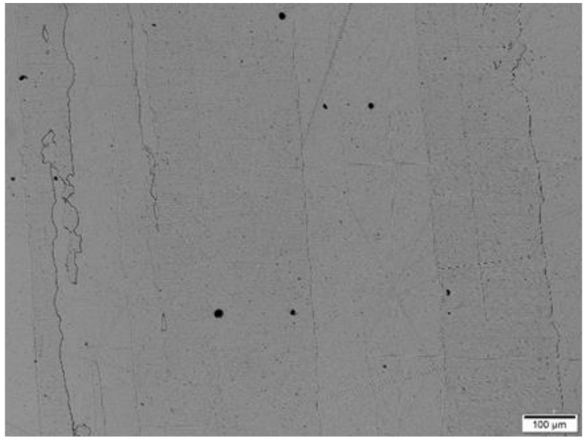
Additive Friction Stir Deposition

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

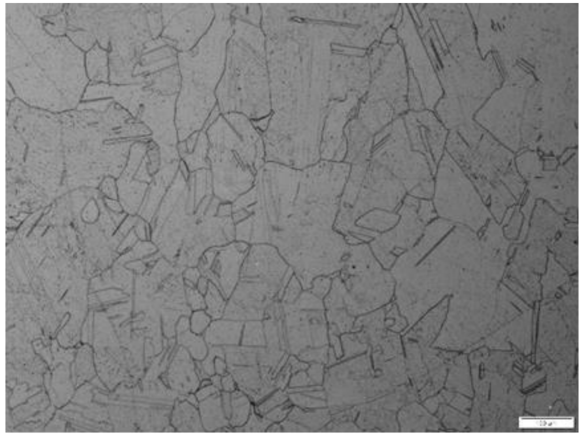
- Gamon, A., Arrieta, E., Gradl, P.R., Katsarelis, C., Murr, L.E., Wicker, R.B., Medina, F., 2021. Microstructure and hardness comparison of as-built Inconel 625 alloy following various additive manufacturing processes. Results in Materials 12. https://doi.org/10.1016/j.rinma.2021.100239
- Gradl, P.,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

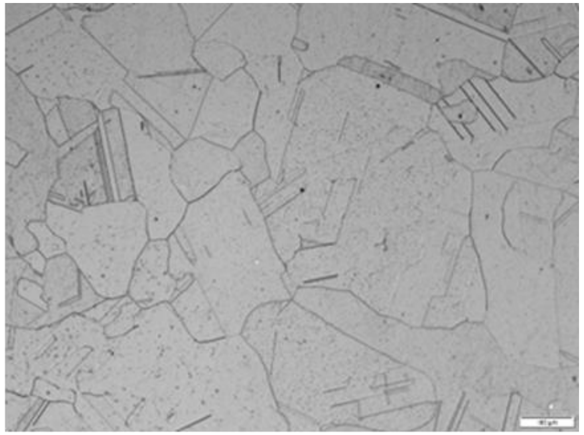
Laser Powder Bed Fusion



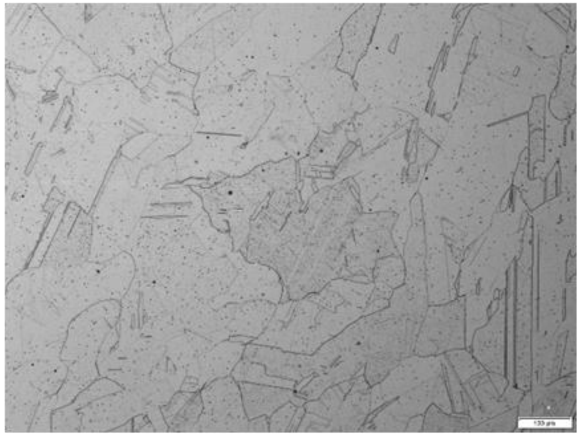
Electron Beam PBF



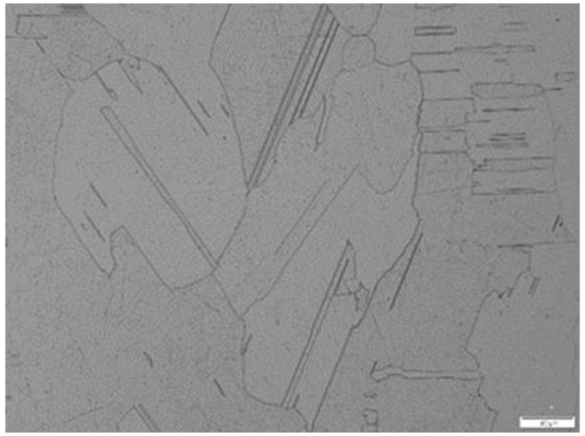
Laser Powder DED (1070 W)



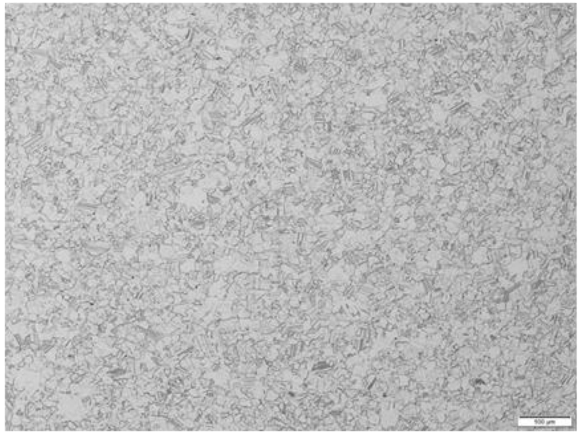
Electron Beam Wire DED



Laser Wire DED



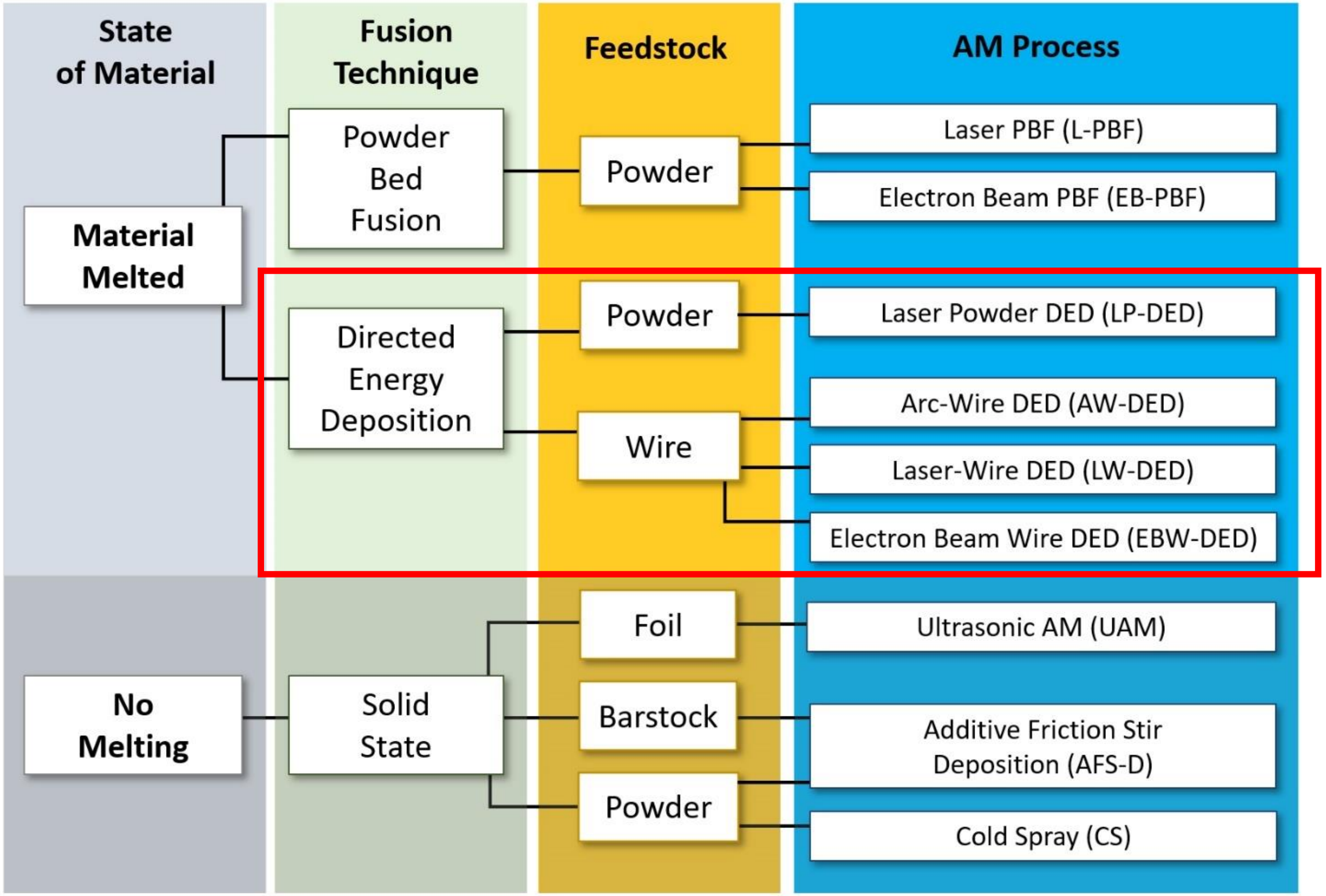
Arc Wire DED



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, 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

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).

Acknowledgements

This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the National Aeronautics and Space Administration (NASA) or the United States Government.

John Fikes
Auburn University
National Center for Additive Manufacturing Excellence (NCAME)
Nima Shamsaei
Drew Hope
Matt Melis
RPM Innovations (RPMI)
Tyler Blumenthal / RPMI
DM3D
Bhaskar Dutta / DM3D
GKN Aerospace
Keystone

Tal Wammen
Scott Chartier
Test Stand 115 crew
Kevin Baker

Matt Medders
Adam Willis
Marissa Garcia
Dwight Goodman
Will Brandsmeier
Jonathan Nelson
Bob Witbrodt
Shawn Skinner
Will Evans
John Ivester
John Bili
Will Tilson
Zach Jones
Dave Ellis
Jim Lydon
Judy Schneider / UAH
PTR-Precision Technologies
Westmoreland Mechanical Testing

David Myers
Ron Beshears
James Walker
Steve Wofford
Johnny Heflin
Mike Shadoan
Keegan Jackson
Chris Croft
Christopher Allison
Many others in Industry, commercial space and others