Metal Additive Manufacturing for Spaceflight

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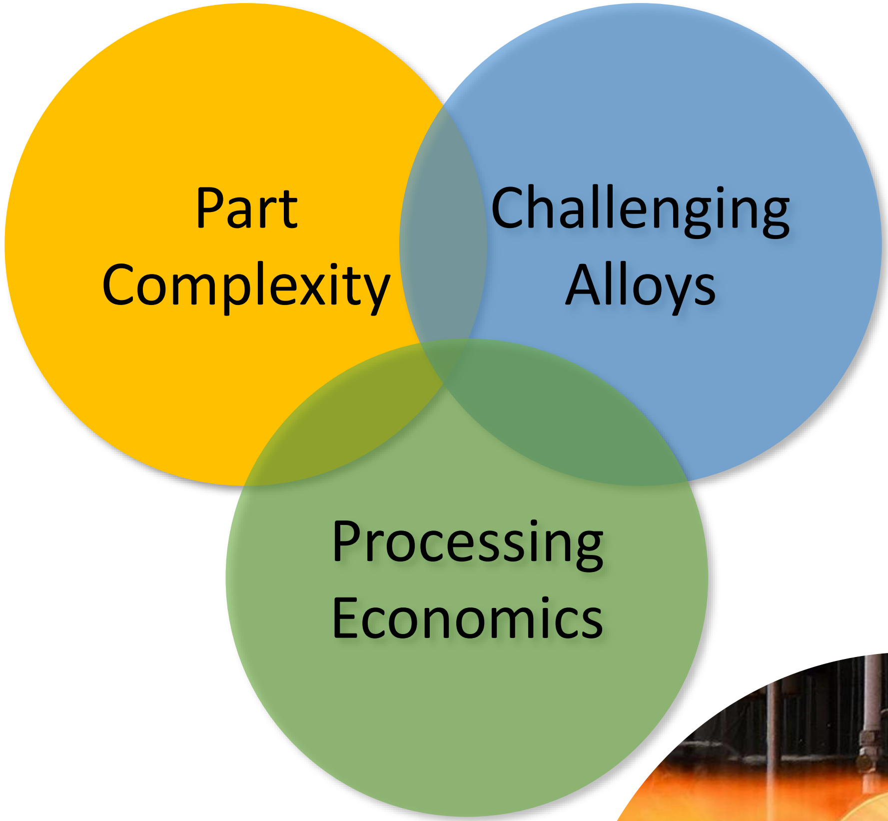
The Case for Additive Manufacturing in Propulsion

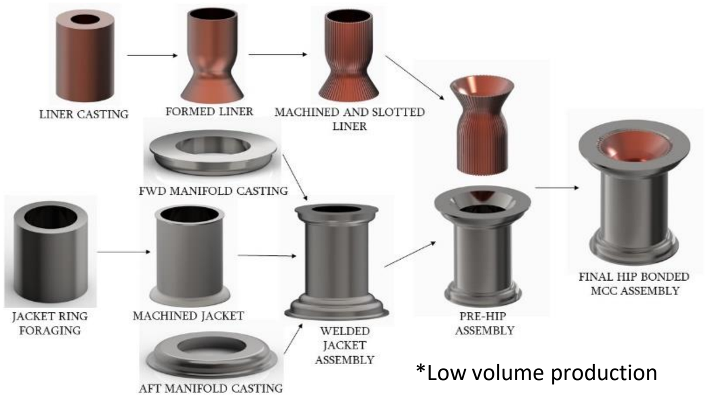
- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%

- Complexity is inherent in liquid rocket engines and AM provides new designs, part consolidation, 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.



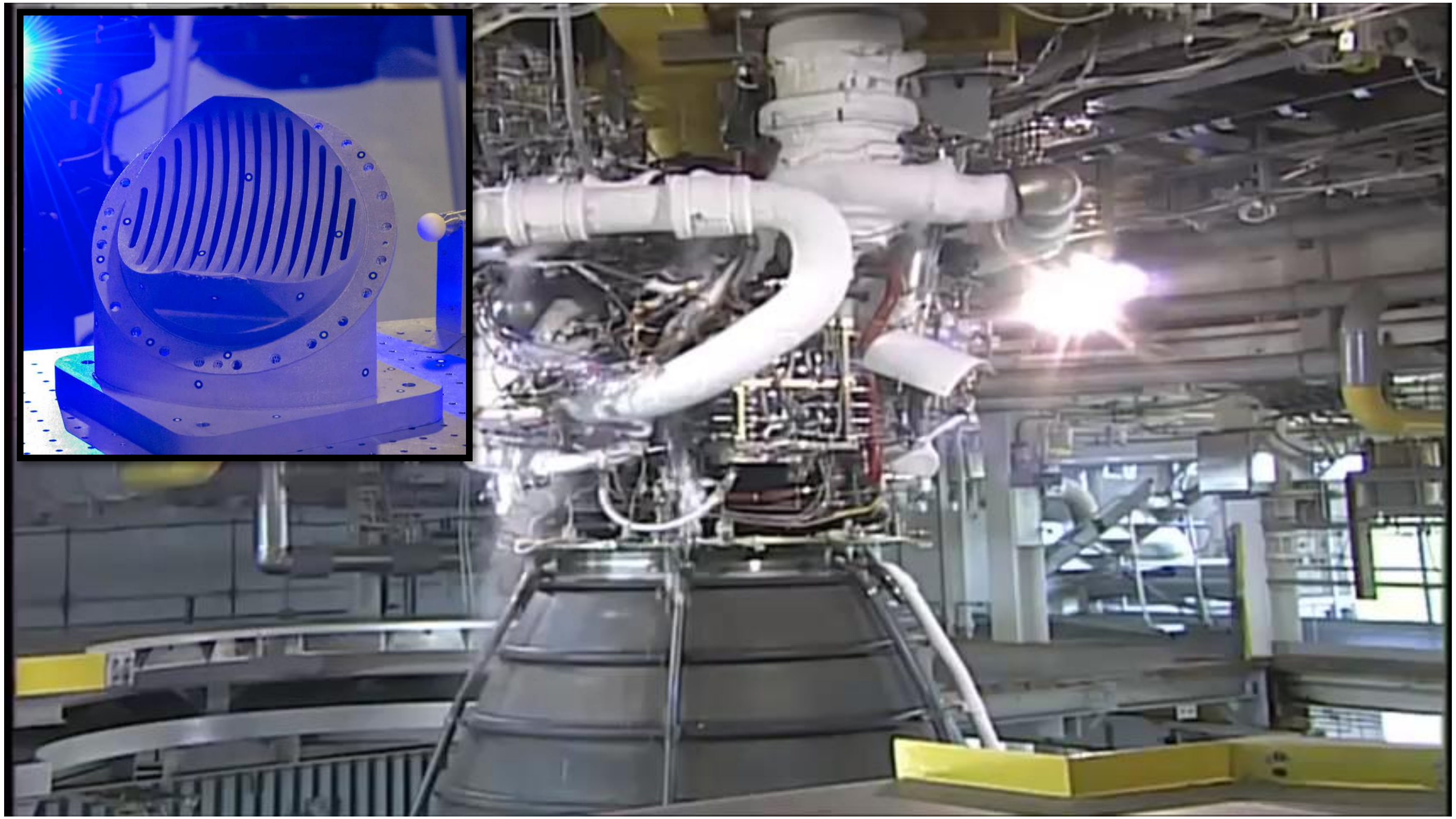
A rocket combustion chamber case study for AM



Category	Traditional Manufacturing	Initial AM Development	Evolving AM Development
Design and Manufacturing Approach	Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly	Four-piece assembly using multiple AM processes; limited by AM machine size. Two-piece L-PBF GRCop-84 liner and EBW-DED Inconel 625 jacket	Three-piece assembly with AM machine size restrictions reduced and industrialized. Multi-alloy processing; one-piece L-PBF GRCop-42 liner and Inconel 625 LP-DED jacket
Schedule (Reduction)	18 months	8 months (56%)	5 months (72%)
Cost (Reduction)	$310,000	$200,000 (35%)	$125,000 (60%)

As AM process technologies evolve using multi-materials and processes, additional design and programmatic advantages are being discovered

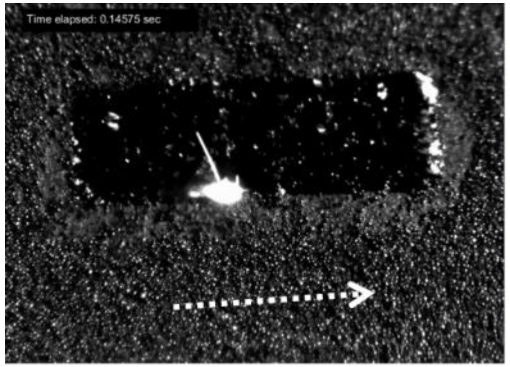
Additive Manufacturing in use on NASA Space Launch System (SLS)



Successful hot-fire testing of full-scale additive manufacturing (AM) Part to be flown on SLS RS-25
RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from <u>127 welds to 4 welds</u>

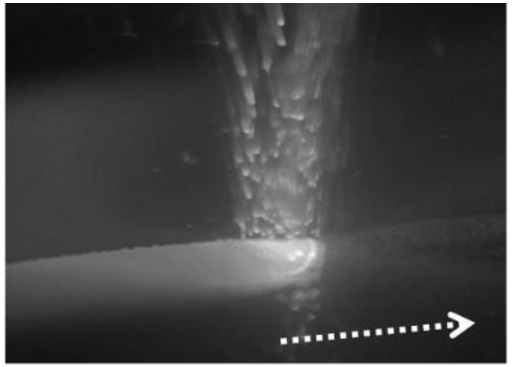
Ref: Andy Hardin, Steve Wofford/ NASA MSFC

AM Processes for various applications

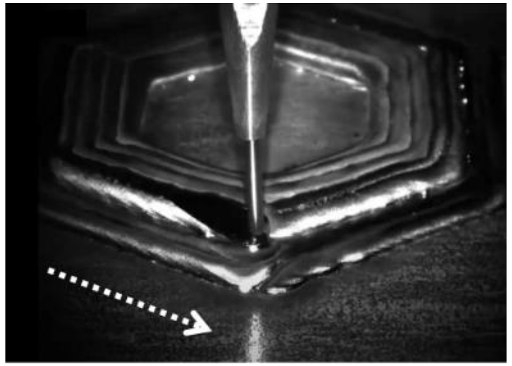


Laser Powder Bed Fusion

Electron Beam Powder Bed Fusion

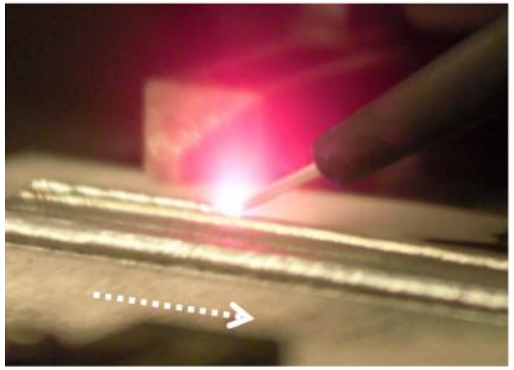


Laser Powder DED

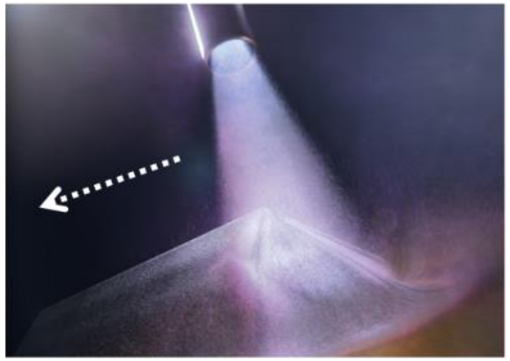


Laser Wire DED

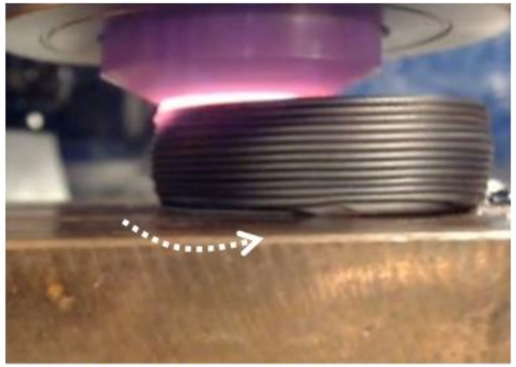
Arc Wire DED



Electron Beam Wire DED



Cold Spray



Additive Friction Stir Deposition

Ultrasonic Additive Manufacturing

**Not inclusive of all metal AM processes*

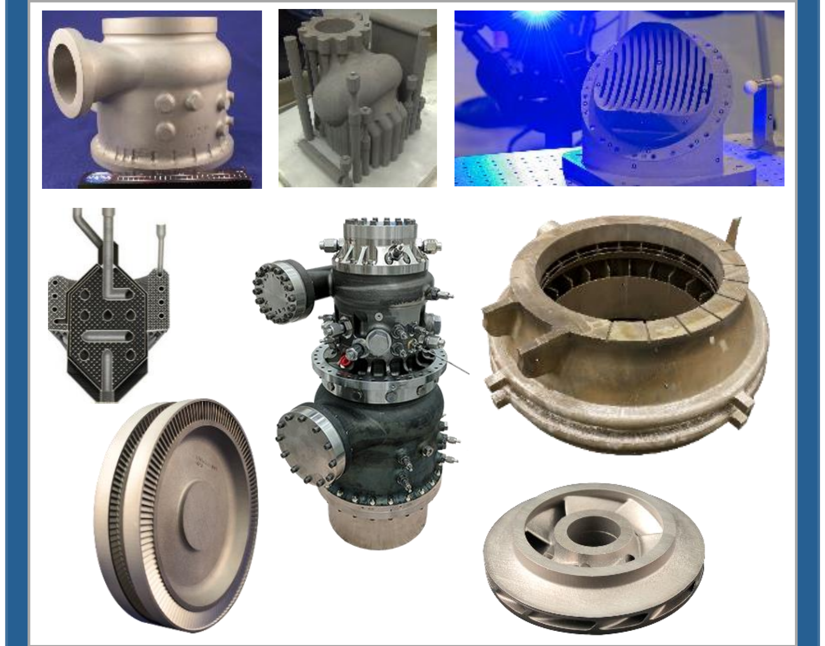
A) Laser Powder Bed Fusion [https://doi.org/10.1016/j.actamat.2017.09.051], B) Electron Beam Powder Bed Fusion *[Credit: Courtesy of Freemelt AB, Sweden],* C) Laser Powder DED *[Credit: Formalloy],* D) Laser Wire DED *[Credit: Ramlab and Cavitar],* E) Arc Wire DED *[Credit: Institut Maupertuis and Cavitar],*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

Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Release)

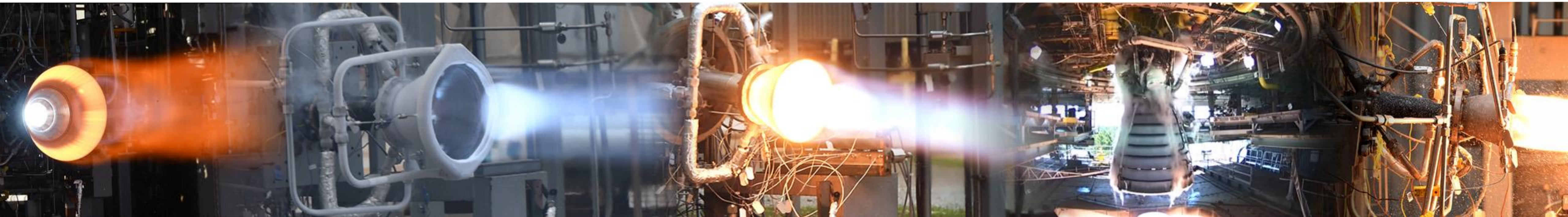
Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

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

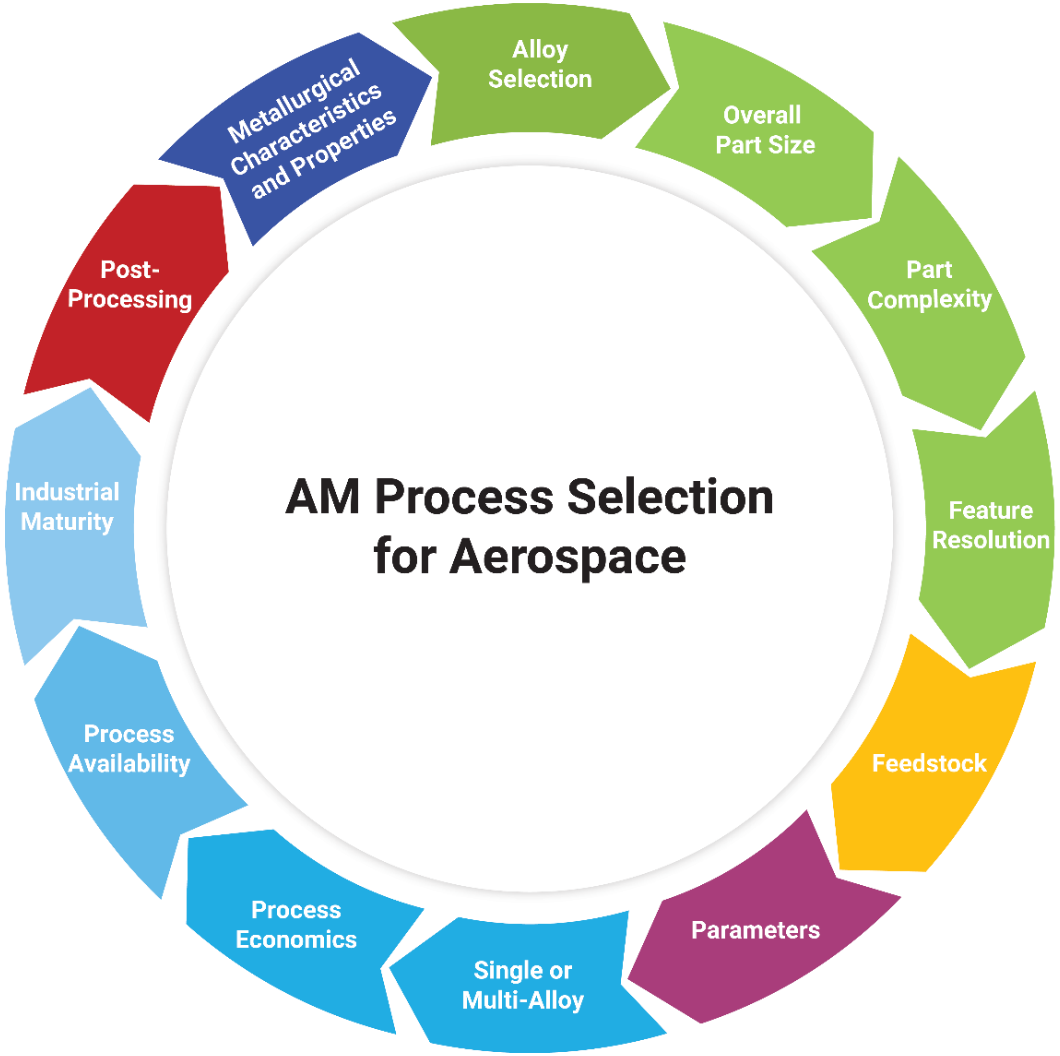
Directed Energy Deposition



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



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?

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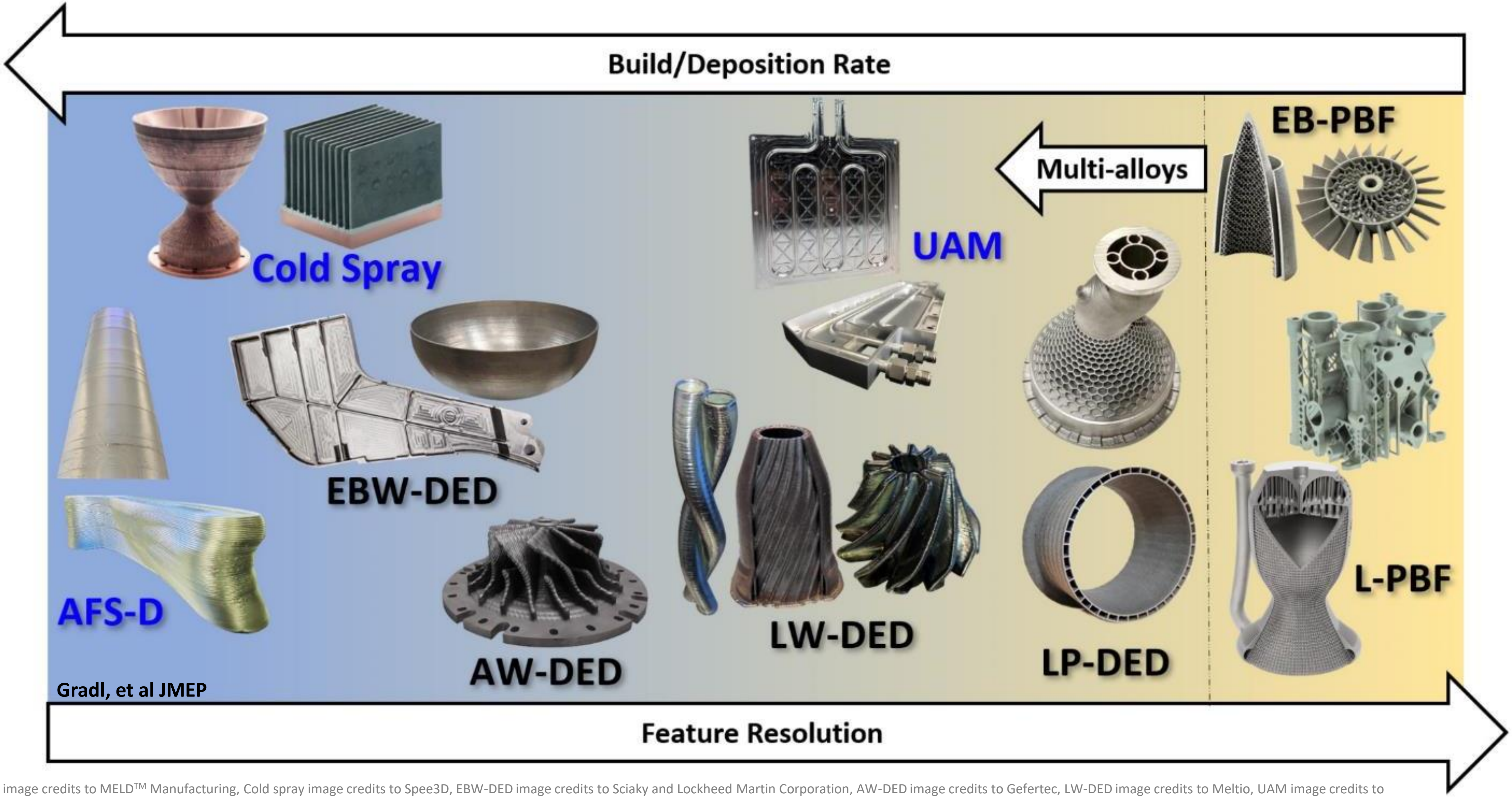
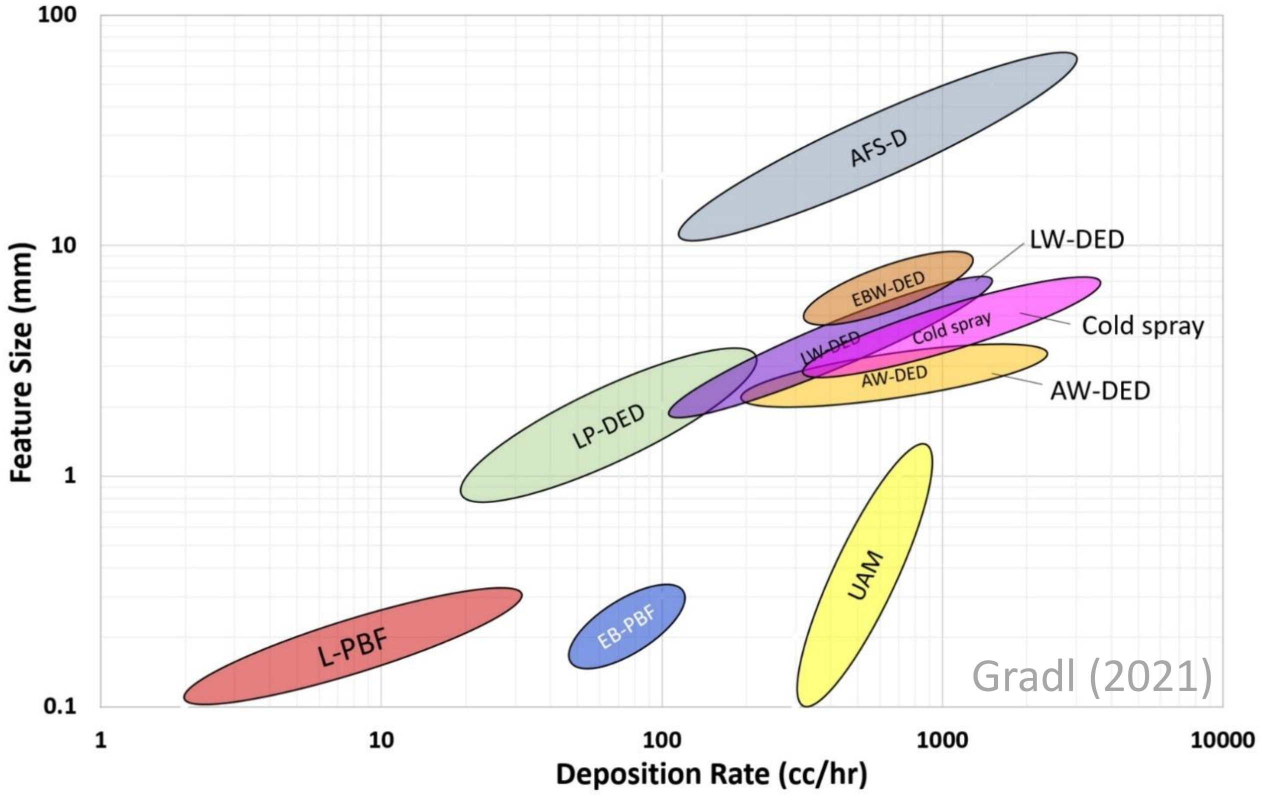
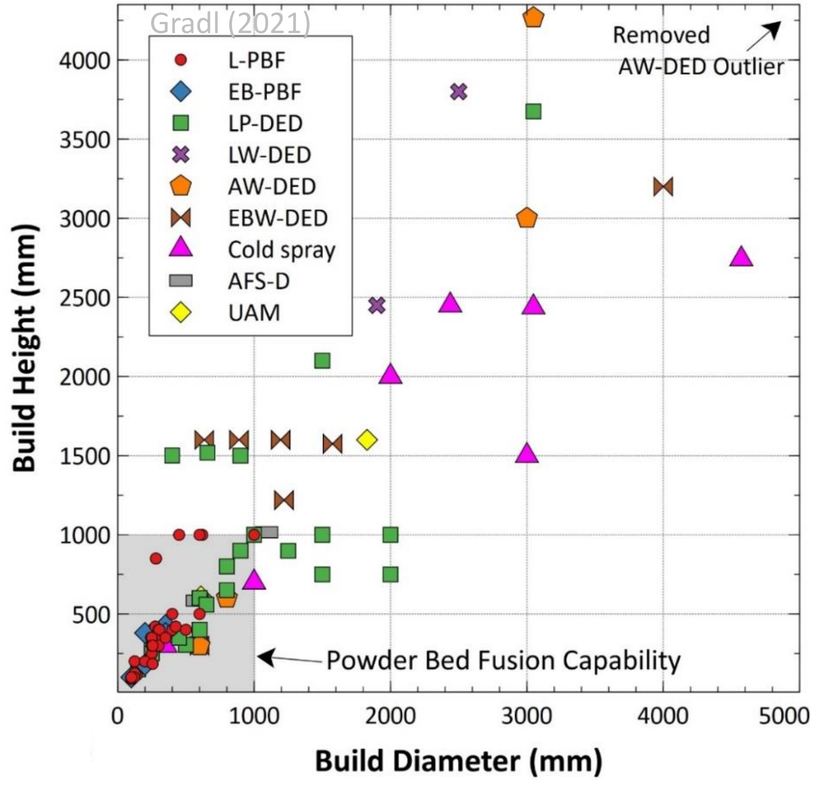
Criteria and Comparison Various Metal AM Processes



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.

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

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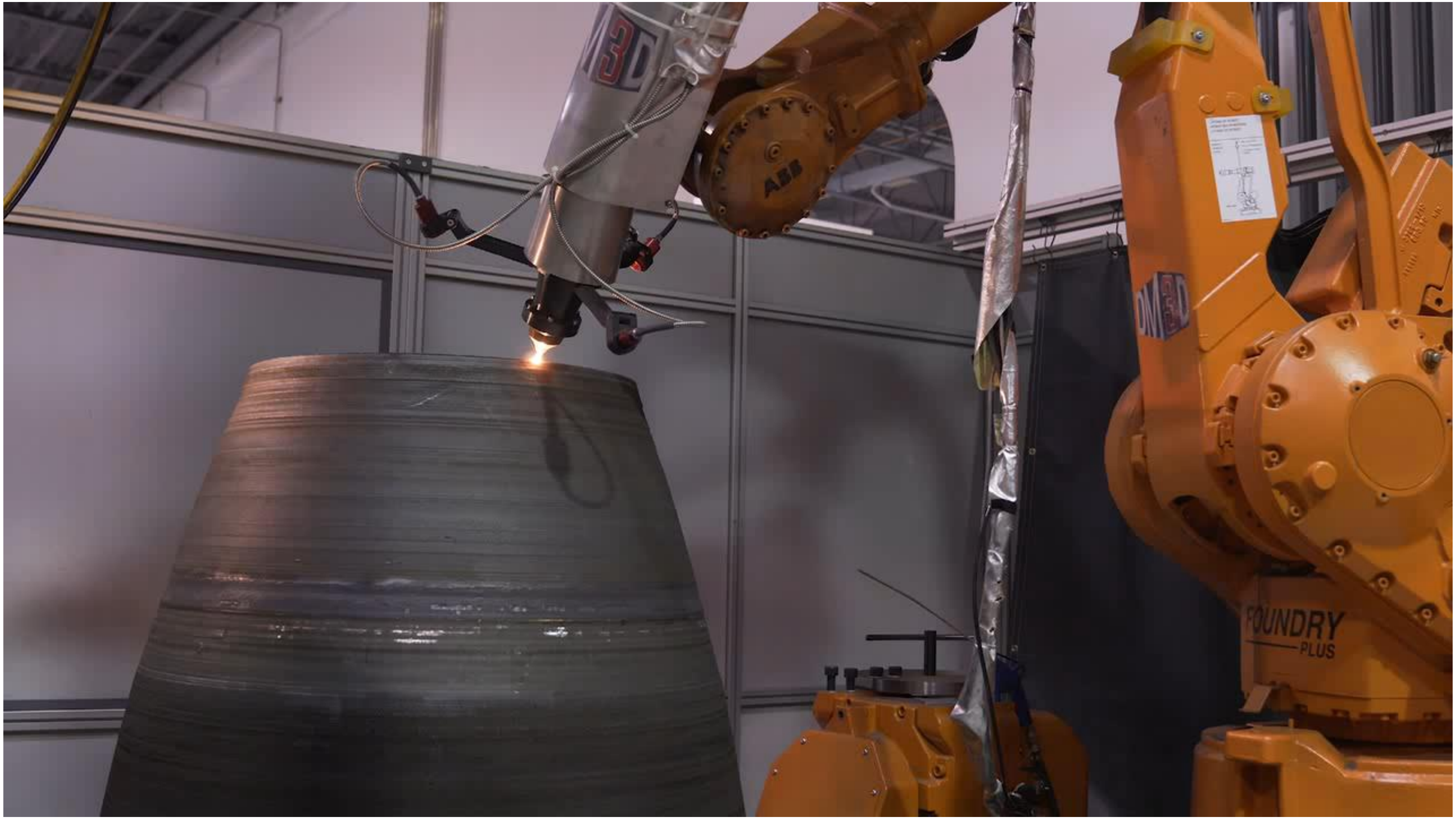
Laser Powder Directed Energy Deposition (DED)



LP-DED Large Scale Nozzle Development

60” (1.52 m) diameter and 70” (1.78 m) height with integral channels

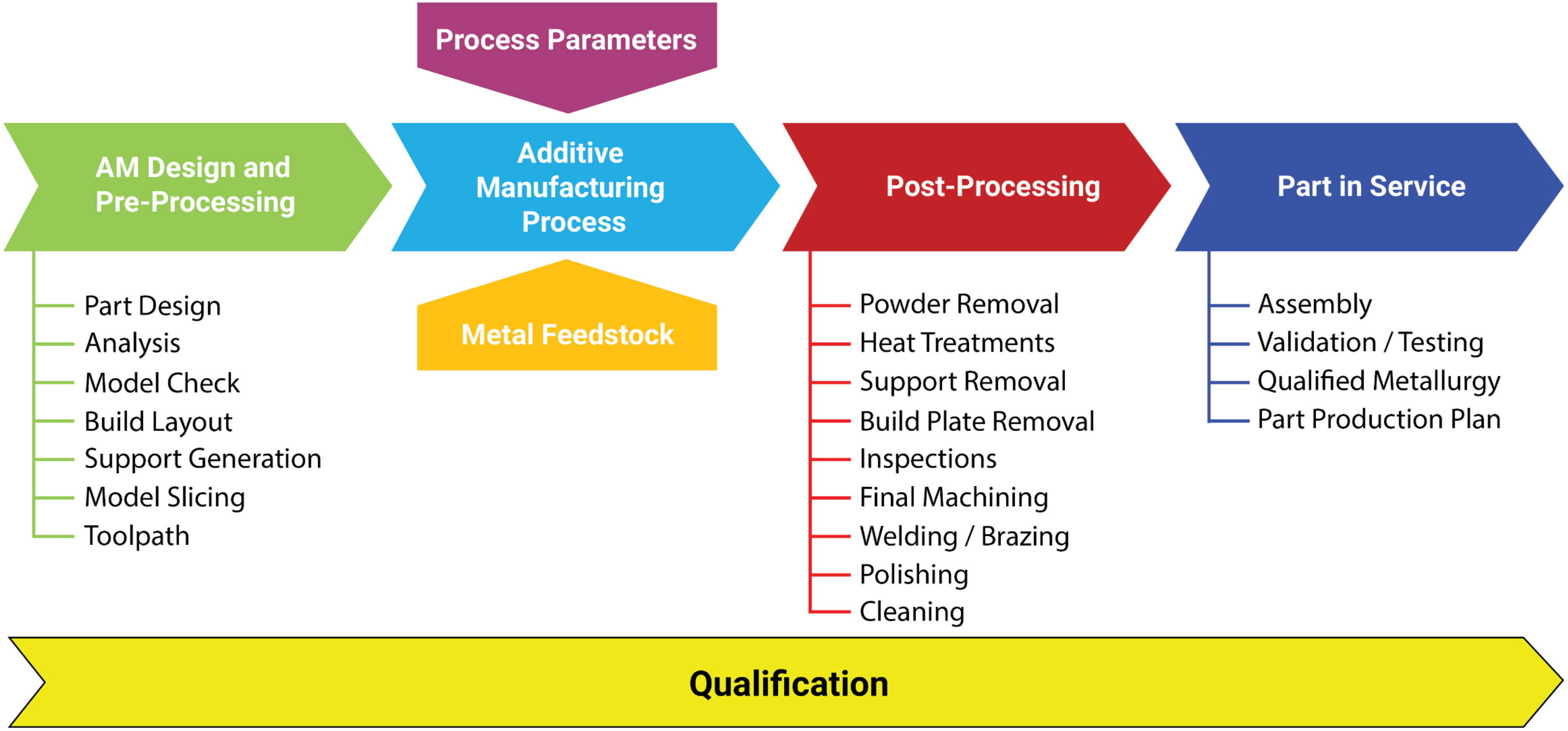
90 day deposition

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

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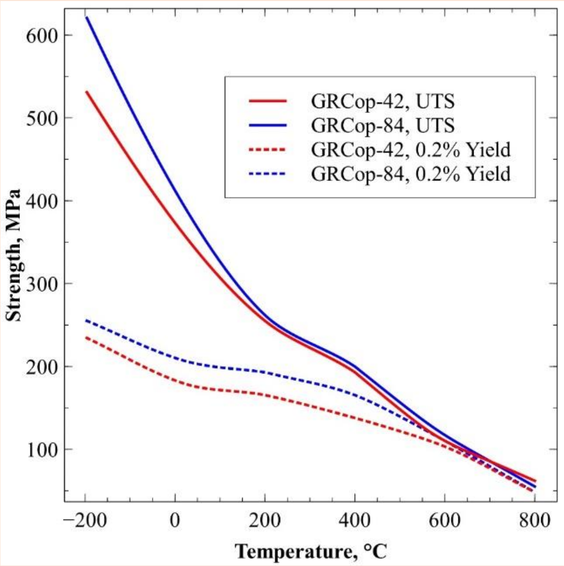
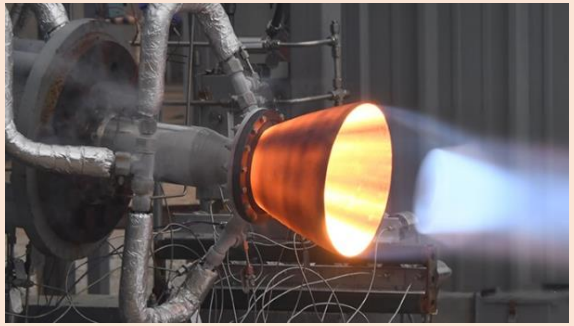
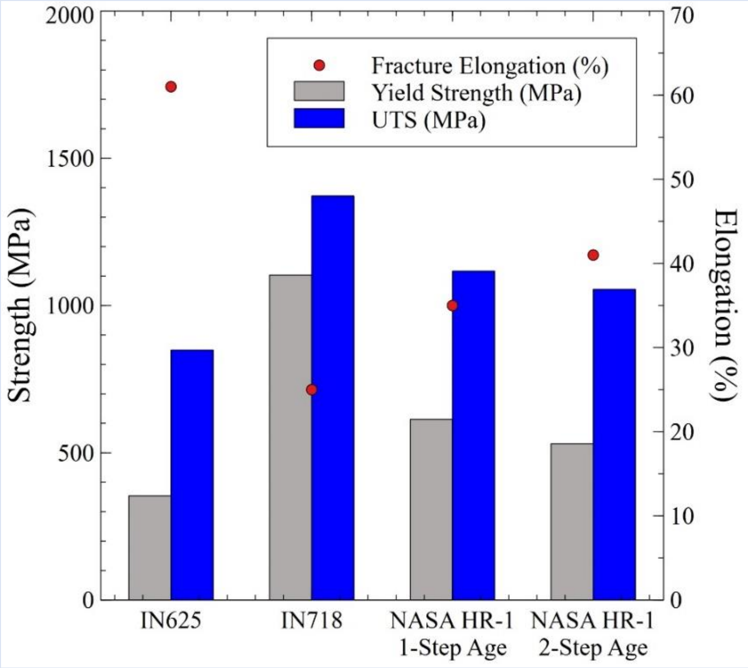
Enabling New Alloy Development using Additive Manufacturing

GRCop-42, High conductivity and strength for high heat flux applications

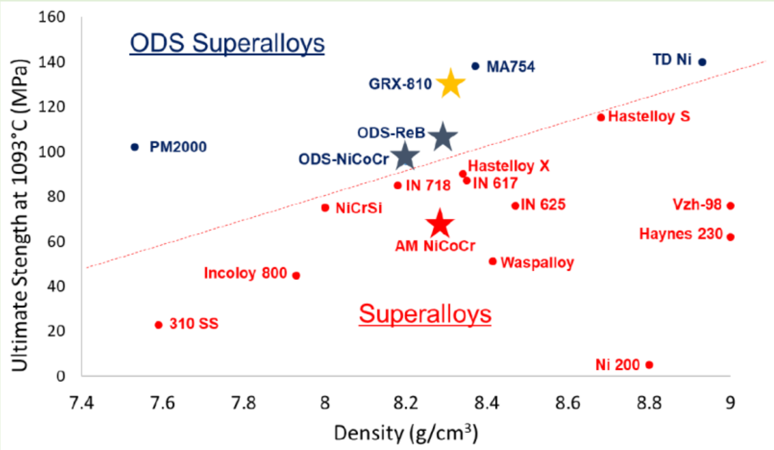




NASA HR-1, high strength superalloy for hydrogen environments

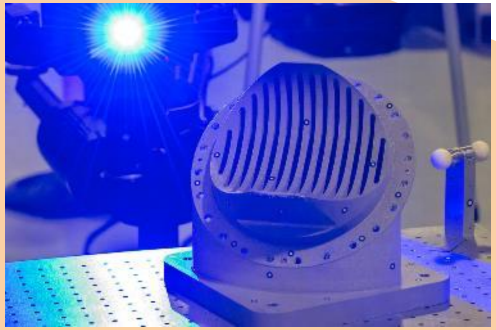


GRX-810, high strength, low creep rupture and oxidation at extreme temperatures



Ref: Tim Smith, Christopher Kantzos / NASA GRC

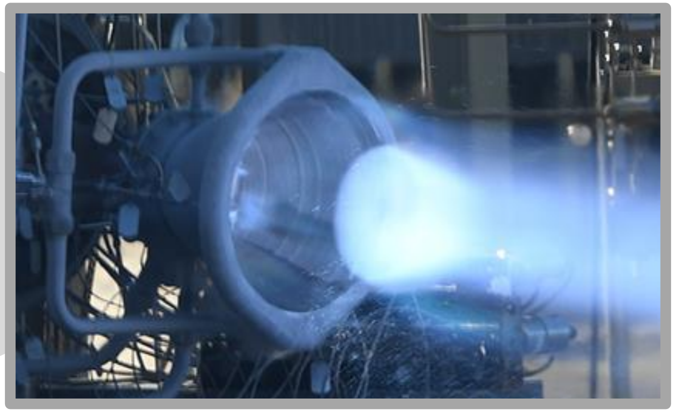
Industrial Maturity and TRL of AM Processes



L-PBF

Cold spray

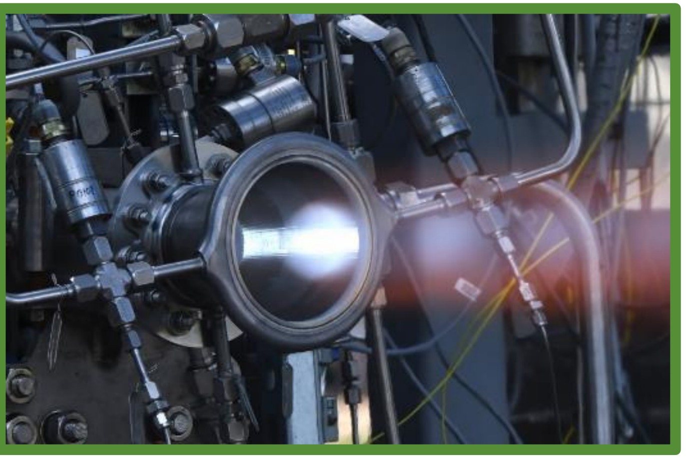
LP-DED



L-PBF

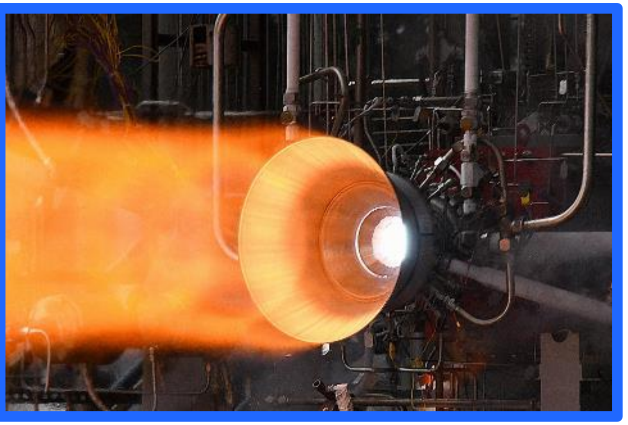
AW-DED

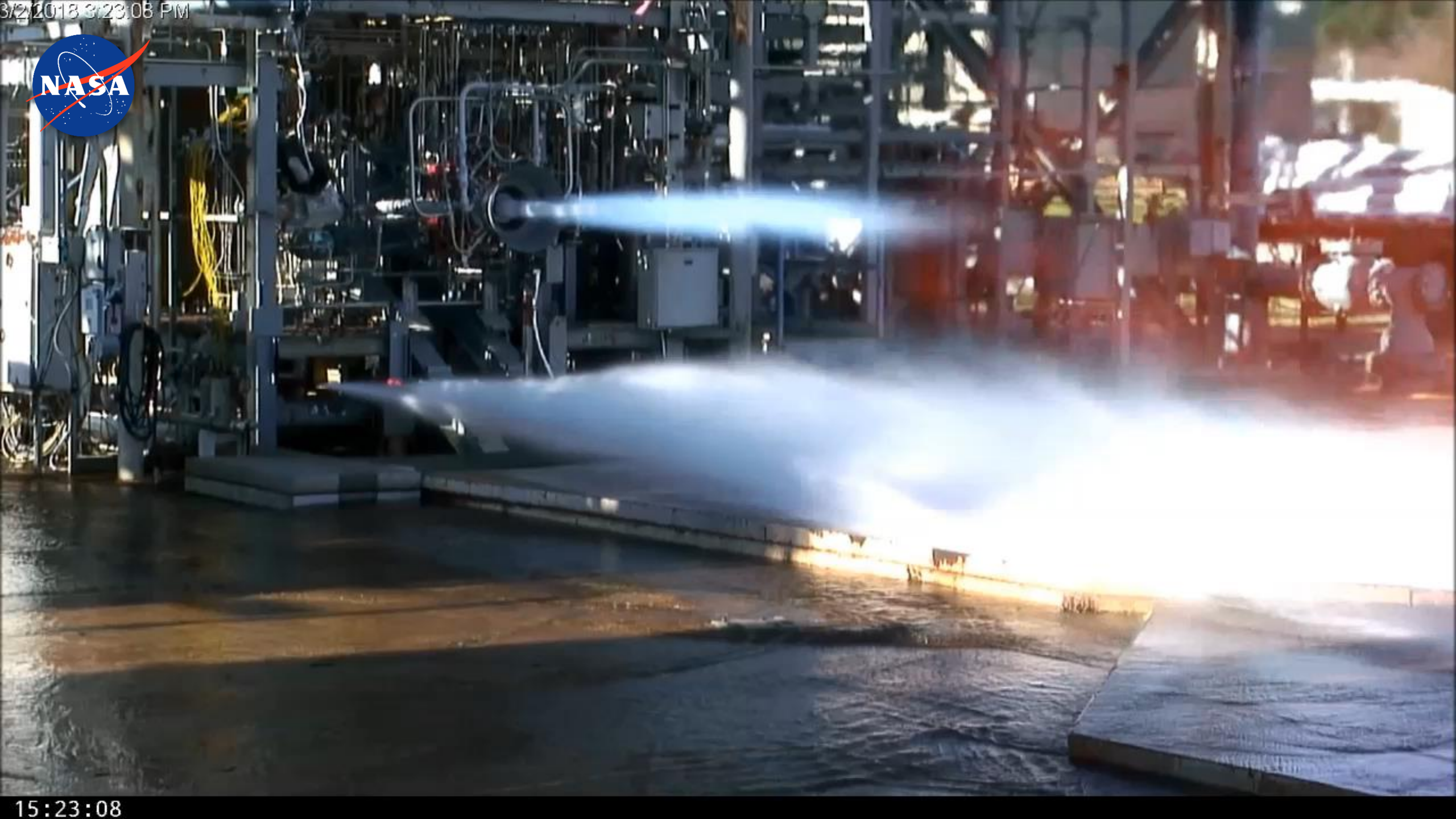
LW-DED



L-PBF

EBW-DED

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NASA
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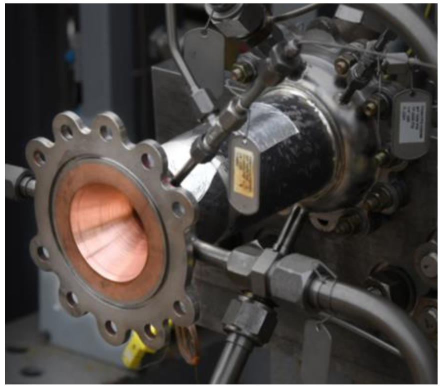
Emerging Areas of Development for Metal AM

- Maturing each of the AM processes and understanding of microstructure, properties, build limitations, and methods for design and post-processing.
- Ongoing development for large scale AM using DED and other processes.
- Continuous hot-fire and component testing to advance various combustion chambers, injectors, nozzles, ignition systems, turbomachinery, valves, lines, ducts, in-space thrusters.
- Polishing (surface enhancements internally) and post-processing development.
- Combining various AM processes for multi-alloy solutions or additional design options.
- Advancement of commercial supply chain for unique alloys (GRCop-42, NASA HR-1, JBK-75).
- New alloy development (Refractory, Ox-rich environments, AM-specific alloys).
- Material database of metal AM properties to allow for conceptual design – tensile, fatigue and thermophysical.
- Design complexity using lattices and thin-wall structures.
- Standards and certification of metal AM are evolving for human spaceflight.

Summary

- Various AM processes have matured for rocket propulsion applications each with unique advantages and disadvantages.
- AM is not a solve-all; consider trading with other manufacturing technologies and use only when it makes sense.
- **Complete understanding of the design process, build-process, feedstock, and post-processing is critical to take full advantage of AM.**
- Additive manufacturing takes practice!
- Standards and certification of the AM processes are in-work.
- AM is evolving and imagination is the limit.





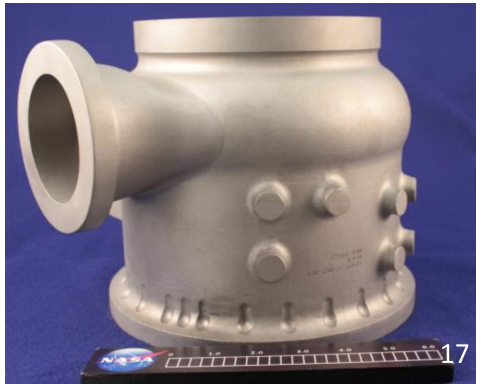



Photo: NASA/Ben Smegelsky

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Bimetallic AM for combustion chambers

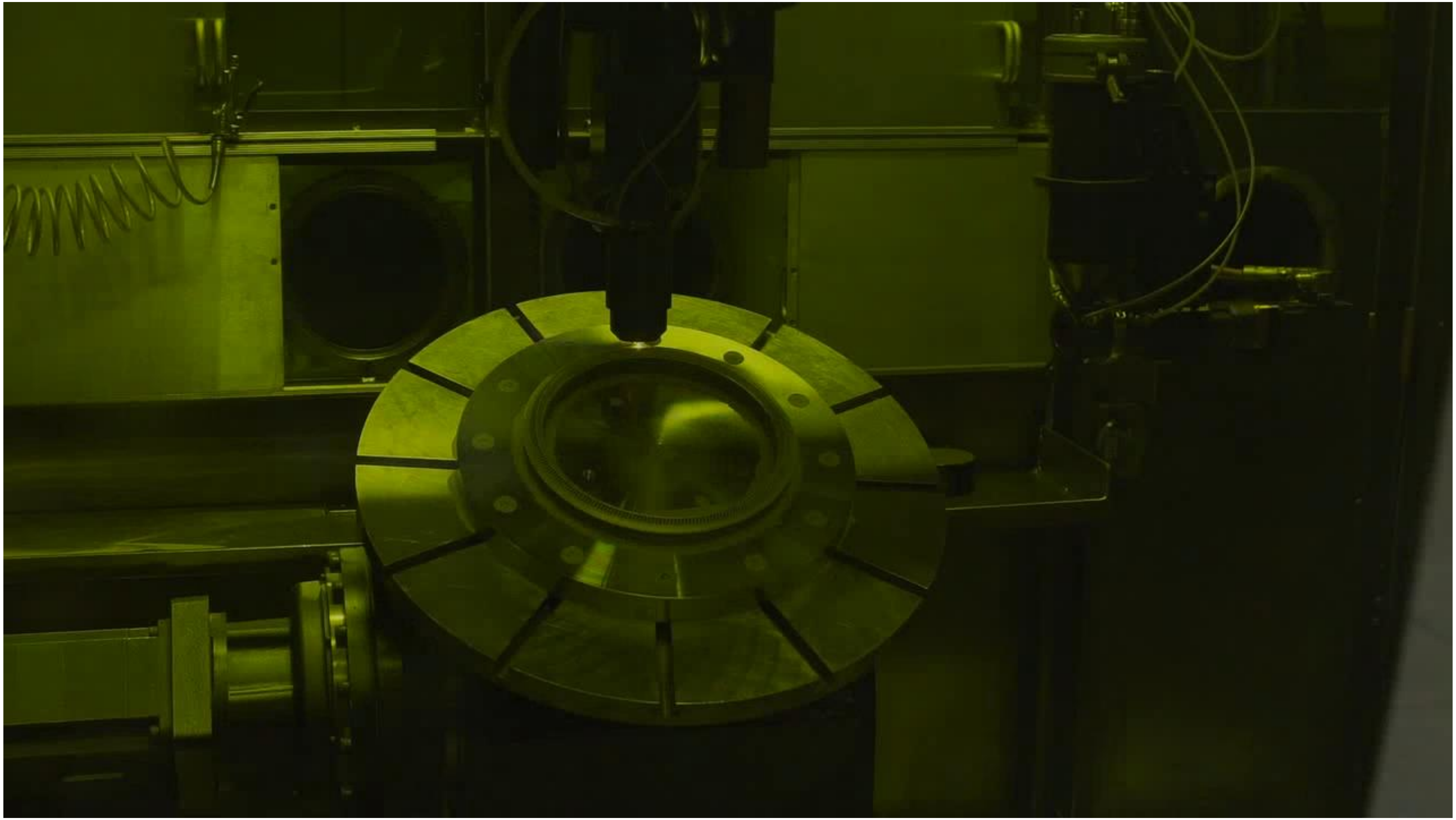
LP-DED Jacket

Cold spray Jacket

Direct deposit LP-DED nozzle (Axial Bimetallic)

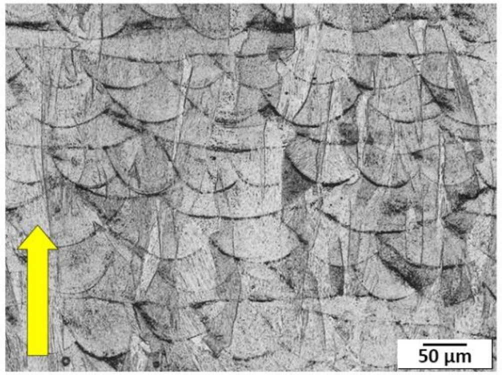
EBW-DED Jacket

Example of LP-DED with small features

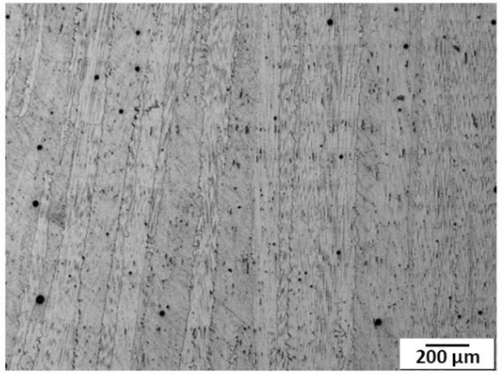


Microstructure of Various AM Processes
Alloy 625

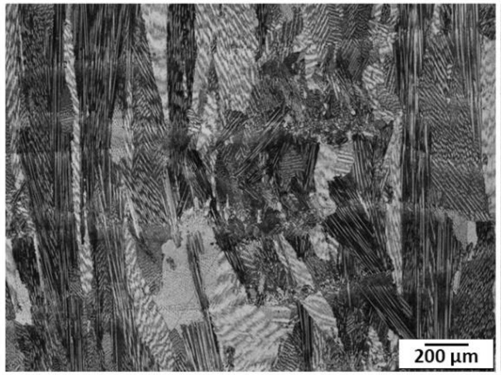
As-built microstructure of Alloy 625 => Requires proper post-processing heat treatments



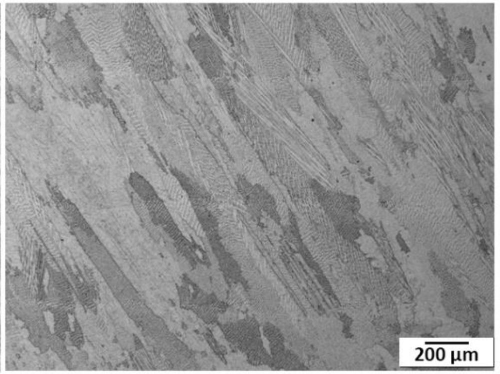
A) Laser Powder Bed Fusion



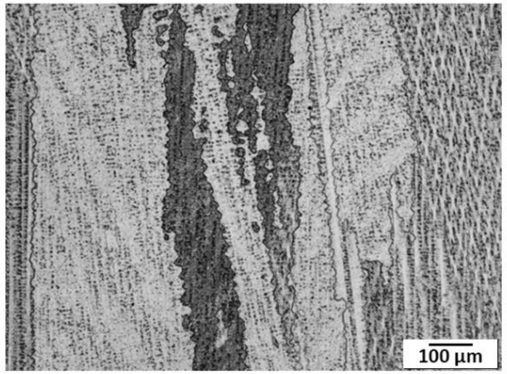
B) Electron Beam Powder Bed Fusion



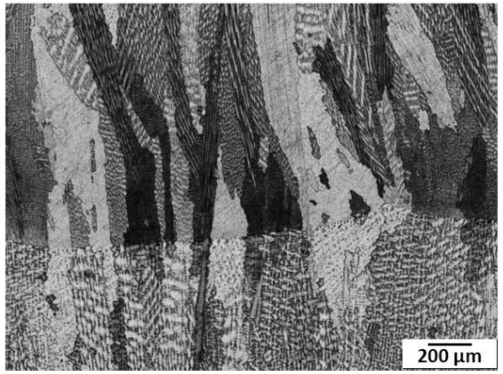
C) Laser Powder DED (1070 W)



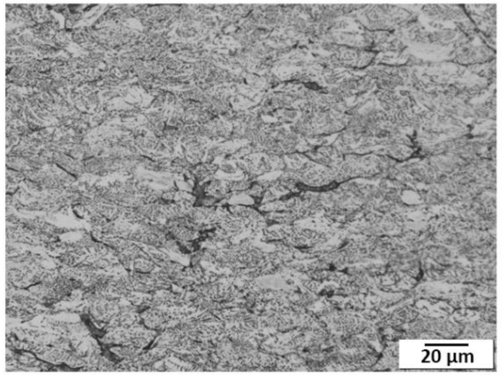
D) Laser Wire DED



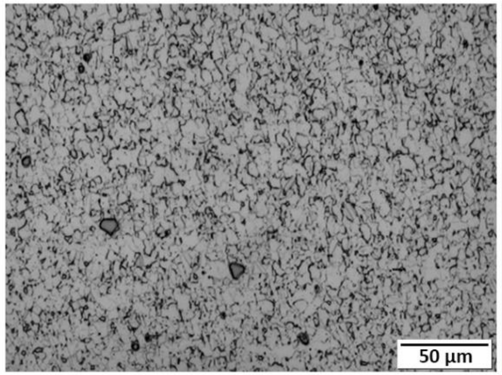
E) Arc Wire DED



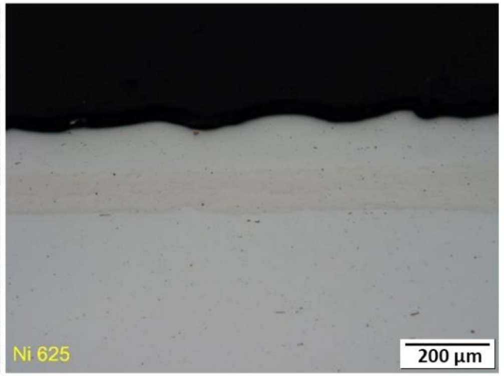
F) Electron Beam Wire DED



G) Cold Spray



H) Additive Friction Stir Deposition



I) Ultrasonic Additive Manufacturing

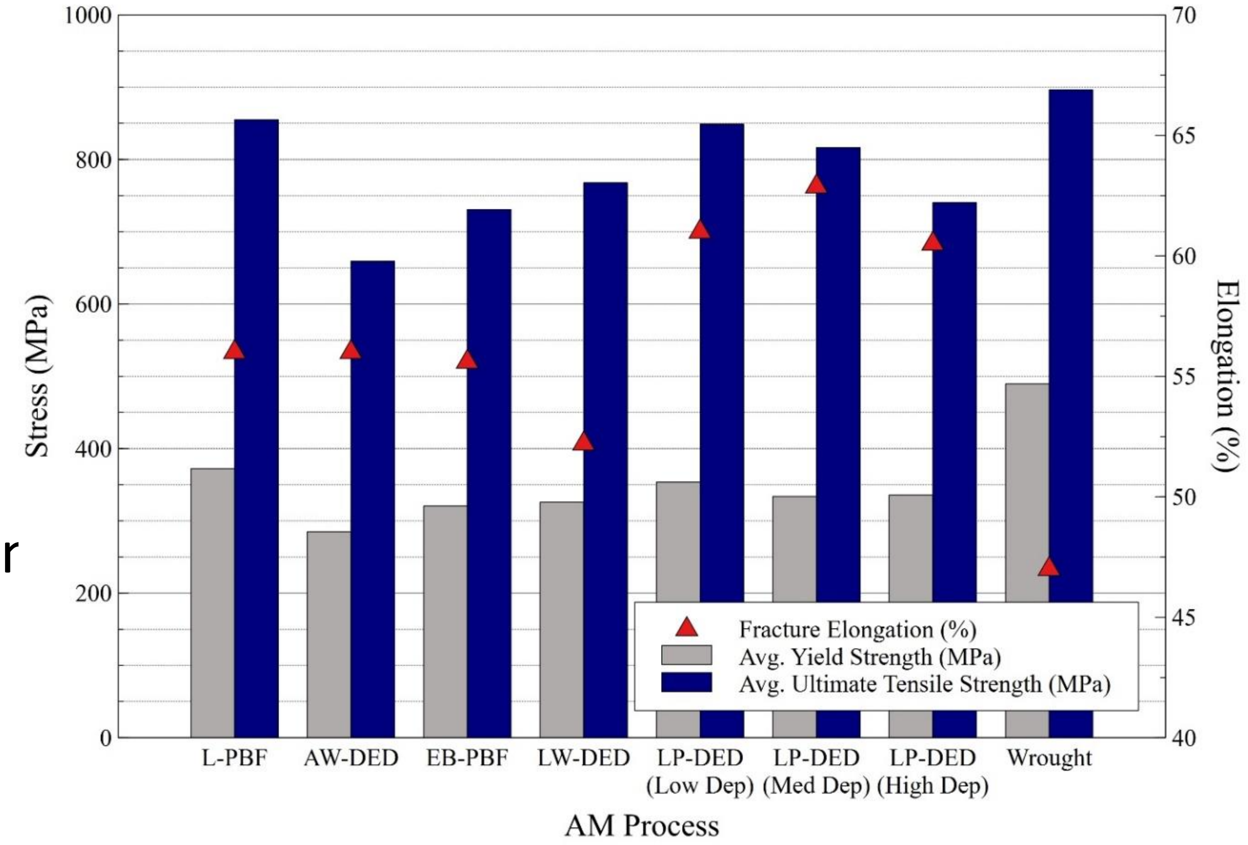
Each AM process results in different grain structures, which ultimately influence properties

- Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Review)
- 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

Material Properties for Various AM Processes

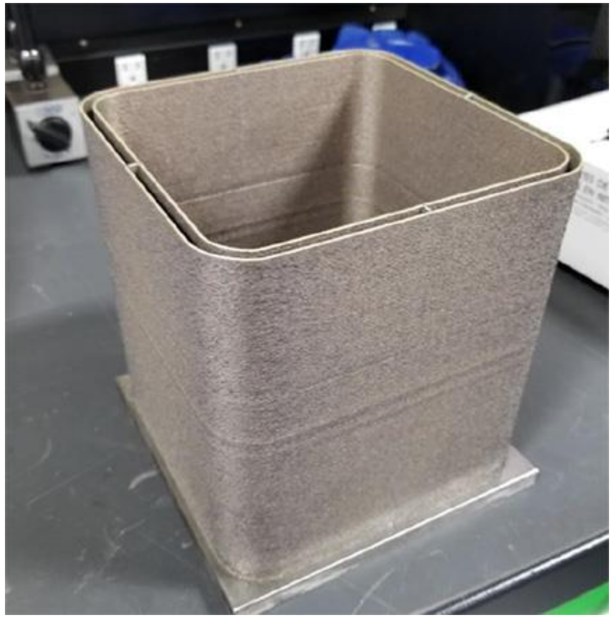
- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Cold spray….), the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build.
- Each AM process results in different grain distributions, precipitates, and porosity,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

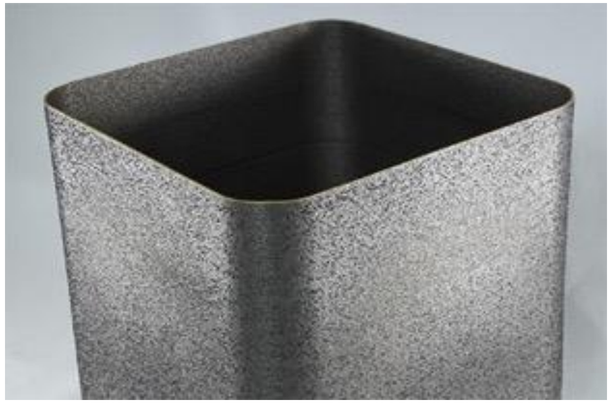
Alloy 625 – Room Temperature UTS

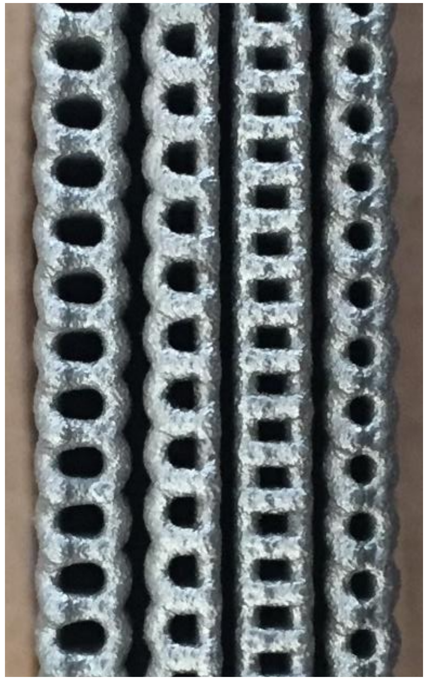


*Not design data and provided as an example only

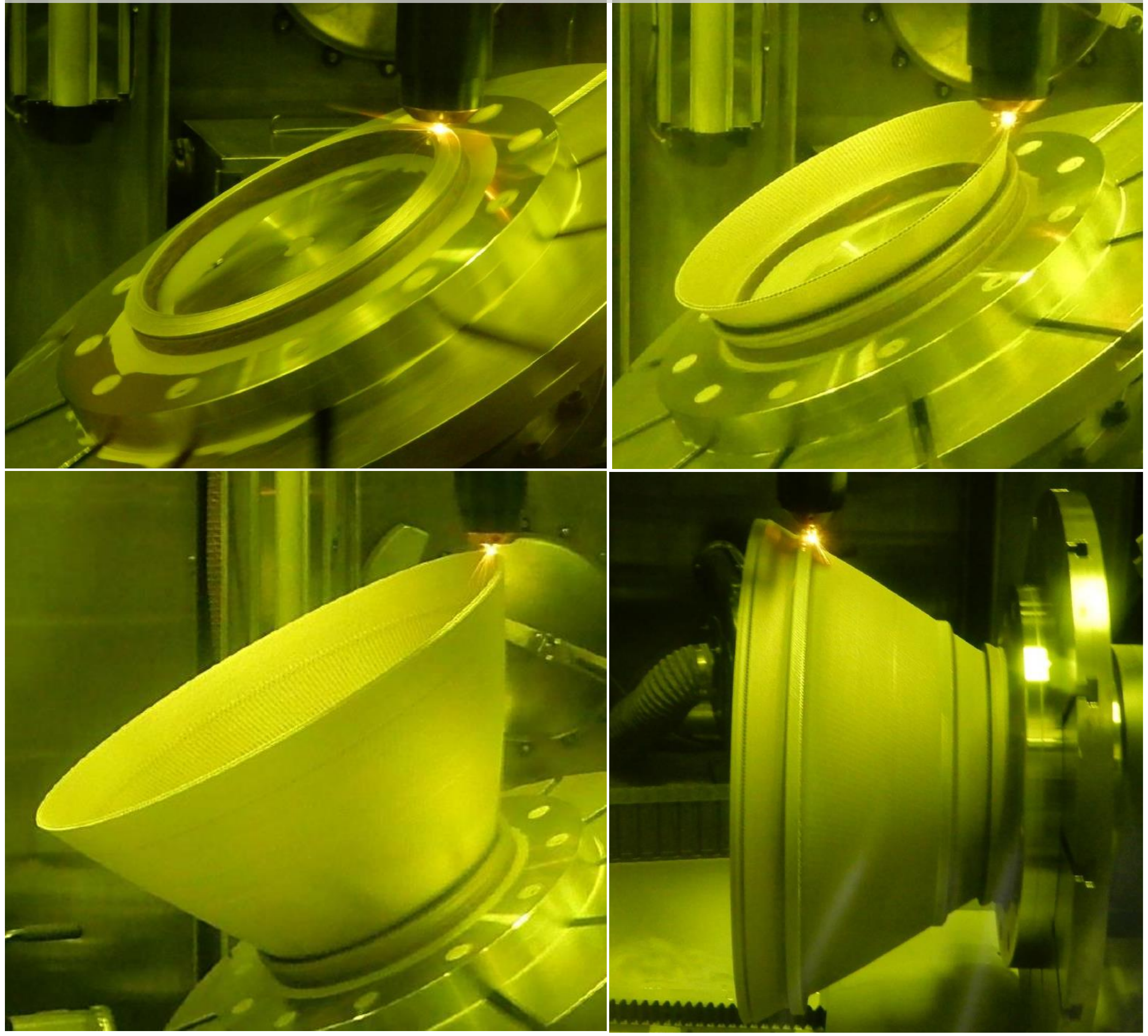
Large-scale Thin Wall Deposition of Nozzles



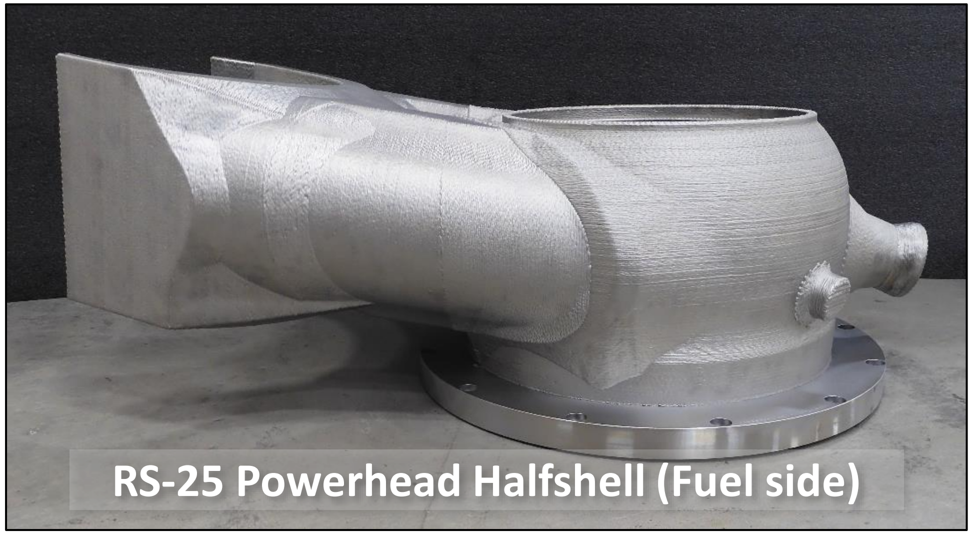




Process Development for DED of nozzles

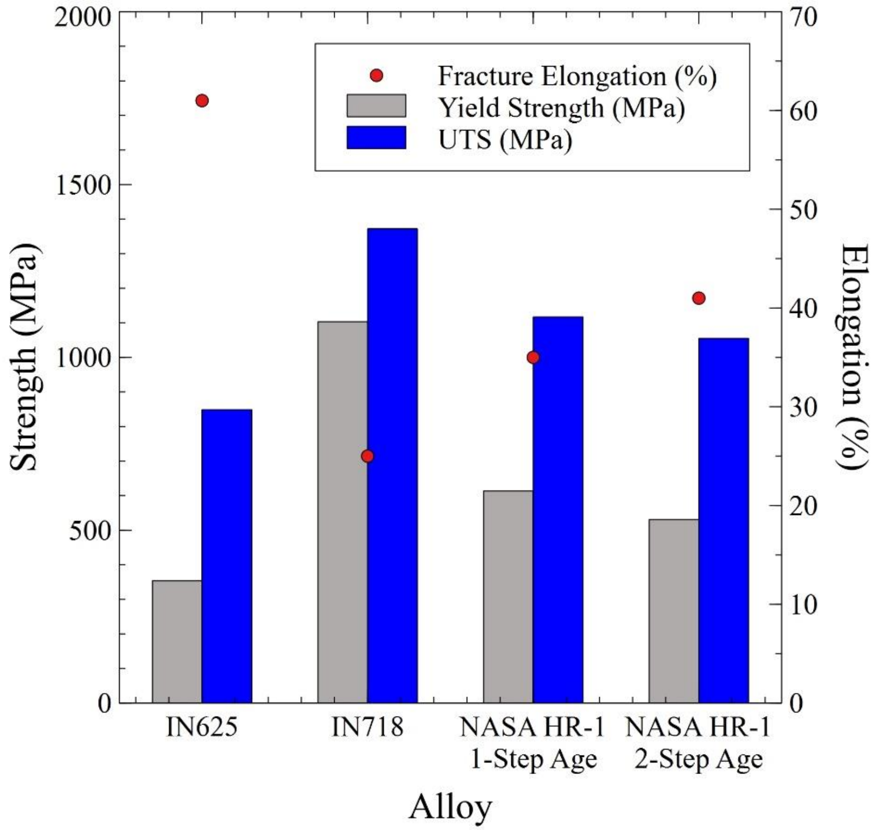


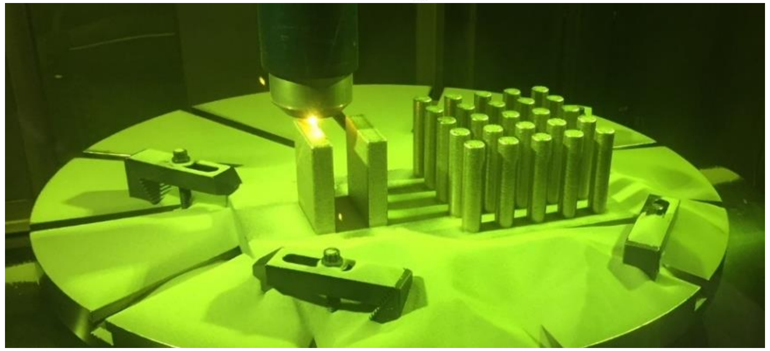
NASA HR-1 Components Fabricated using LP-DED



New Alloy Development using AM – NASA HR-1

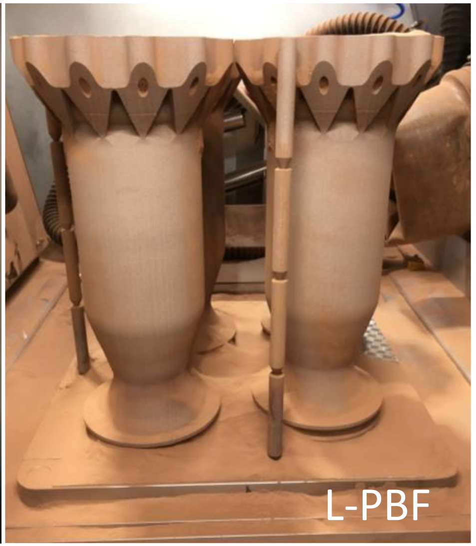
- **NASA HR-1** is an Fe-Ni-Cr alloy developed for high pressure hydrogen environments.
- Derived from JBK-75 and designed for higher strength and improved weldability.
- Reformulated for AM LP-DED to reduce Titanium segregation.
- Advanced using LP-DED at different deposition rates to allow for variations in wall thickness and deposition time as well as L-PBF.
- Optimization of heat treatment for H2 embrittlement and required properties.

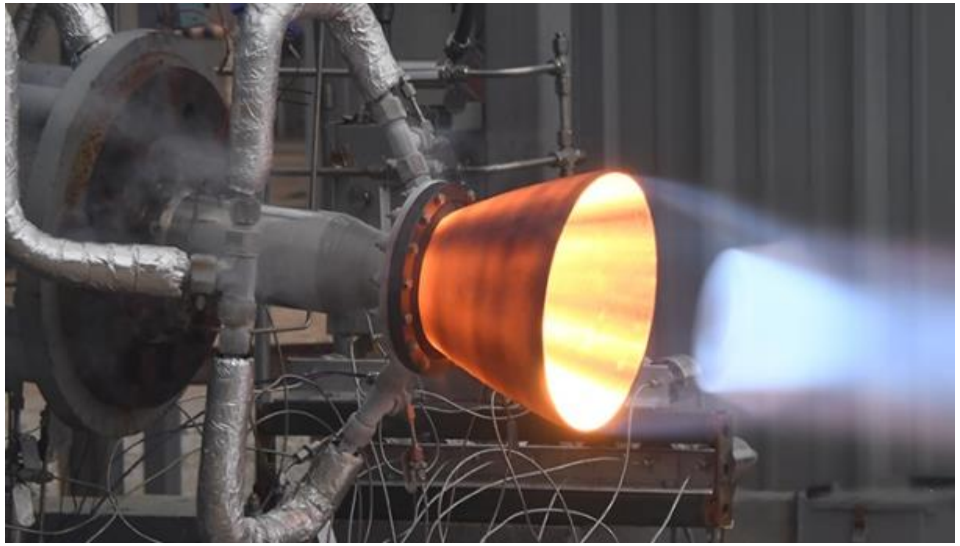




GRCop-42 and GRCop-84 for Combustion Chambers

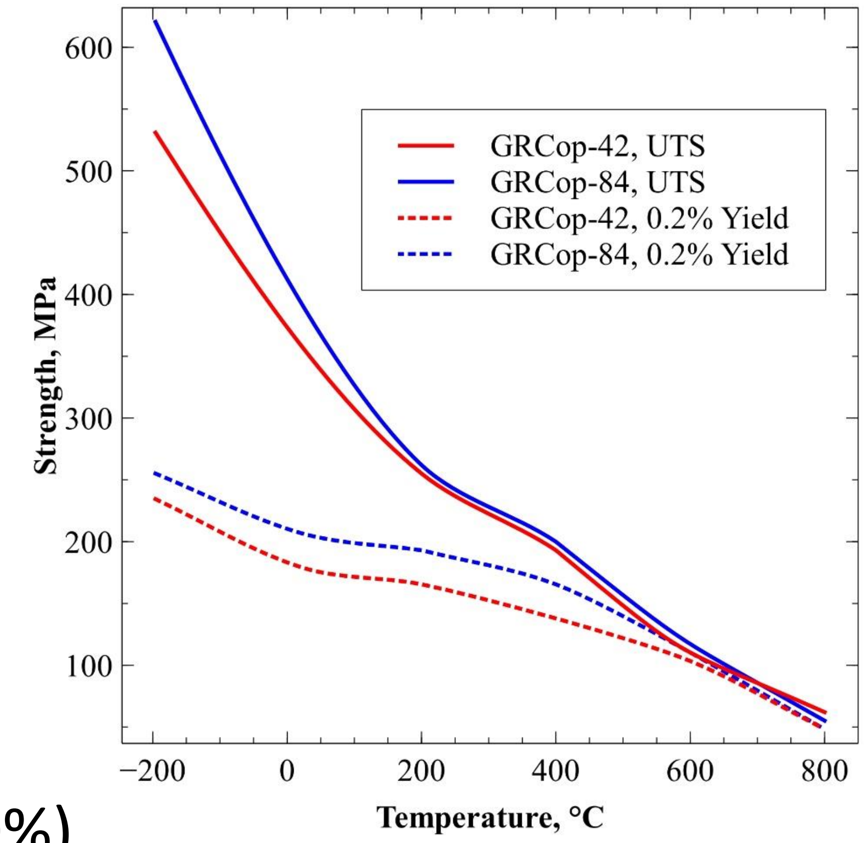
- Oxidation and blanching resistance during thermal and oxidation-reduction cycling.
- Maximum use temperature ~ 800°C, depending upon strength and creep requirements.
- Excellent mechanical properties at high use temperatures (2x of typical copper).
- Lower thermal expansion to reduce thermally induced stresses and low cycle fatigue (LCF).
- Established powder supply chain and commercial supply chain for L-PBF and LP-DED.
- Significant maturity in characterization and hot-fire testing (high TRL).





Comparison of GRCop-84 and GRCop-42

Element	GRCop-42 Wt %	GRCop-84 Wt %
Cu	Balance	Balance
Cr	3.1 – 3.4	6.2 – 6.8
Nb	2.7 – 3.0	5.4 – 6.0
Fe	*Target <50 ppm*	*Target <50 ppm*
O	*Target <250 ppm*	*Target <250 ppm*
Al	*Target <100 ppm*	*Target <100 ppm*
Si	*Target <100 ppm*	*Target <100 ppm*
Cr:Nb Ratio, %wt	1.13 – 1.18	1.13 – 1.18

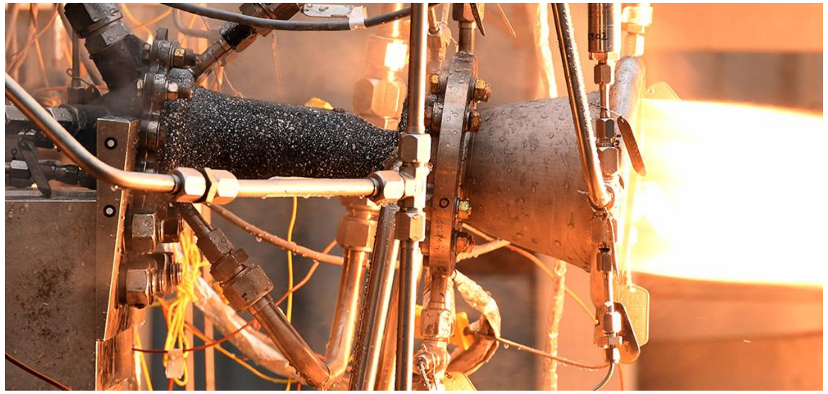


GRCop-42 and GRCop-84 for different applications:

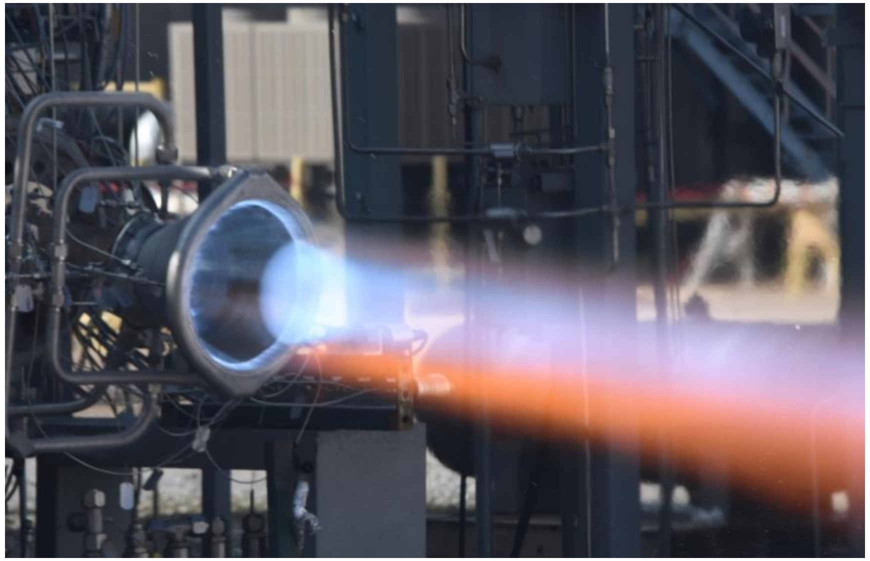
- GRCop-42 has improved thermal conductivity (20-30%).
- GRCop-84 has slightly higher strength and improved LCF properties.
- GRCop-42 has matured supply chain and lower cost.
- Both require only Hot Isostatic Pressing (HIP) post-build.

GRCop-alloy Hot-fire Testing and Development

- High TRL and maturity of mechanical and thermophysical properties, component application, and supply chain.
- Over 41,033 seconds of hot-fire time and 1,015 starts on >30 chambers.
- Single L-PBF chamber unit achieved 296 starts and >10,600 seconds.

LOX/RP-1

LOX/CH4

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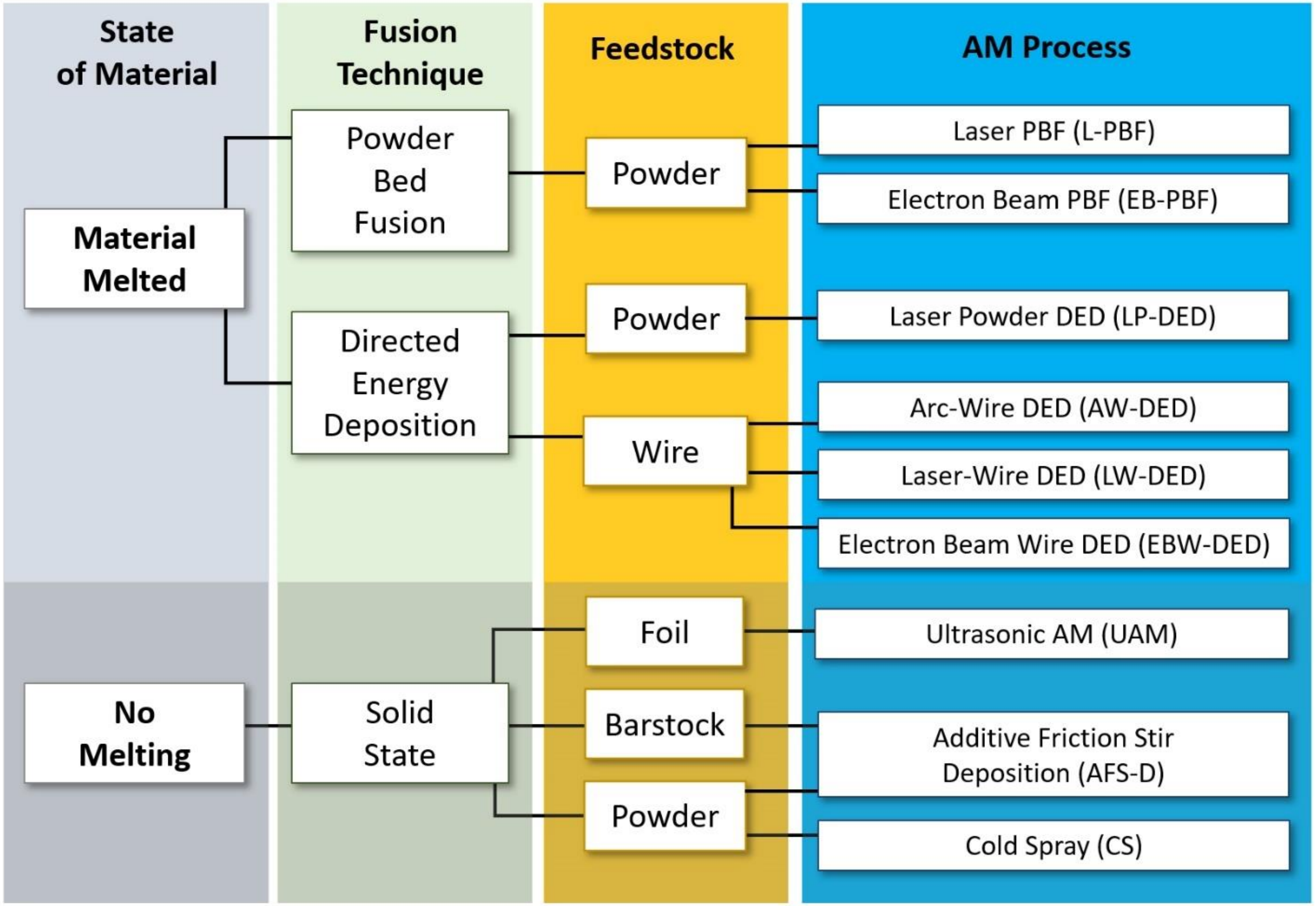
Various Metal AM Processes



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

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