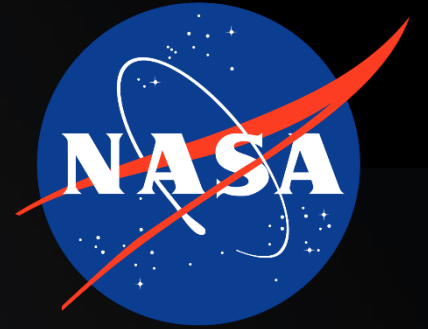


National Aeronautics and Space Administration



Metal Additive Manufacturing for Propulsion Applications

Paul Gradl

National Aeronautics and Space Administration (NASA)

Danish AM Hub Roundtable

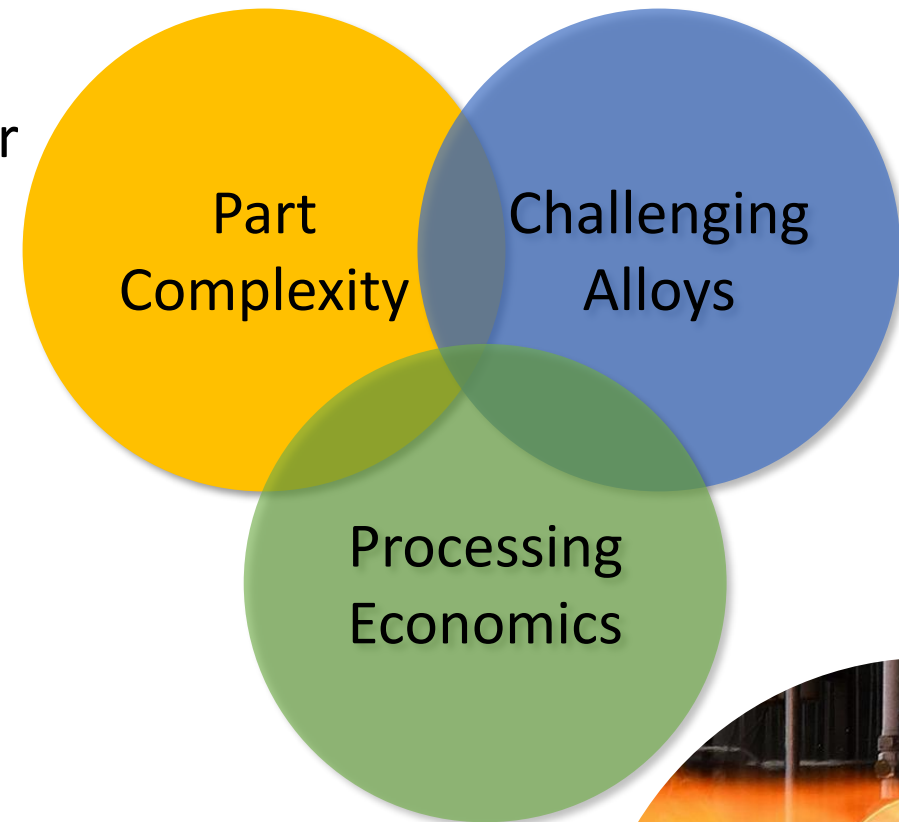
20 September 2023



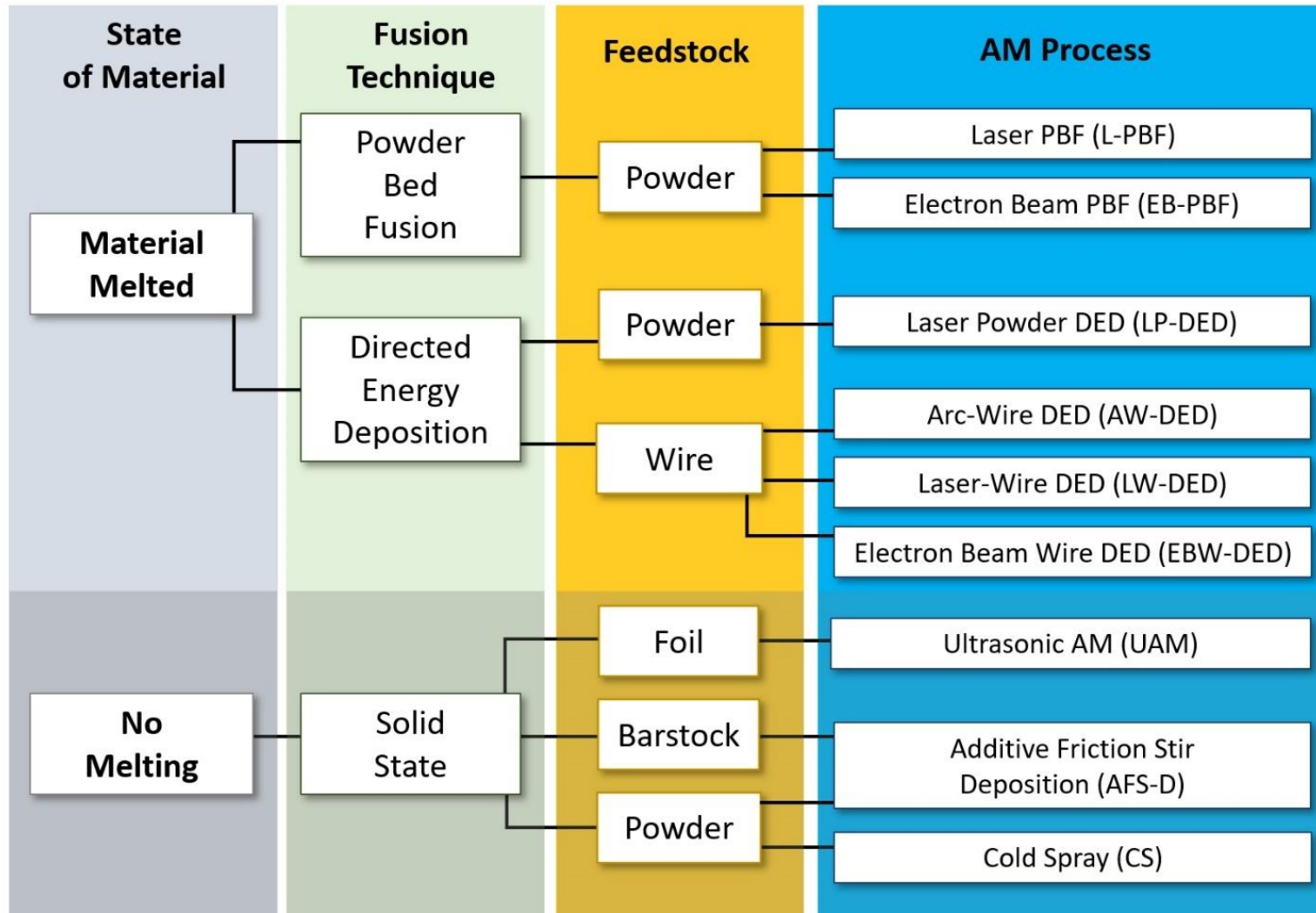
The Case for Additive Manufacturing in Propulsion



- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
 - Lead times reduced by 2-10x
 - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities.
- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing.
- Part consolidation – reduce process steps
- Rapid iterations of design: Design => Fail => Fix

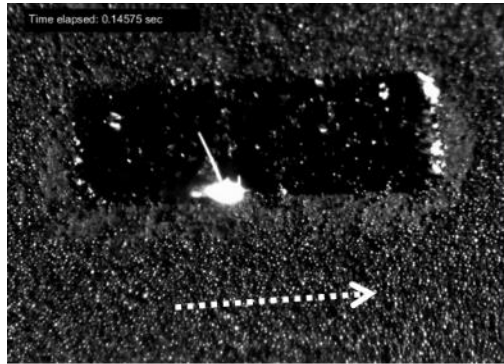


Various Metal AM Processes

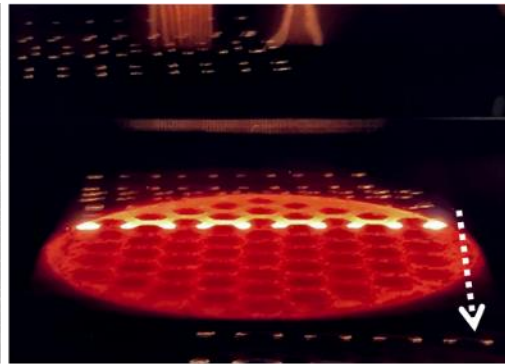


Many AM processes exist and must be traded (along with traditional techniques) to fully optimize

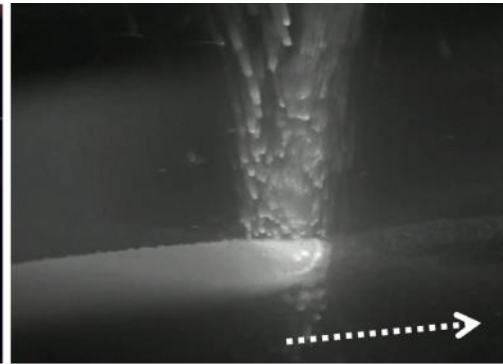
AM Processes for various applications



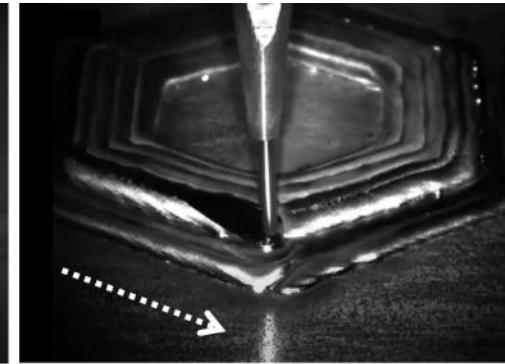
Laser Powder Bed Fusion



Electron Beam Powder Bed Fusion



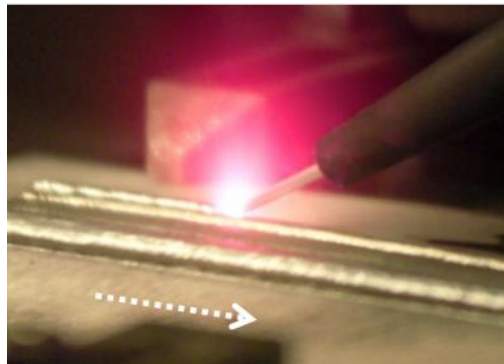
Laser Powder DED



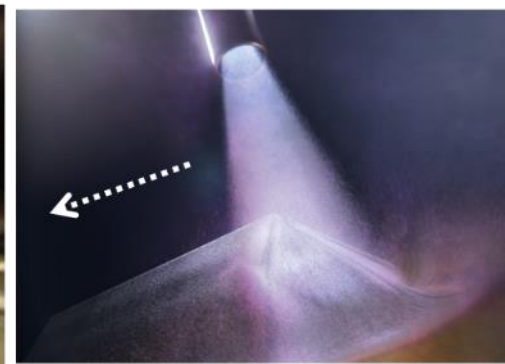
Laser Wire DED



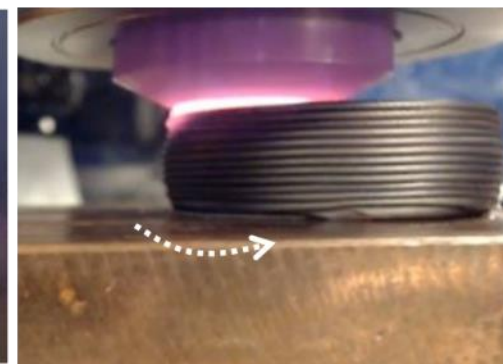
Arc Wire DED



Electron Beam Wire DED



Cold Spray



Additive Friction Stir Deposition



Ultrasonic Additive Manufacturing

A) Laser Powder Bed Fusion [<https://doi.org/10.1016/j.actamat.2017.09.051>], B) Electron Beam Powder Bed Fusion [Credit: Courtesy of Freemelt AB, Sweden], C) Laser Powder DED [Credit: Formally], D) Laser Wire DED [Credit: Ramlab and Cavitar], E) Arc Wire DED [Credit: Institut Maupertuis and Cavitar], F) Electron Beam DED [NASA], G) Cold spray [Credit: LLNL], H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM [Credit: Fabrisonic].



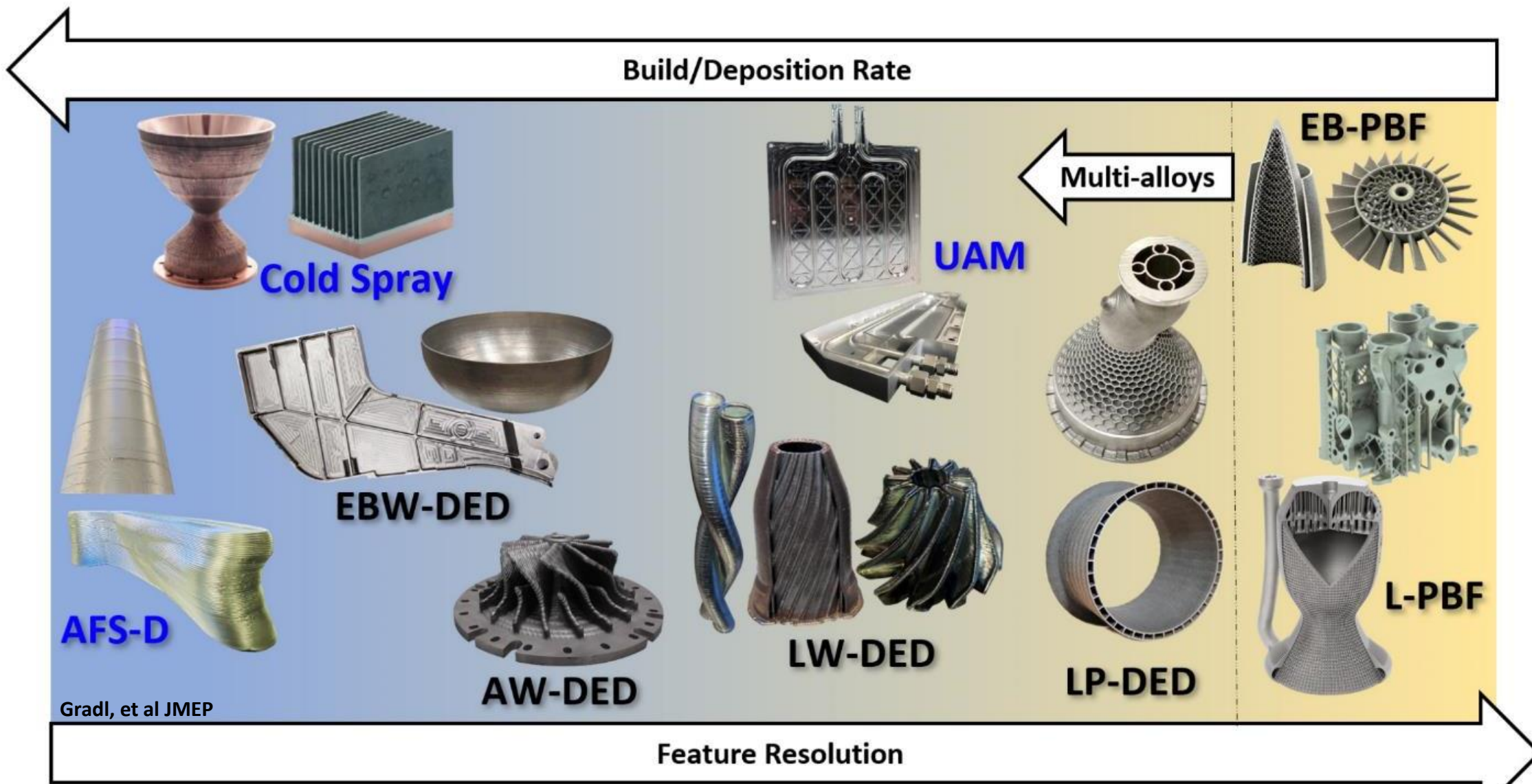
Methodical AM Process Selection



- What is the **alloy** required for the application?
- What is the **overall part size**?
- What is the **feature resolution** and internal **complexities**?
- Is it a **single alloy** or **multiple**?
- What are **programmatic requirements** such as cost, schedule, risk tolerance?
- What are the end-use environments and **properties required**?
- What is the **qualification/certification** path for the application/process?

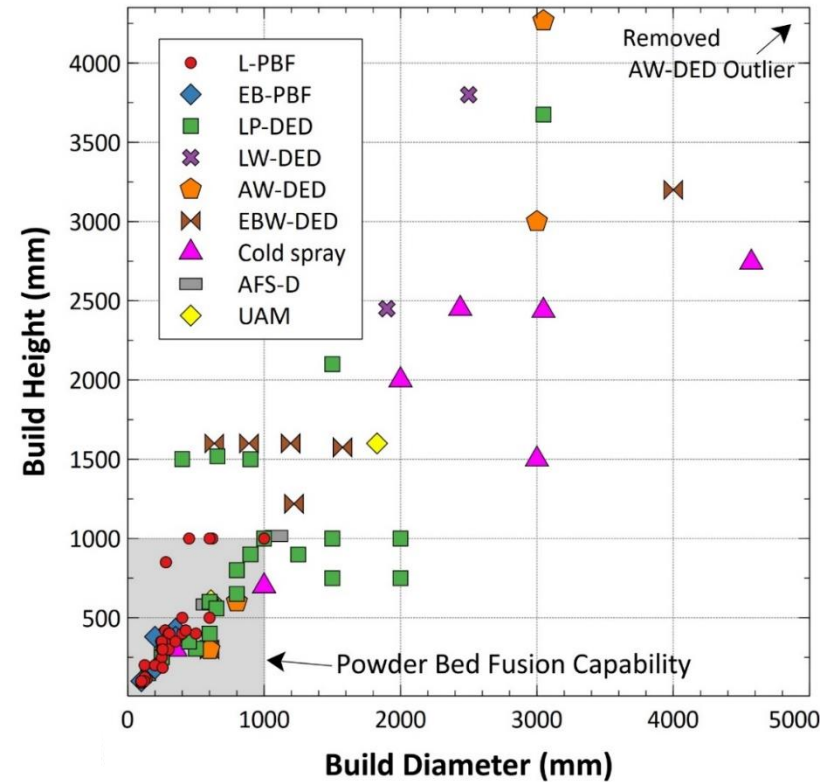
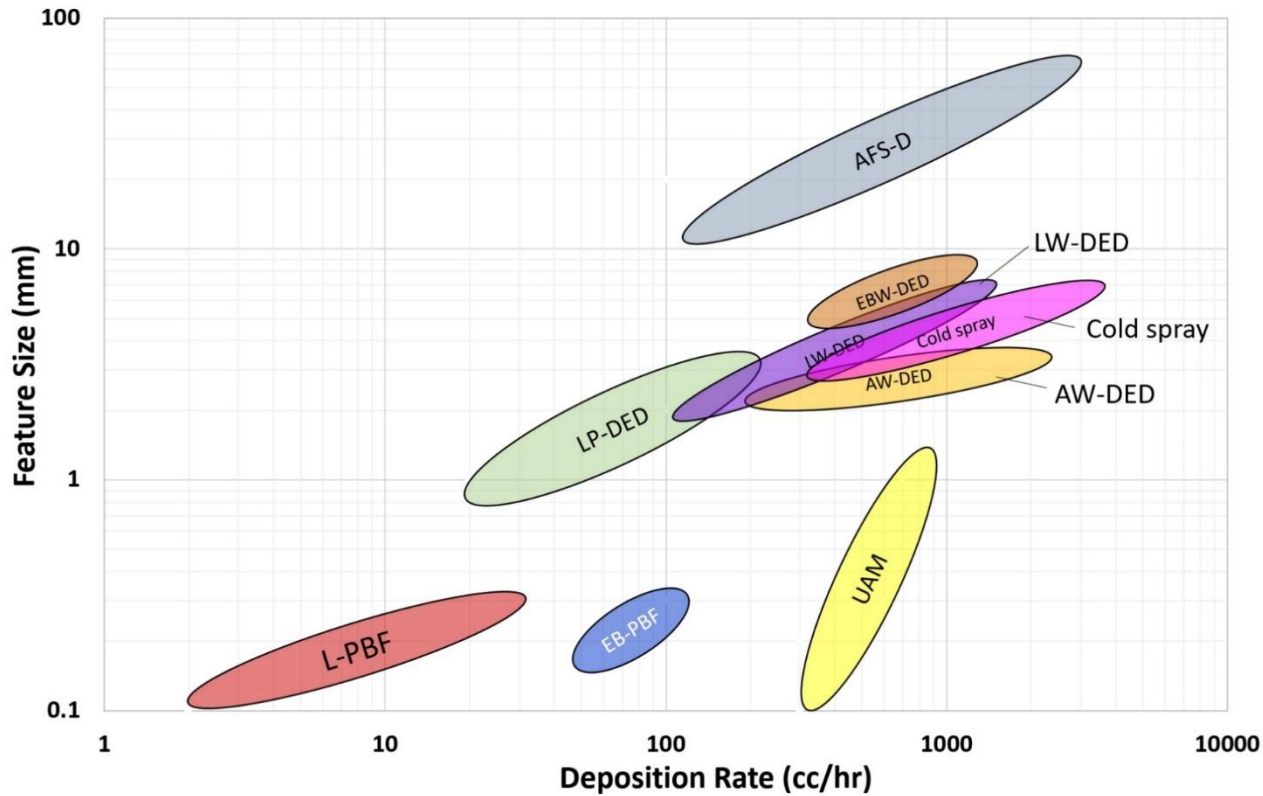


Criteria and Comparison Various Metal AM Processes





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

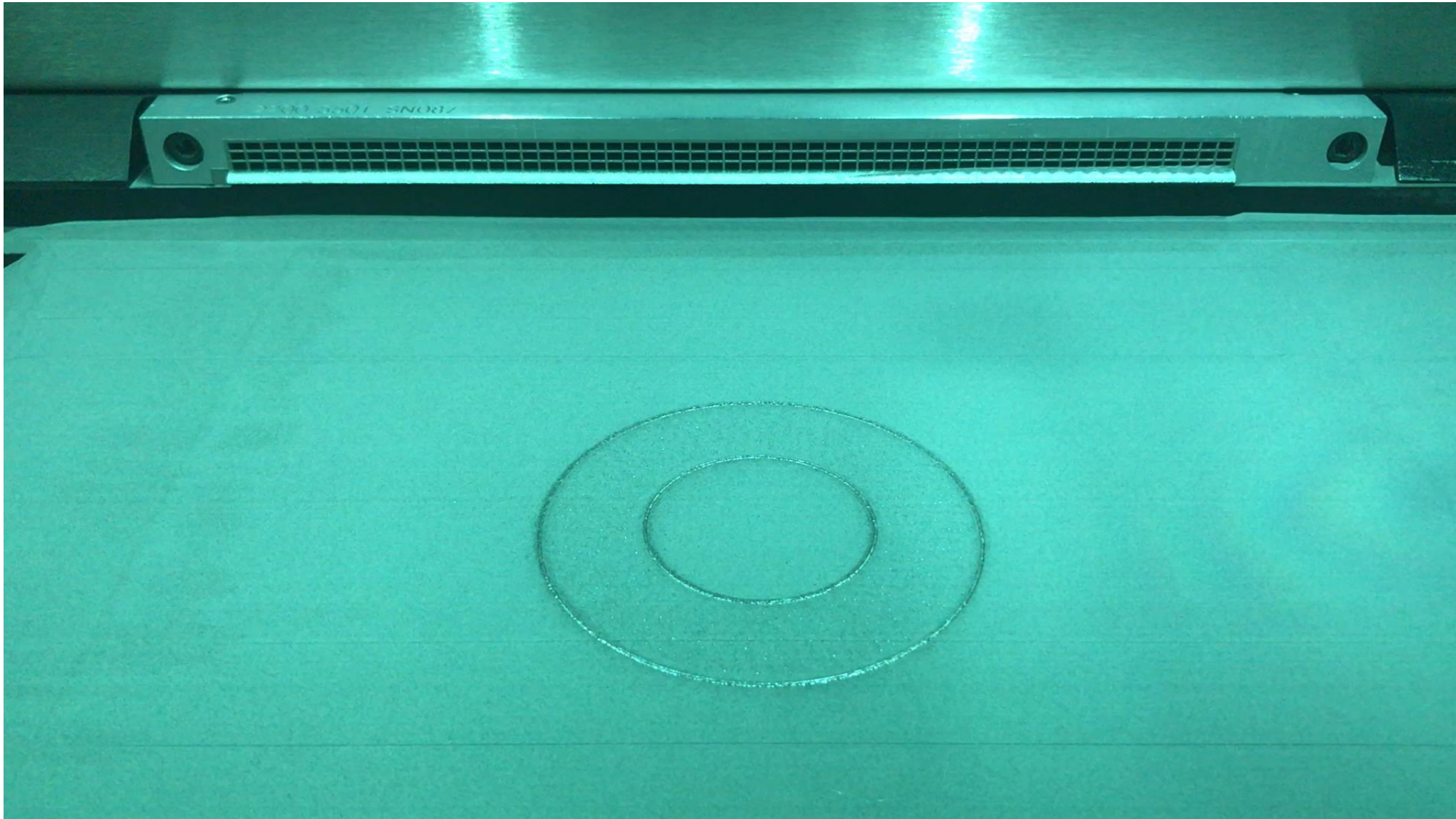
Post Processing

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>
- Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia, 2022. Metal Additive Manufacturing for Propulsion Applications, 1st ed, Metal Additive Manufacturing for Propulsion Applications. American Institute of Aeronautics and Astronautics, Inc., Reston, VA. <https://doi.org/10.2514/4.106279>



Laser Powder Bed Fusion (L-PBF)

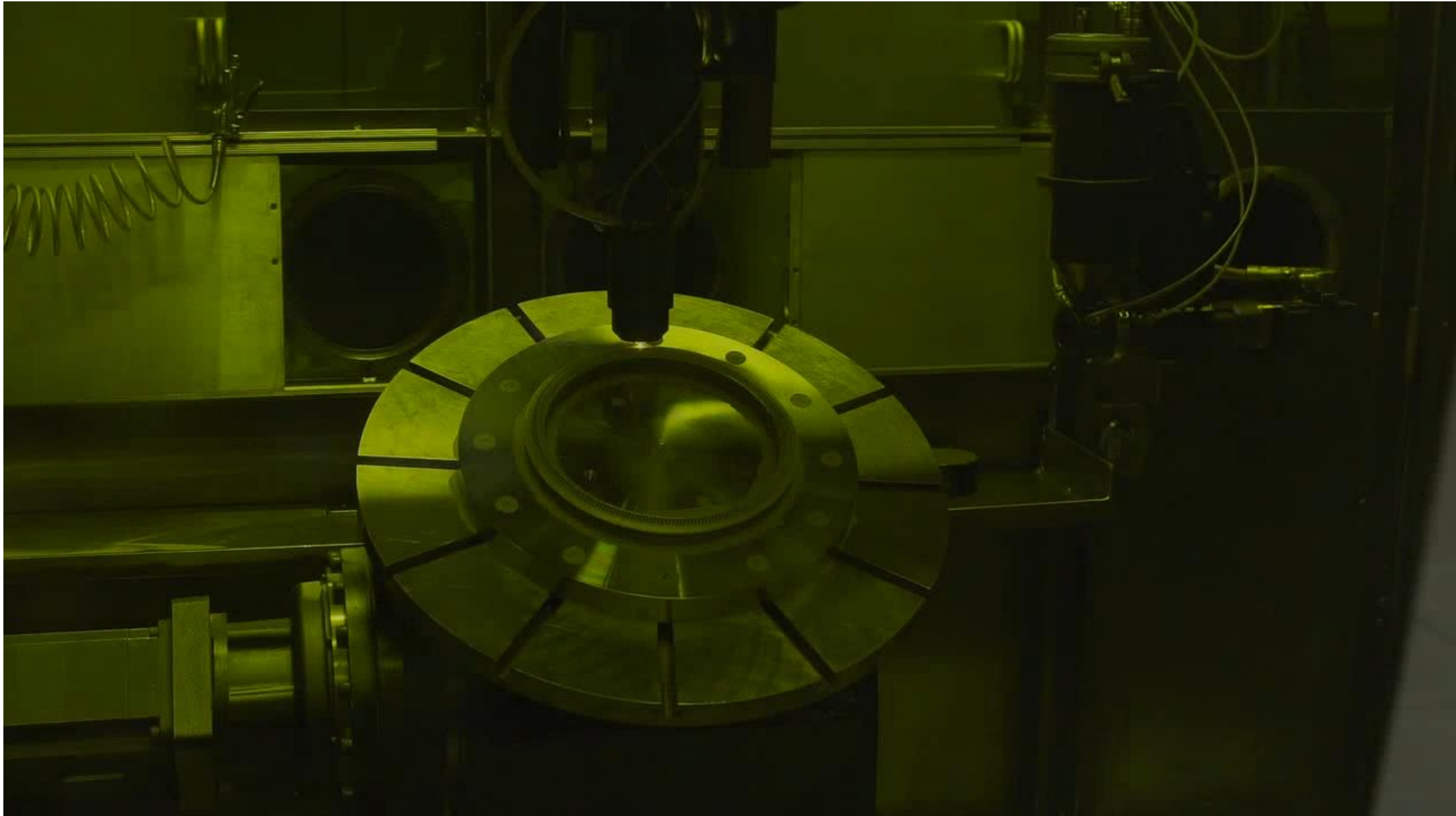




Laser Powder Directed Energy Deposition



Example of LP-DED with small features





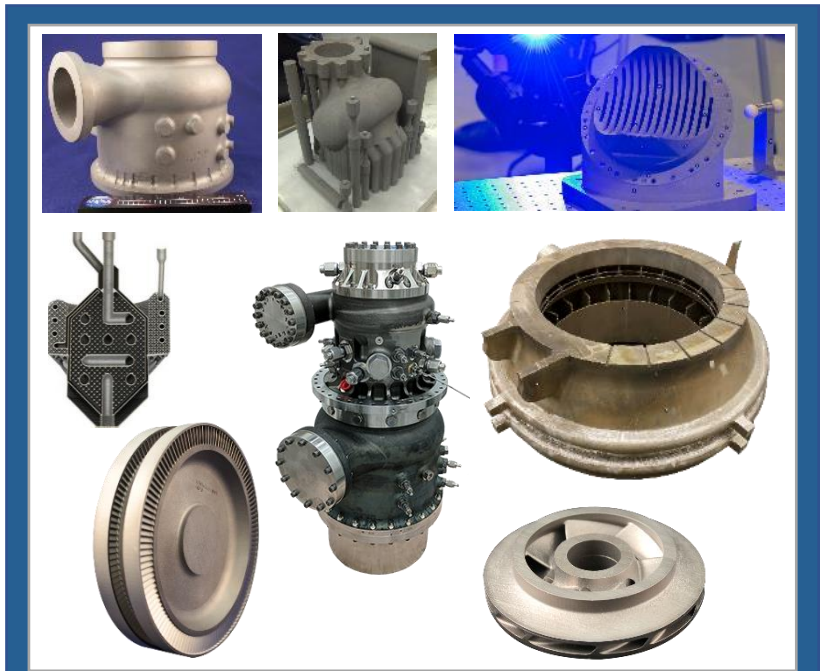
Metal Additive Manufacturing Development for Rocket Engines



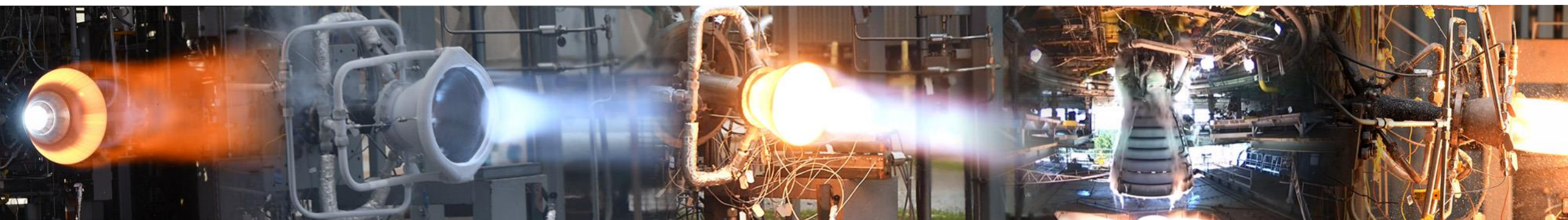
Laser Powder Bed Fusion (L-PBF)
Copper Alloys combined with other
AM processes to provide bimetallic



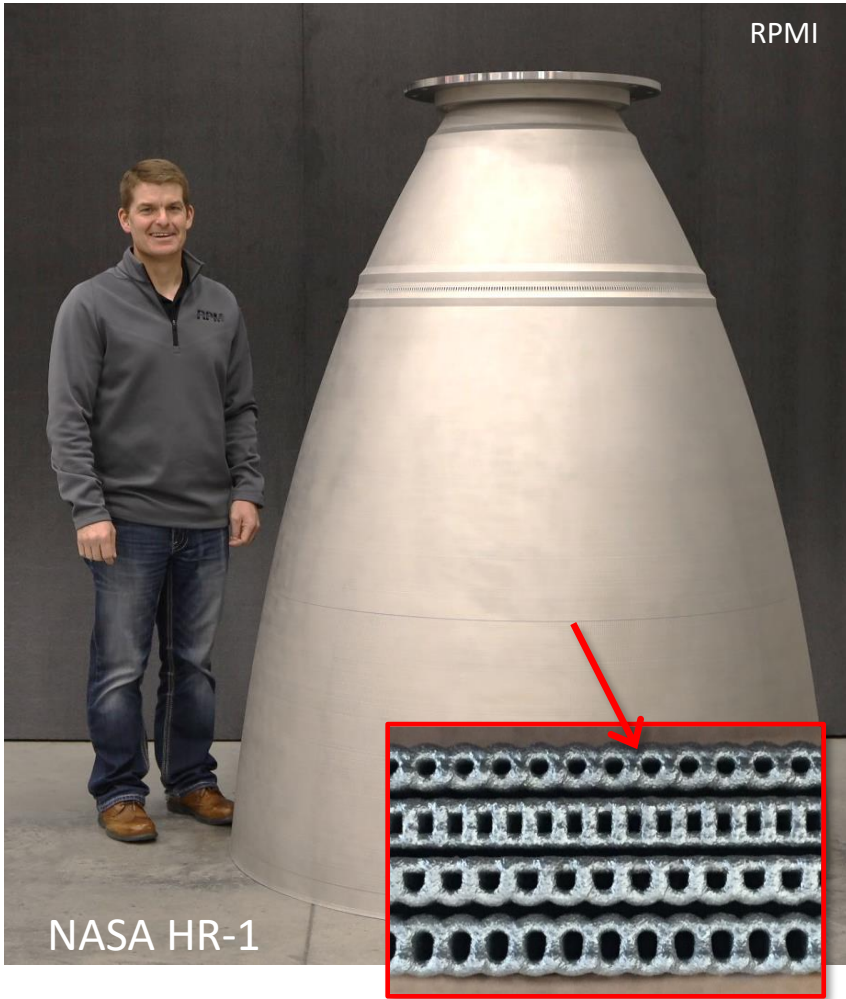
Directed Energy Deposition



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



Large Scale LP-DED Nozzle Development



60" (1.52 m) diameter and 70" (1.78 m) height with integral channels
90 day deposition

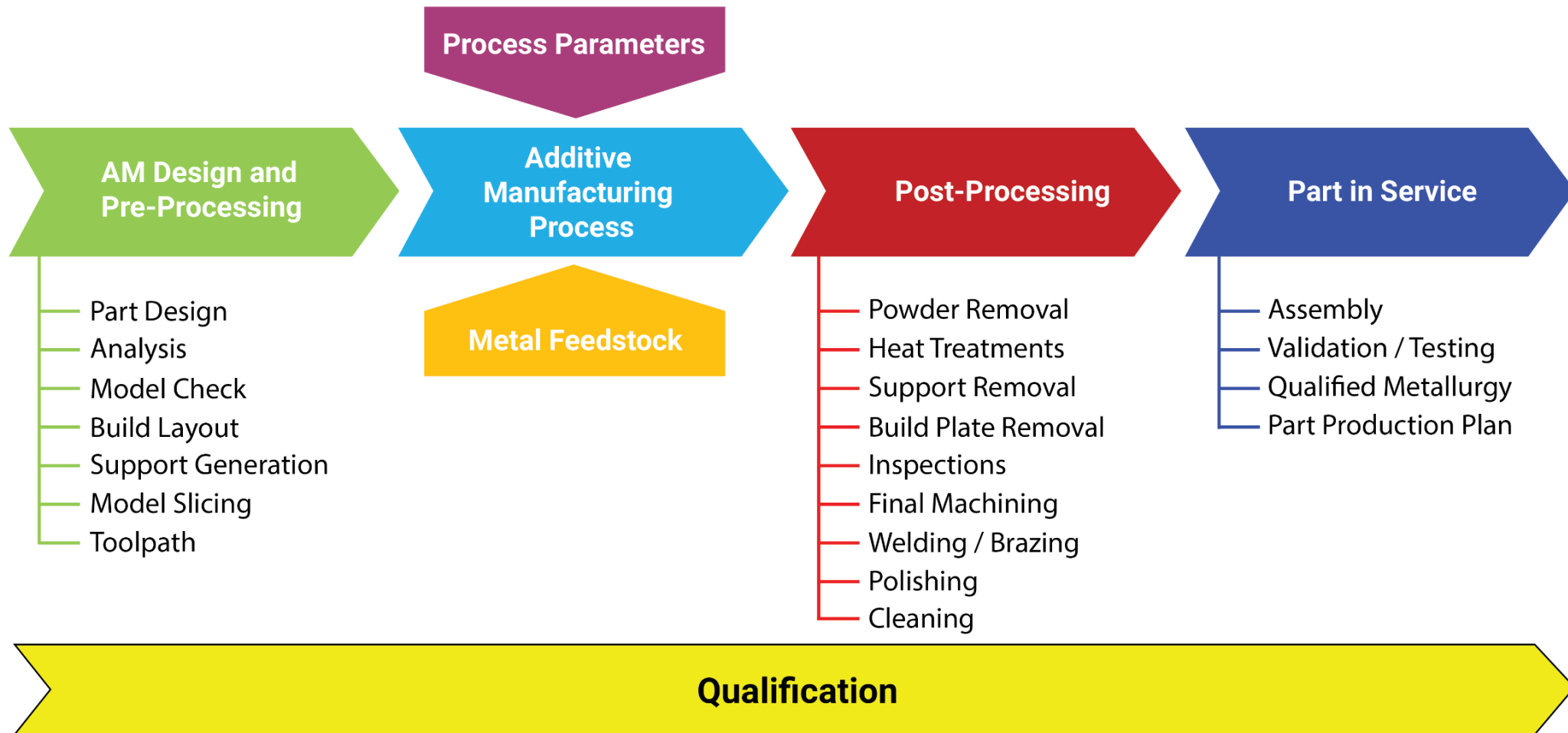


95" (2.41 m) dia and 111" (2.82 m) height
Near Net Shape Forging Replacement

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>.



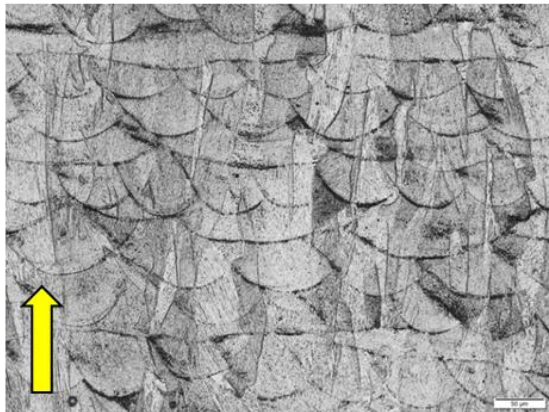
Additive Manufacturing Typical Process Flow



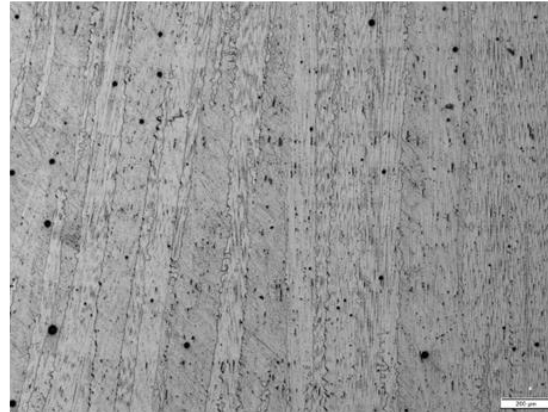
Proper AM process selection requires an integrated evaluation of all process lifecycle steps

Microstructure of Various AM Processes

Alloy 625 – **As-Built**



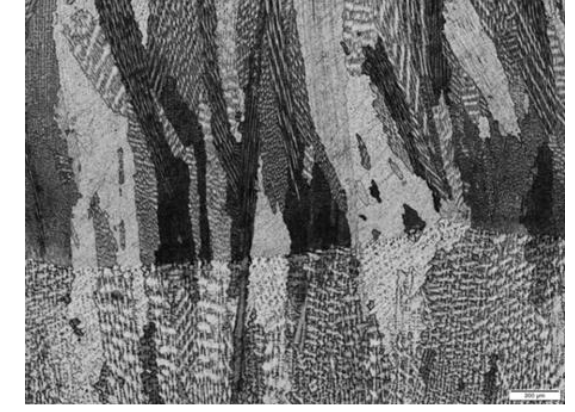
Laser Powder Bed Fusion



Electron Beam Powder Bed Fusion



Laser Powder DED (1070 W)



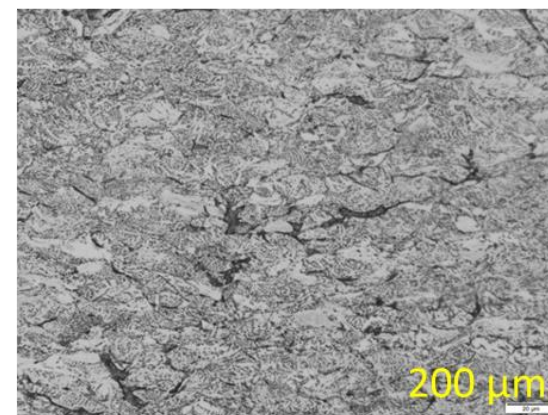
Electron Beam Wire DED



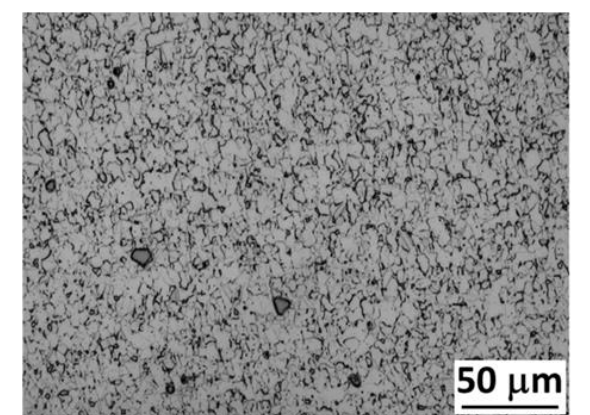
Laser Wire DED



Arc Wire DED



Cold Spray



Additive Friction Stir Deposition

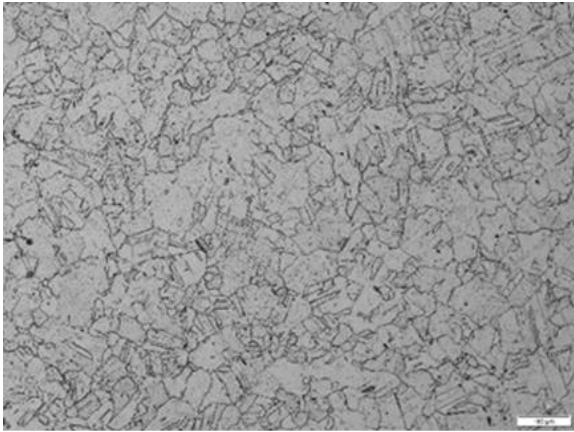
Each AM process results in different grain structures, which ultimately influence properties

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

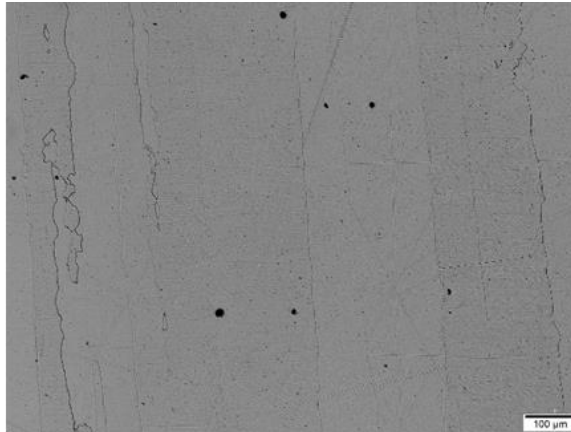


Microstructure of Various AM Processes

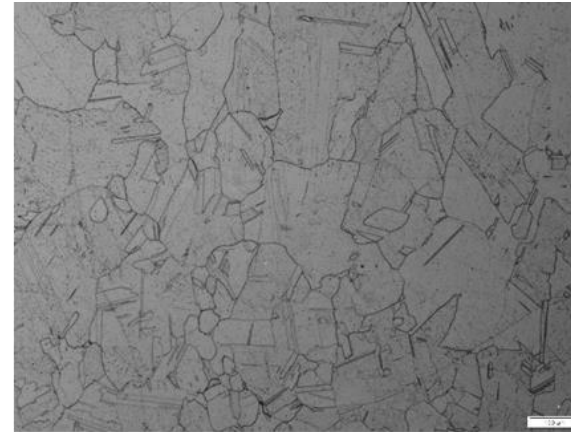
Alloy 625 – Stress Relief, HIP, Solution per AMS 7000



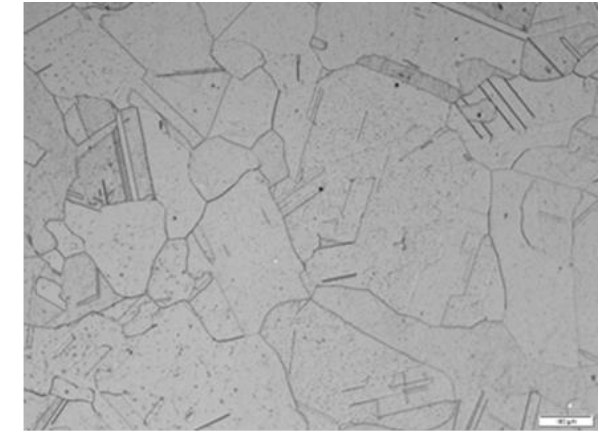
Laser Powder Bed Fusion



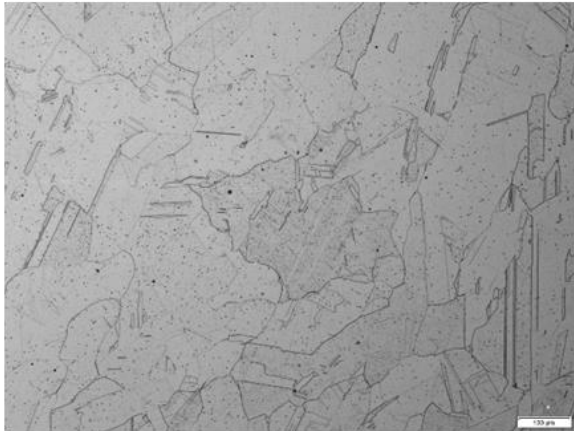
Electron Beam PBF



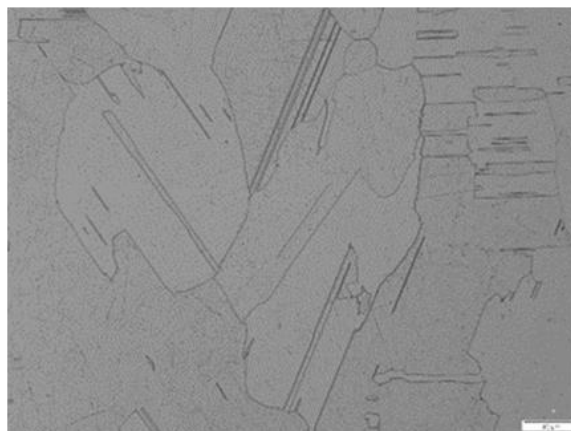
Laser Powder DED (1070 W)



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>



AM Alloys and Processes In-work



Material	Process
Haynes 282	L-PBF
Haynes 282	LP-DED
Hastelloy X	L-PBF
Hastelloy X	LP-DED
Inconel 625	L-PBF
Inconel 625	LP-DED
Inconel 625	LW-DED
Inconel 625	AW-DED
Inconel 718	L-PBF
Inconel 718	LP-DED
Inconel 718	AW-DED
Inconel 939	L-PBF
Haynes 230	L-PBF
Haynes 230	LP-DED
Haynes 214	L-PBF
Haynes 233	L-PBF
Haynes 233	LP-DED

Material	Process
NASA HR-1	L-PBF
NASA HR-1	LP-DED
JBK-75	L-PBF
JBK-75	LP-DED
CoCr	L-PBF
CoCr	LP-DED
Invar 36	LP-DED
Stellite 21	LP-DED
316L	LP-DED
15-5	LP-DED
17-4	L-PBF
17-4	LP-DED
Scalmalloy	L-PBF
6061-RAM2	L-PBF
6061-RAM2	LP-DED
F357	L-PBF
F357	LP-DED
1000-RAM10	L-PBF
AlSi10Mg	L-PBF
AlSi10Mg	LP-DED
7A77	L-PBF

Material	Process
Monel K500	LP-DED
Monel K500	L-PBF
GRCop-42	L-PBF
GRCop-42	LP-DED
GRCop-84	L-PBF
C-18150	L-PBF
Ti6Al-4V	L-PBF
Ti6Al-4V	LP-DED
Ti6Al-4V	LW-DED
Ti6Al-4V	EBW-DED
Ti6242	L-PBF
Ti6242	LP-DED
GRX-810	L-PBF
GRX-810	LP-DED
Haynes 214-ODS	L-PBF
C-103	LP-DED

55+ Alloys in characterization



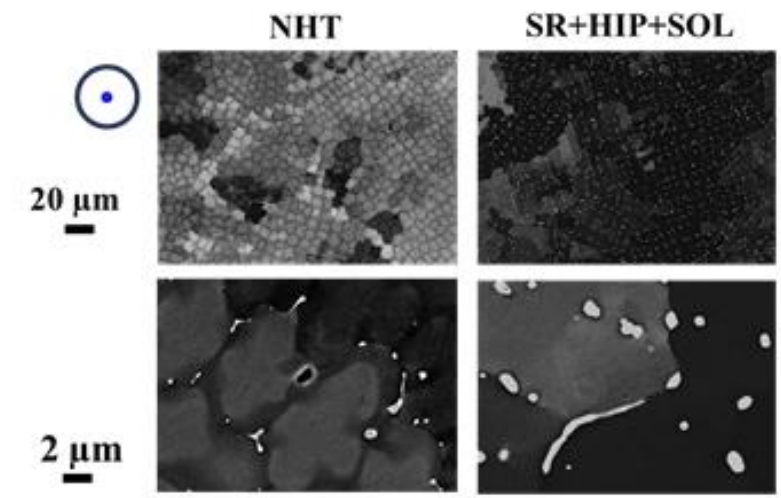
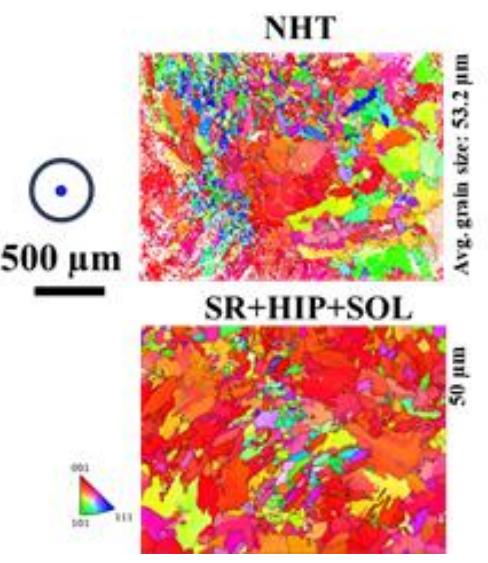
Data example of Haynes 230 LP-DED



Power (W)	Layer height (μm)	Travel speed (mm/min)	Powder feed rate (g/min)
1070	381	1016	19.10

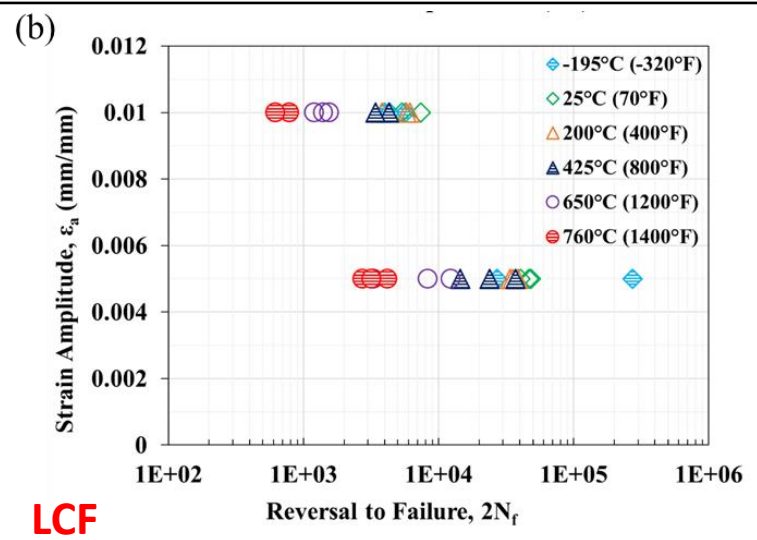
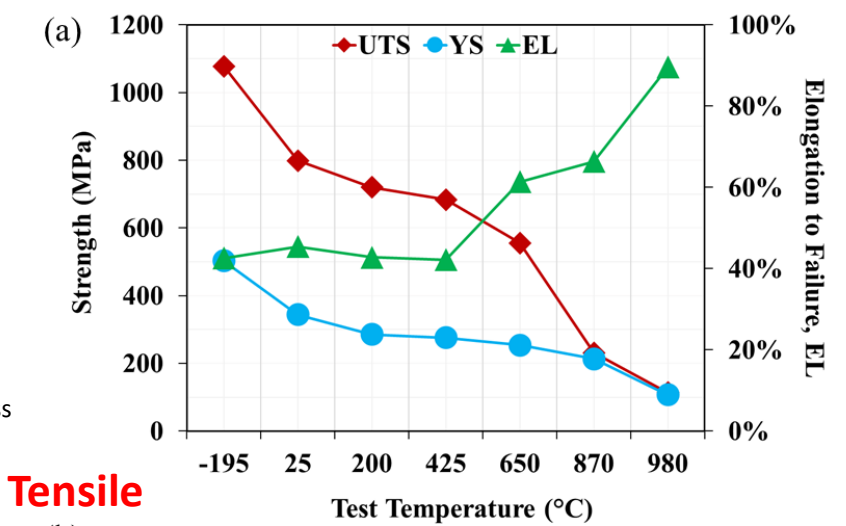
Procedure (Designation)	Temperature (°C)	Time (hrs)	Cooling
Stress Relief (SR)	1066	1.5	Furnace cool
HIP [2]	1163/103 MPa	3	Furnace cool
Solution Annealing (SOL)	1177	3	Argon quench

As-Built
Full Heat Treated



[2] HIP per ASTM F3301

Data from Gradl, Mireles, Protz, Garcia. "Metal Additive Manufacturing for Propulsion Applications", AIAA Progress Series. (2022). Appendix A.





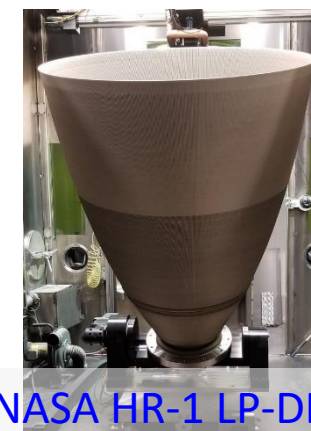
NASA's Effort on New Alloy Development



Max. Use Temp. (°C)	Alloy Family	Purpose	Novel AM Alloys	Propulsion Use
200	Aluminum	Light weighting	-	Various
750	Copper	High conductivity; strength at temperature	GRCop-42 GRCop-84	Combustion Chambers
800	Iron-Nickel	High strength and hydrogen resistance	NASA HR-1	Nozzles, Powerheads
900	Nickel	High strength to weight	-	Injectors, Turbines
1100	ODS Nickel	High strength at elevated temp; reduced creep	GRX-810 Alloy 718-ODS	Injectors, Turbines
1850	Refractory	Extreme temperature	C-103, C-103-CDS, Mo, W	Uncooled Chambers



GRCop-42 L-PBF



NASA HR-1 LP-DED



GRX-810 L-PBF

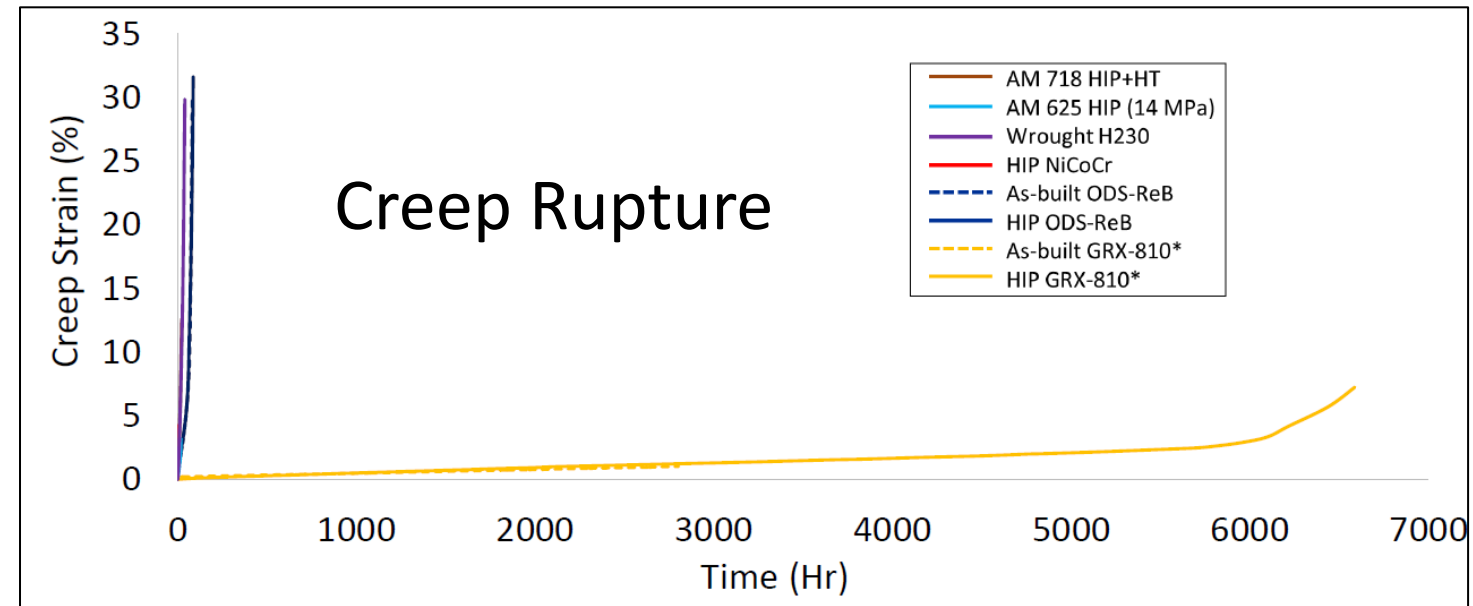
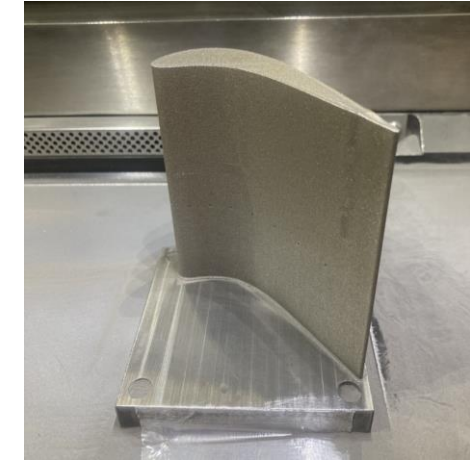
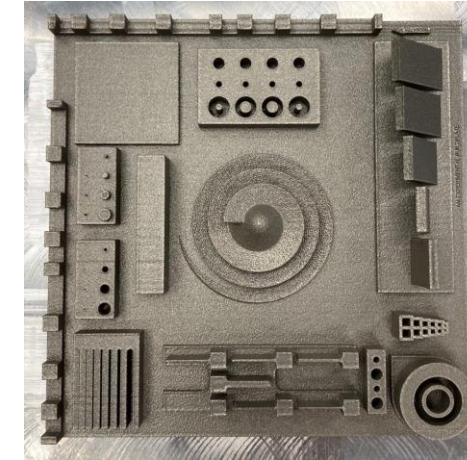
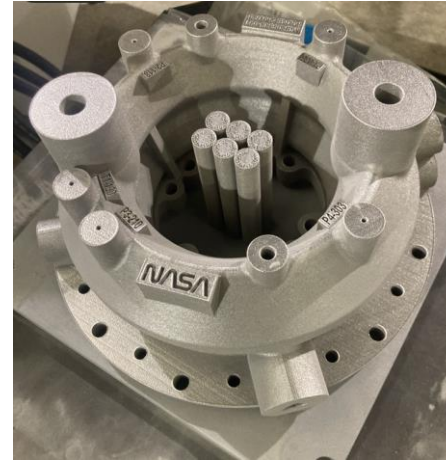
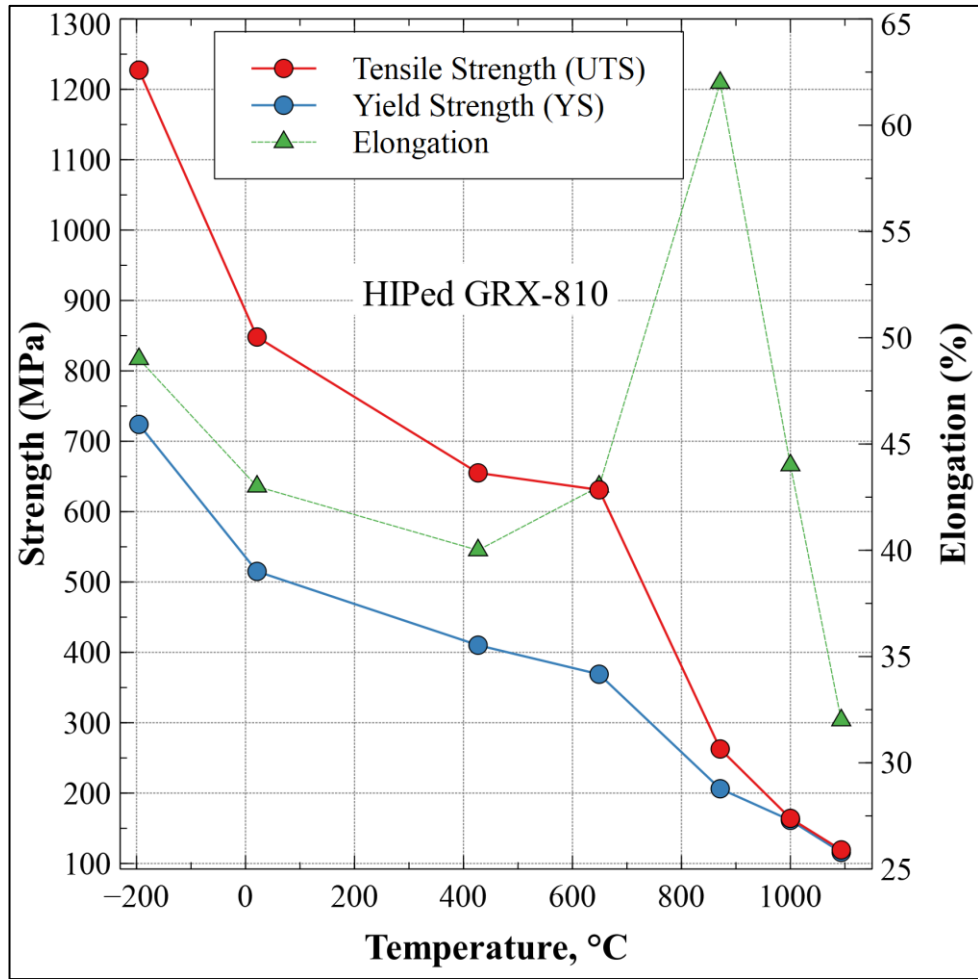


C103 L-PBF

New alloy development using various additive manufacturing processes (PBF and DED) can yield performance improvements over traditional alloys



GRX-810 Oxide Dispersion Strengthened (ODS) Alloy



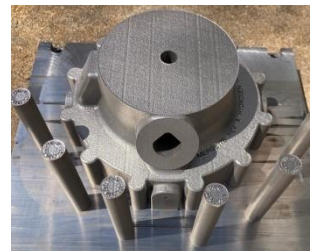


GRX-810 Novel ODS Alloy Maturation



Demonstrate the Laser Powder Bed Fusion (L-PBF) process to successfully build GRX-810 ODS alloy components and test in a relevant environment

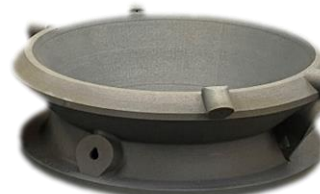
- **Fabrication of multiple combustion device components**
 - Three Injectors for LH2-LOx and LCH4-LOx propellants
 - Three Regenerative Nozzles capable of fuel or oxygen cooling
- **Successful Hot-fire Test of GRX-810 alloy:**
 - Hot-fire testing at NASA Marshall
- **LOX/LCH4 Test Series with a GRX-810 nozzle and injector**
 - The nozzle accumulated 90 starts and 2,309 seconds of runtime.
 - Injector A accumulated 30 starts and 591 seconds.
 - Injector B accumulated 84 starts and 2,228 seconds.
 - Injector provided a significant improvement in life (limited/no erosion) compared to prior injectors built from Inconel 625 and Inconel 718.
- **LOX/LH2 Test Series with a GRX-810 injector**
 - The injector accumulated 9 starts and 303 seconds of test time.



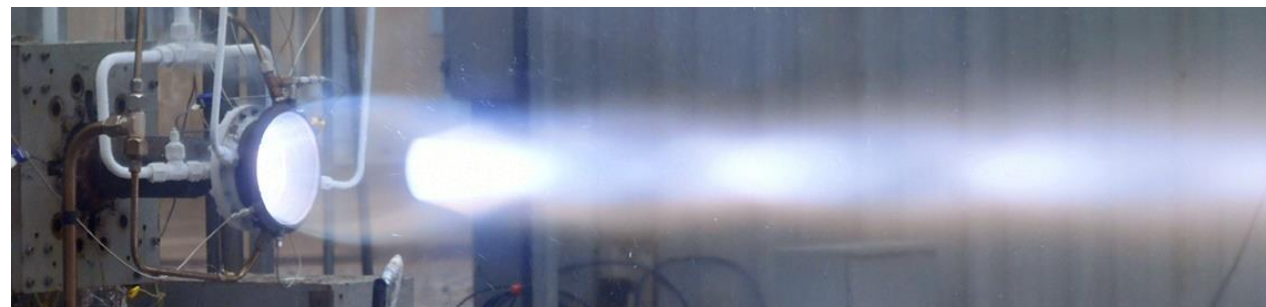
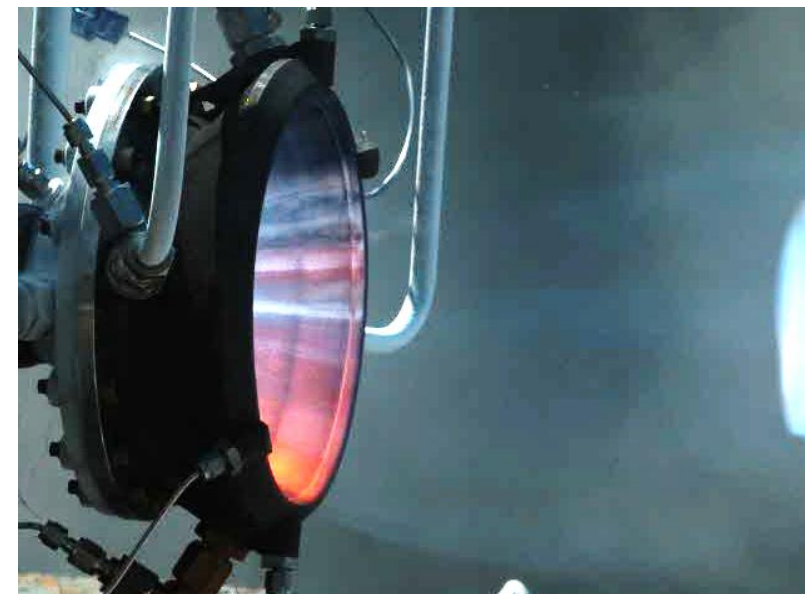
Injector



As-Built Nozzle



Post-HIP Nozzle



Credit: RPMI



L-PBF Liner / LP-DED Jacket



L-PBF Liner / Coldspray Jacket



L-PBF Liner / EBW-DED Jacket



**Direct deposit LP-DED nozzle
(Axial Bimetallic)**

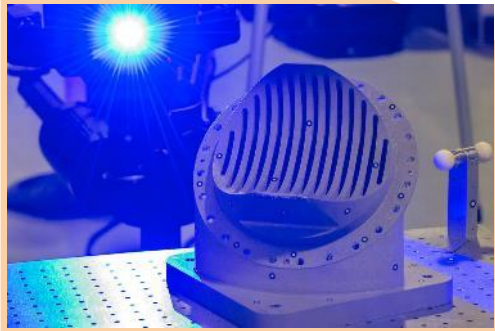


L-PBF GRCop-42 to Inco 625





Industrial Maturity and TRL of AM Processes



L-PBF

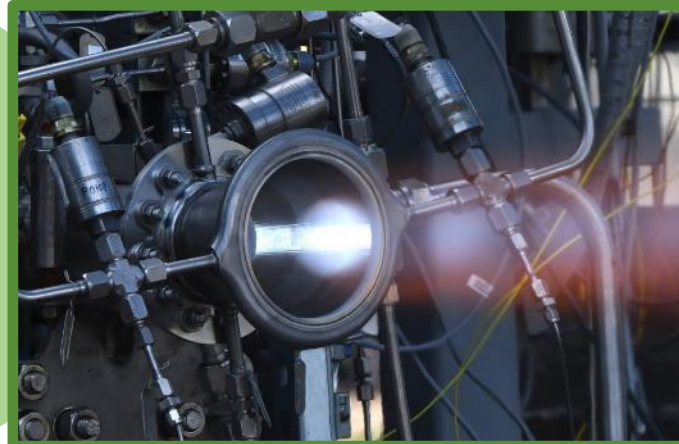


Cold spray

LP-DED



L-PBF



L-PBF

EBW-DED

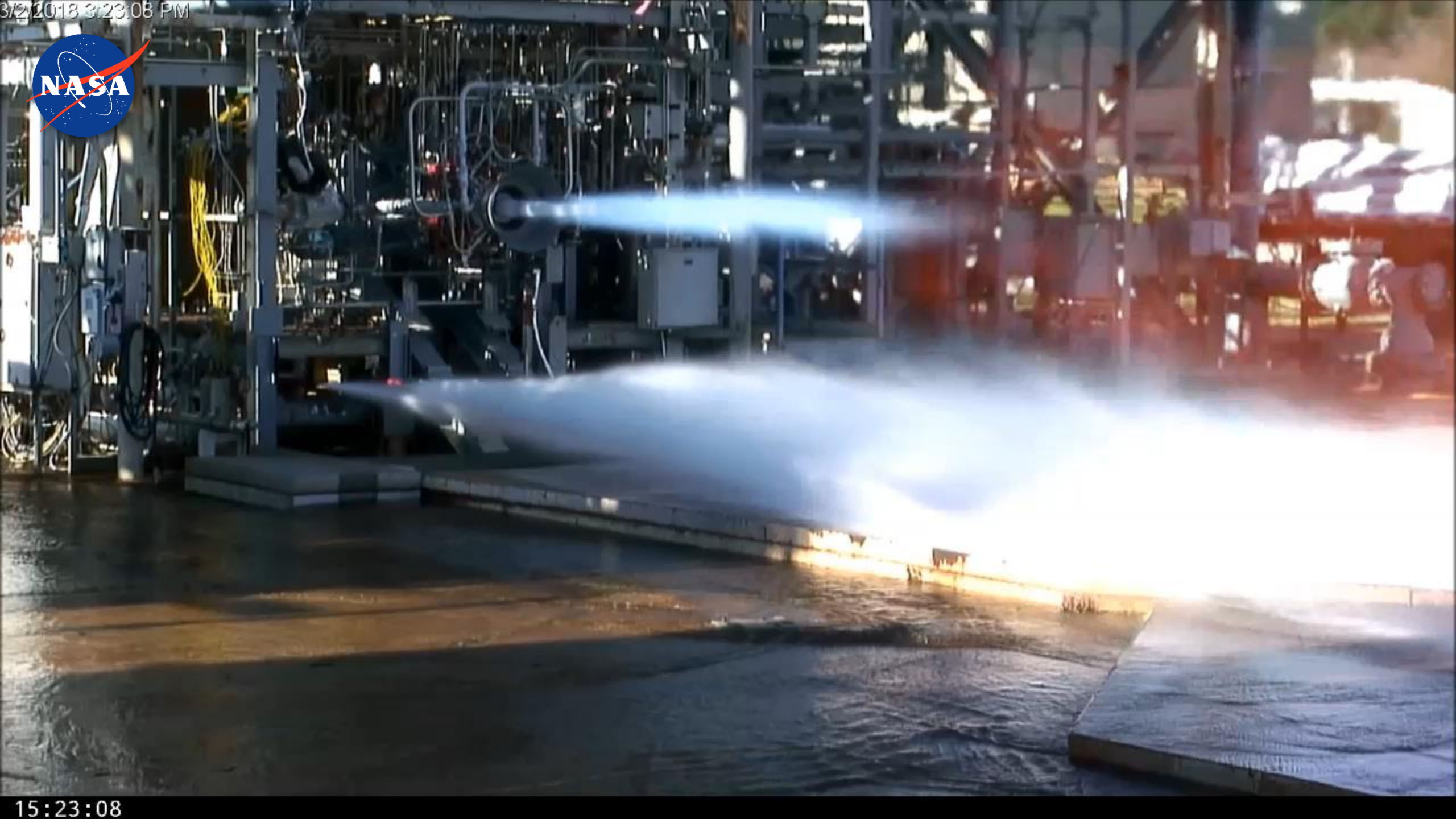


AW-DED



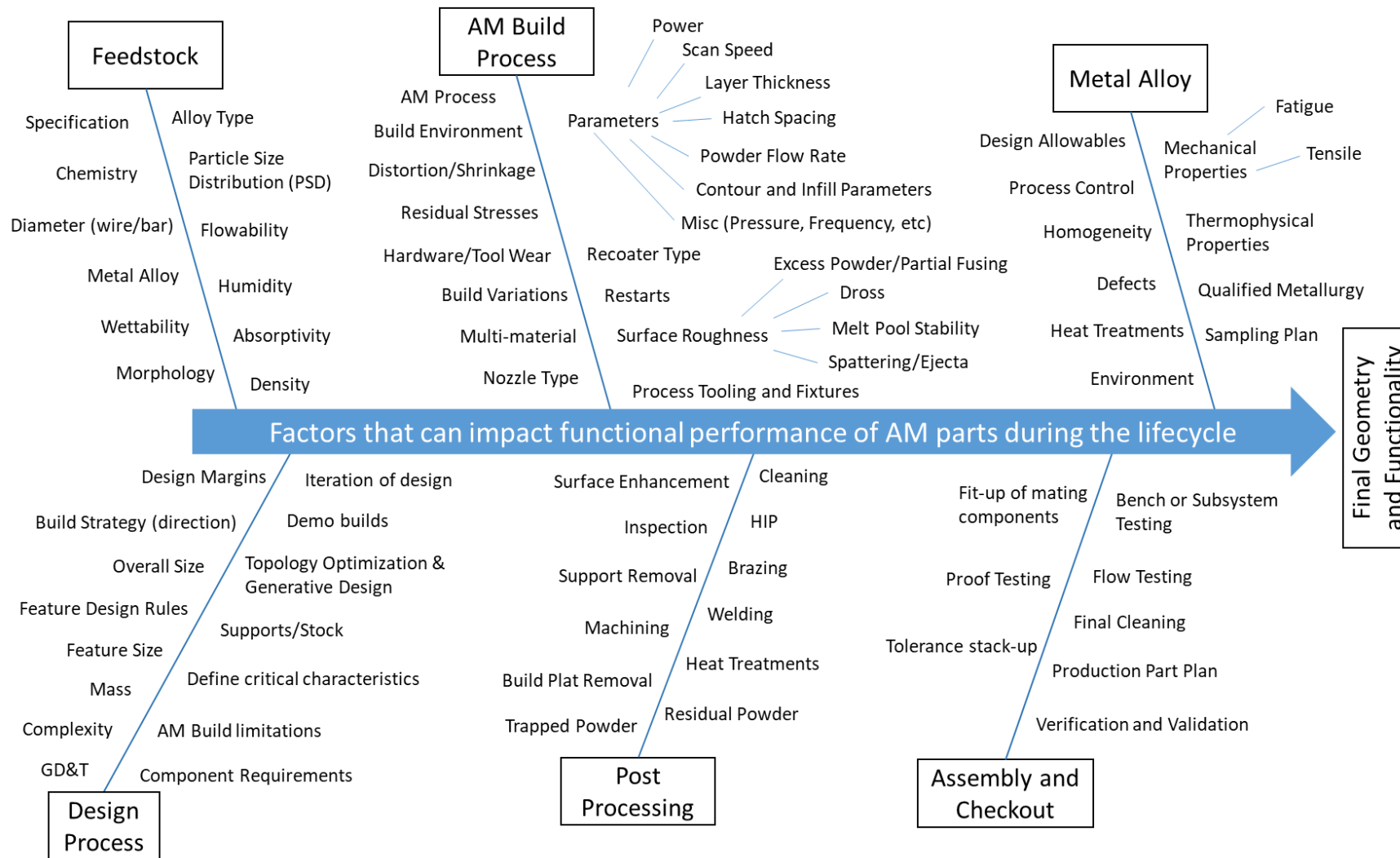
LW-DED

Over 110,000 sec of accumulated hot-fire time on chambers, nozzles, injectors

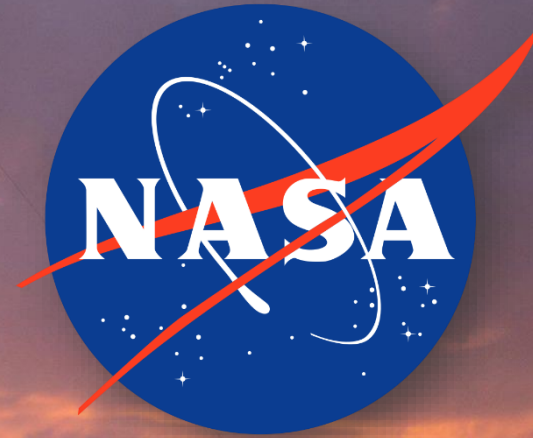




The Challenges with AM Processes



There are a lot of inputs and steps in the AM lifecycle that must go right to meet the expected geometry



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NASA led book on Metal Additive Manufacturing



Metal Additive Manufacturing for Propulsion Applications

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



PROGRESS IN ASTRONAUTICS AND AERONAUTICS

Timothy C. Liewen, Editor-in-Chief
Volume 263

<https://arc.aiaa.org/doi/book/10.2514/4.106279>

Online version and hardcopy available

P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022). *Metal Additive Manufacturing for Propulsion Applications*. AIAA Progress in Astronautics and Aeronautics Book Series.

<https://arc.aiaa.org/doi/book/10.2514/4.106279>

Additive manufacturing (AM) processes are proving to be a disruptive technology and are grabbing the attention of the propulsion industry. AM-related advancements in new industries, supply chains, design opportunities, and novel materials are increasing at a rapid pace. The goal of this text is to provide an overview of the practical concept-to-utilization lifecycle in AM for propulsion applications.