Metal Additive Manufacturing for Rocket Engines: Successes and Failures

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National Aeronautics and Space Administration (NASA)

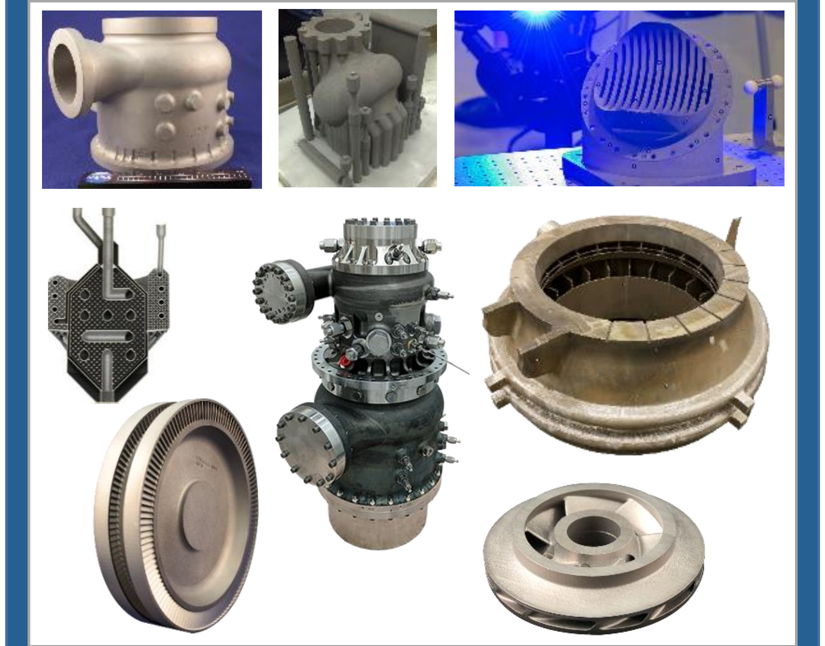
8 February 2023

Additive Manufacturing Strategies 2023

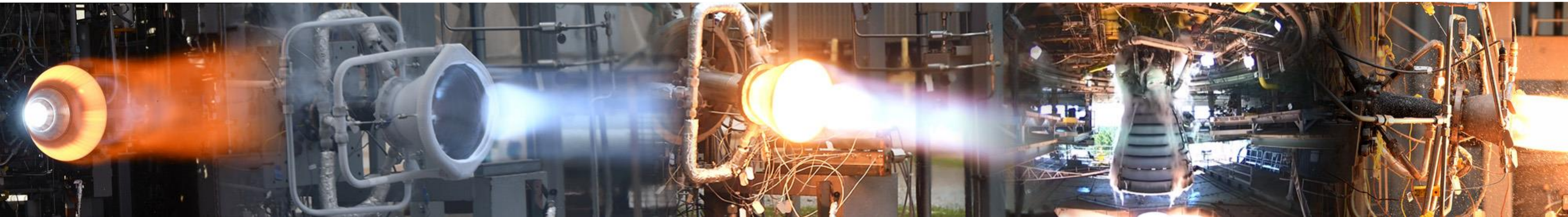
Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

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

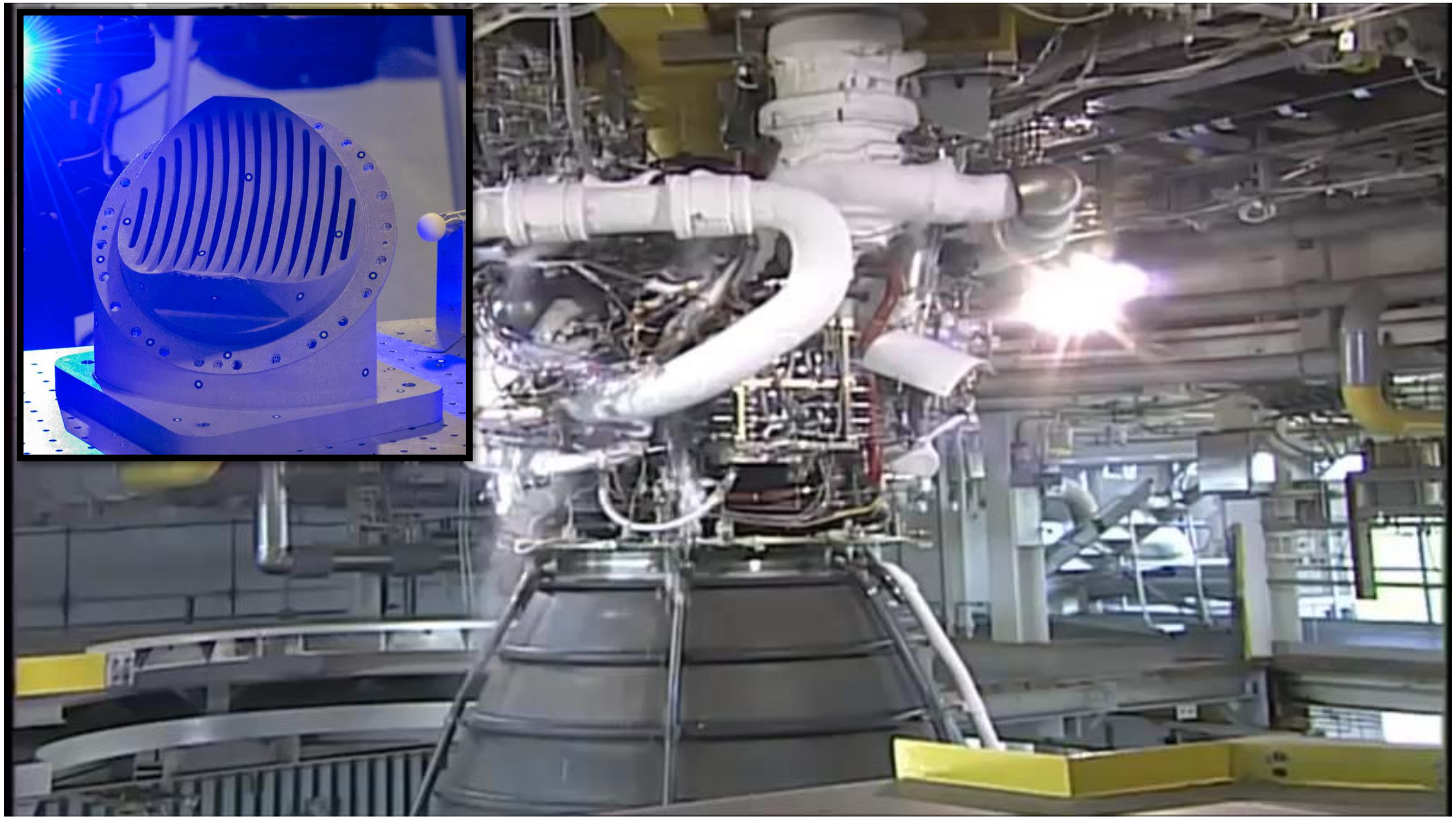
Directed Energy Deposition



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



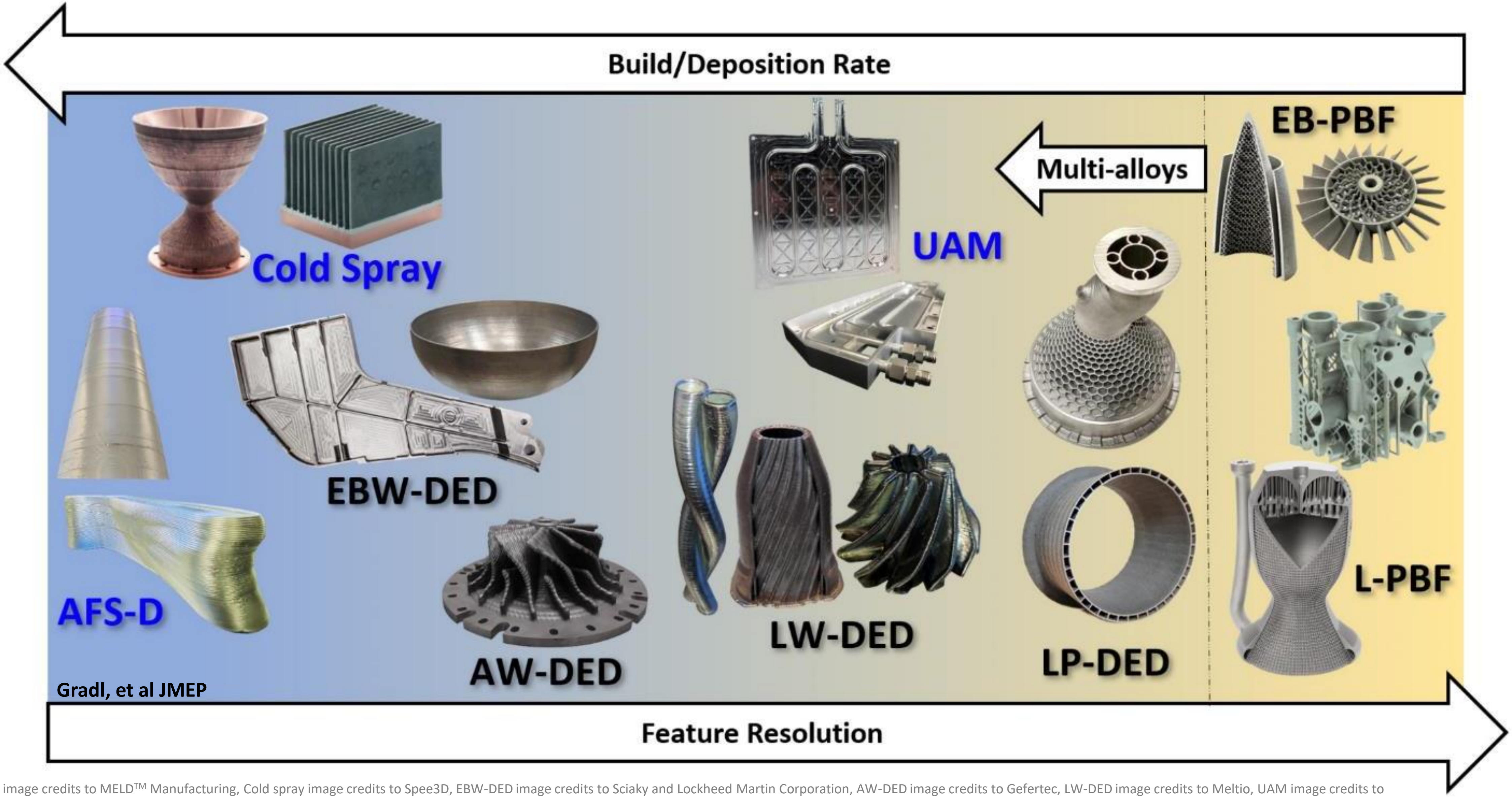
Additive Manufacturing in use on NASA Space Launch System (SLS)



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>

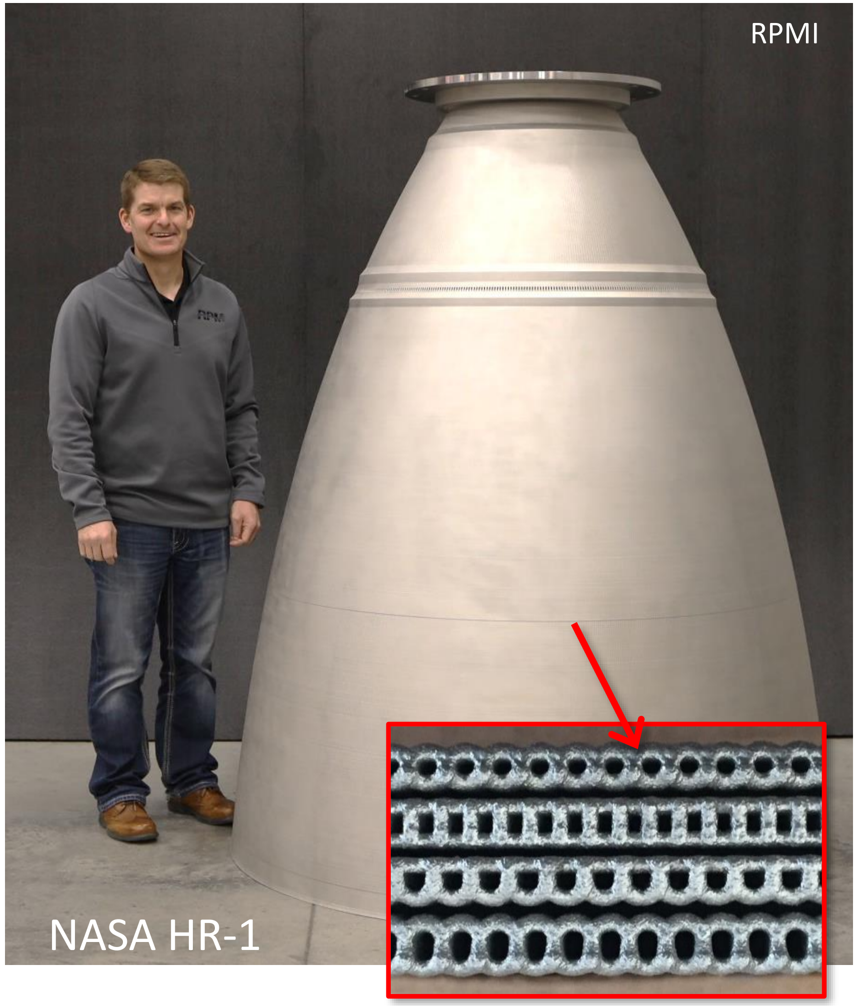
Ref: Andy Hardin, Steve Wofford/ NASA MSFC

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.

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

Process Parameters

AM Design and Pre-Processing
- Part Design
- Analysis
- Model Check
- Build Layout
- Support Generation
- Model Slicing
- Toolpath

Additive Manufacturing Process

Metal Feedstock

Post-Processing
- Powder Removal
- Heat Treatments
- Support Removal
- Build Plate Removal
- Inspections
- Final Machining
- Welding / Brazing
- Polishing
- Cleaning

Part in Service
- Assembly
- Validation / Testing
- Qualified Metallurgy
- Part Production Plan

Qualification

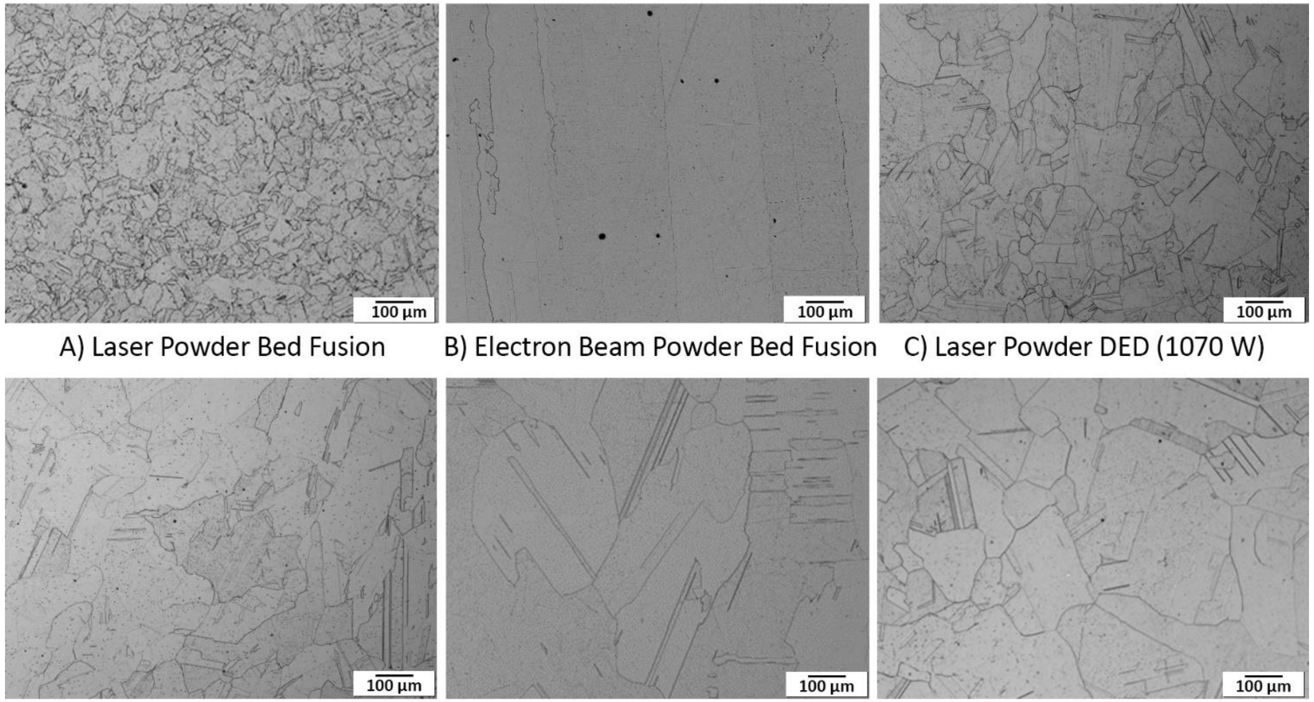
Proper AM process selection requires an integrated evaluation of all process lifecycle steps

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

Material Properties for Various AM Processes

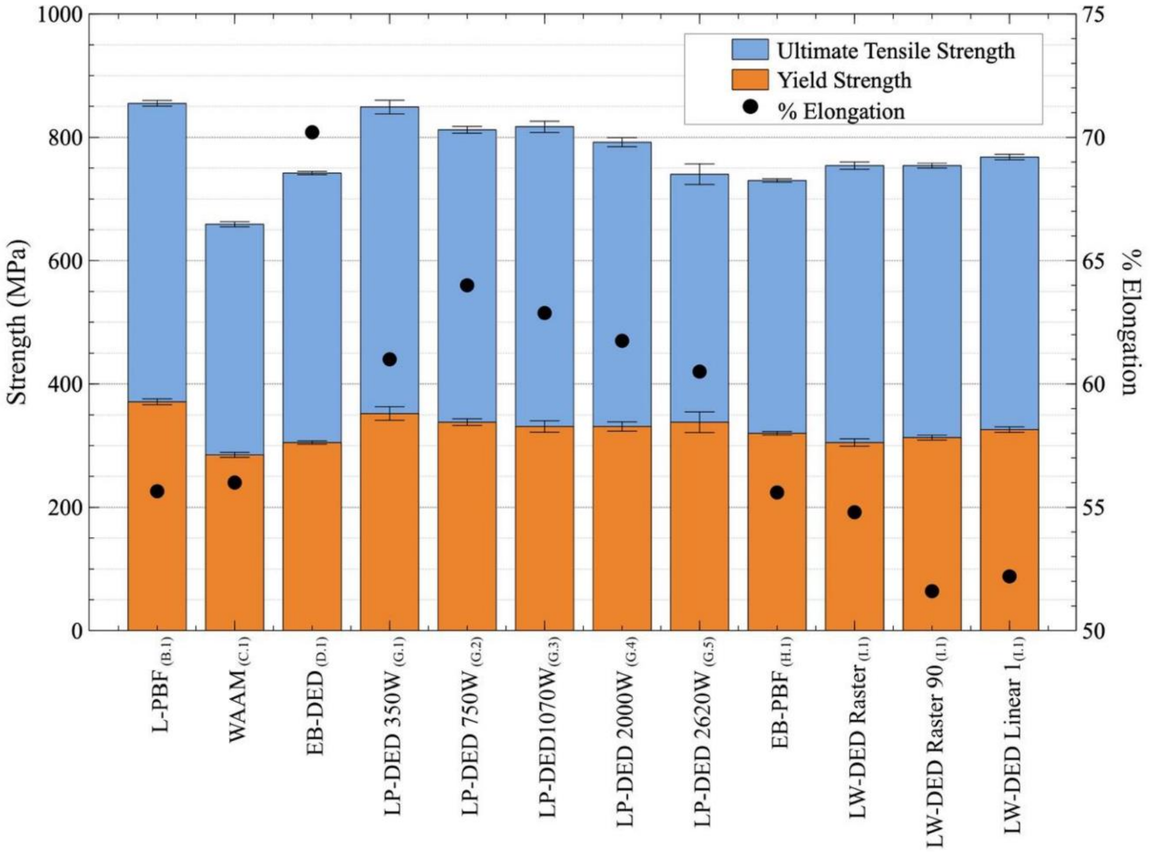
Process → Microstructure → Properties → Performance

Alloy 625, HIP + Heat Treated per AMS 7000



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



- Luna, V.; Trujillo, L.; Gamon, A.; Arrieta, E.; Murr, L.E.; Wicker, R.B.; Katsarelis, C.; Gradl, P.R.; Medina, F. Comprehensive and Comparative Heat Treatment of Additively Manufactured Inconel 625 Alloy and Corresponding Microstructures and Mechanical Properties. *J. Manuf. Mater. Process.* **2022**, *6*, 107. https://doi.org/10.3390/jmmp6050107
- 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

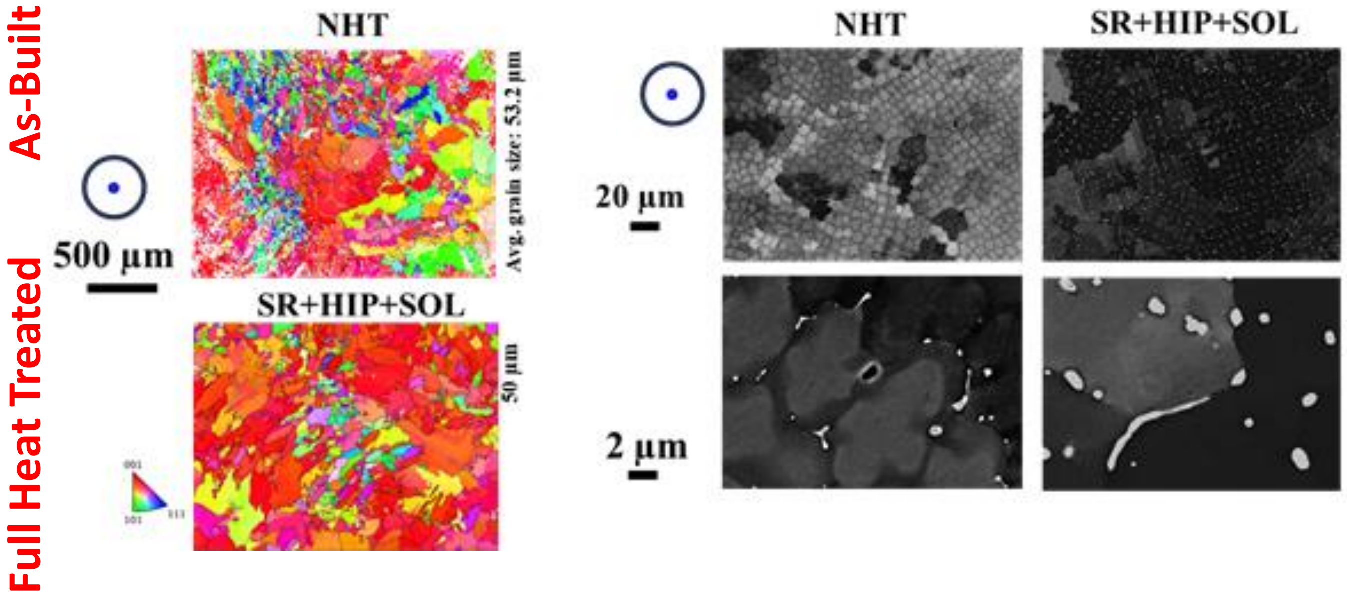
*Not design data and provided as an example only

NASA's AM Property Database Development – Examples: Haynes 230 LP-DED

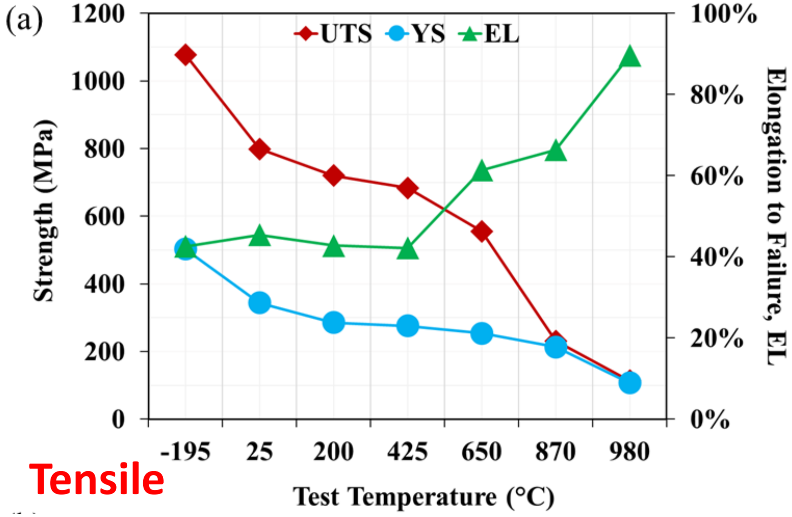
Power (W)	Layer height (µm)	Travel speed (mm/min)	Powder feed rate (g/min)
1070	381	1016	19.10

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

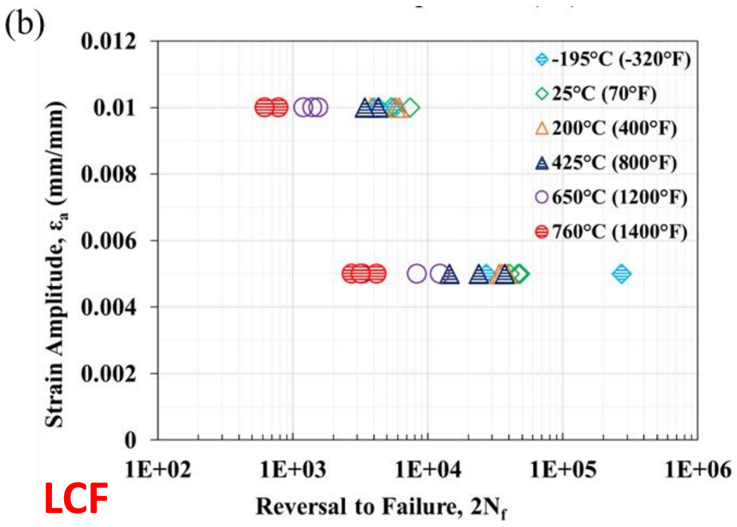
[2] HIP per ASTM F3301



NASA is developing AM properties for 55+ Alloys



Tensile

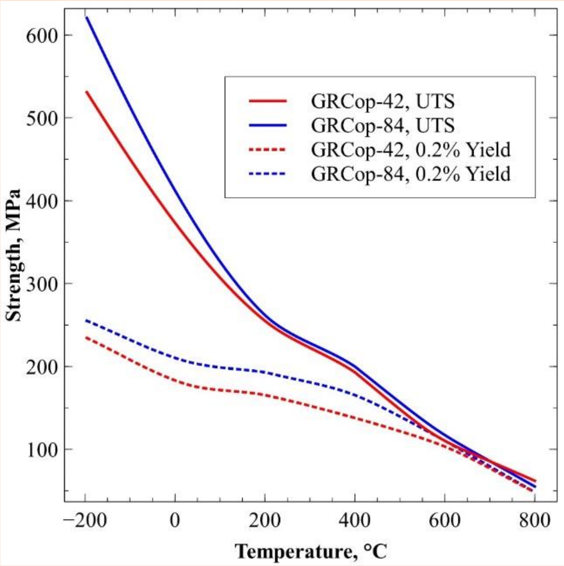


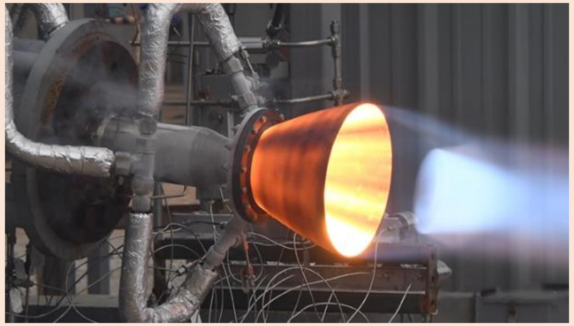
LCF

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

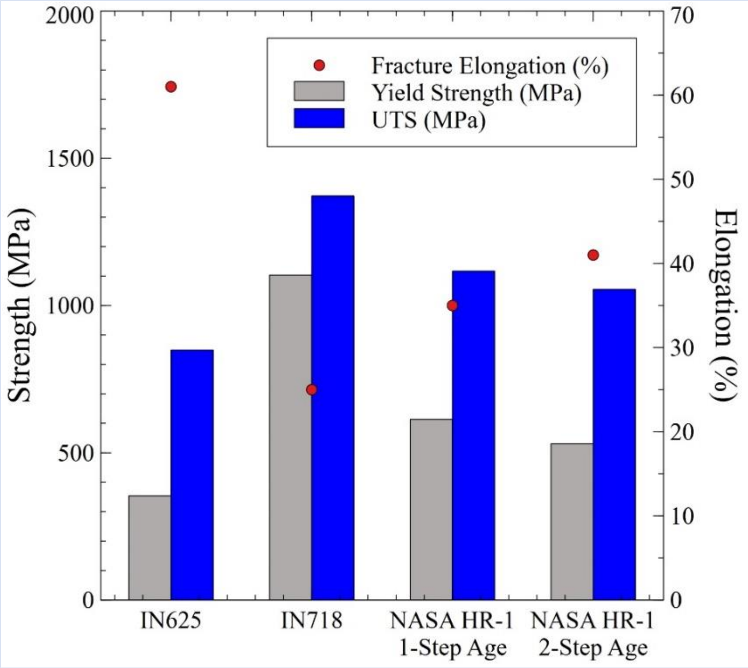
AM Enabling New Alloy Development

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

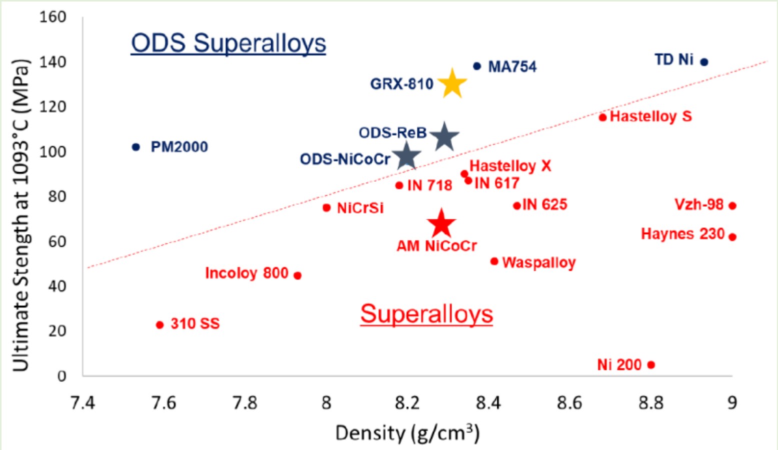




NASA HR-1, high strength superalloy for hydrogen environments



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

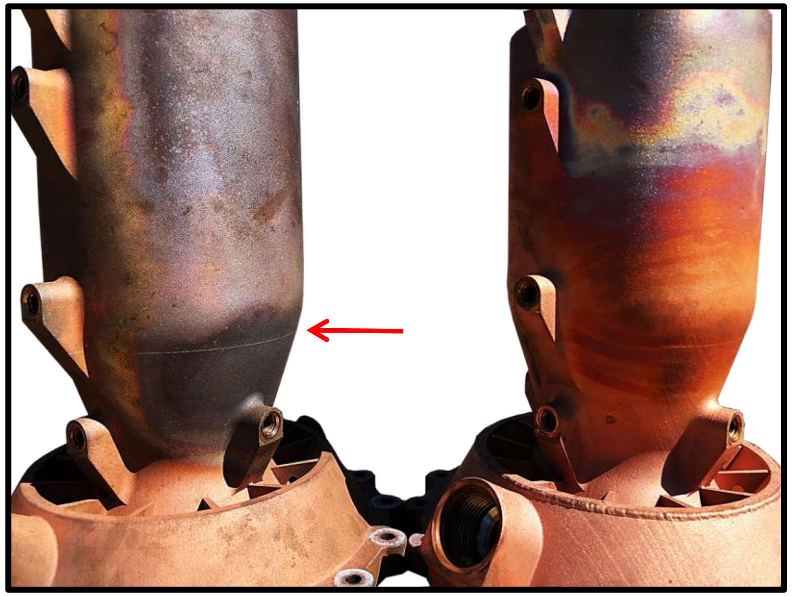


Ref: Tim Smith, Christopher Kantzos / NASA GRC

Process Investigation – Build Interruptions

L-PBF GRCop-42 chamber

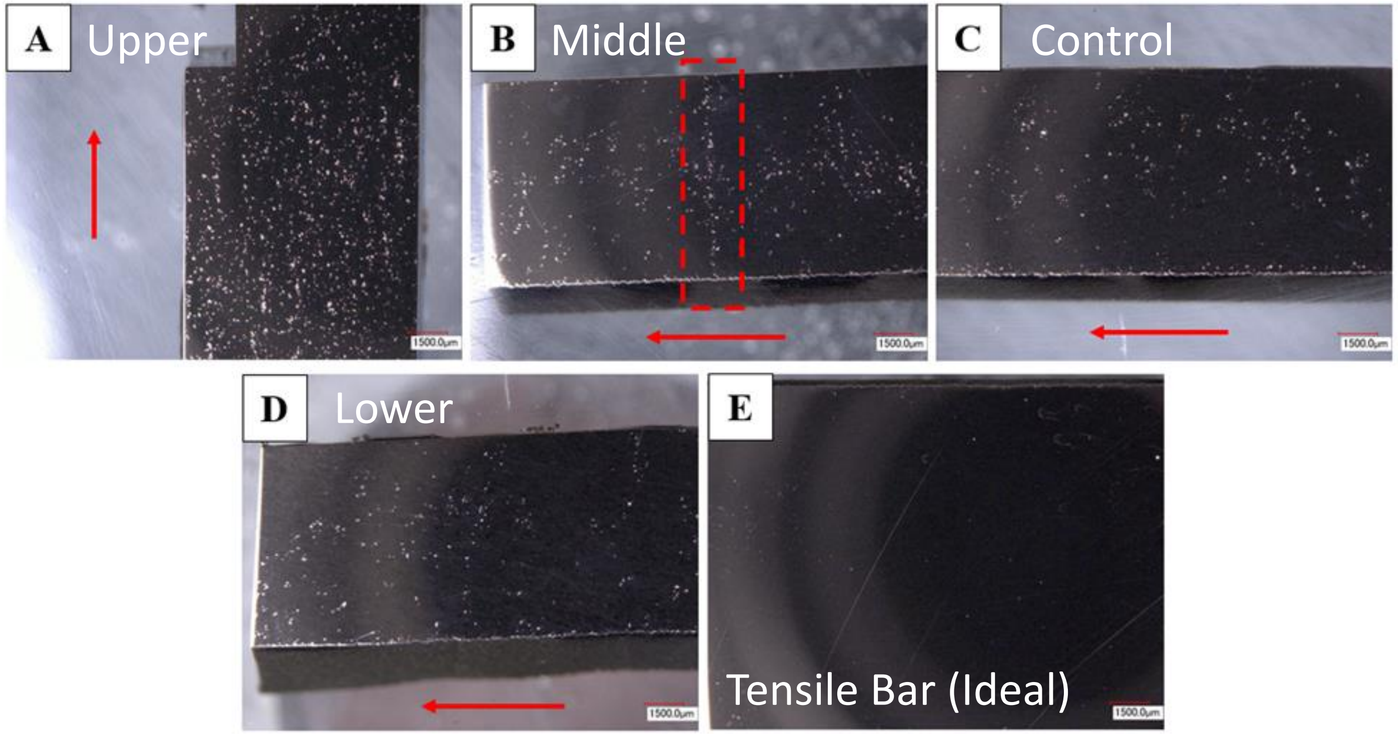
- (4) chambers on the build plate; one other tested 51 times.
- 9 starts and 83.3 sec. accumulated before separation failure.
- No issues observed in prior chamber test data.
- Build interruptions observed (power failure, powder overflow).



Color adjusted in photos to highlight witness lines

Optical Images of Chamber Sections

Label	Section	Porosity
A	Upper Witness Line	0.748%
B	Middle Witness Line	1.906%
C	Control Section	0.511%
D	Lower Witness Line	1.743%
E	* Tensile Bar	0.006%

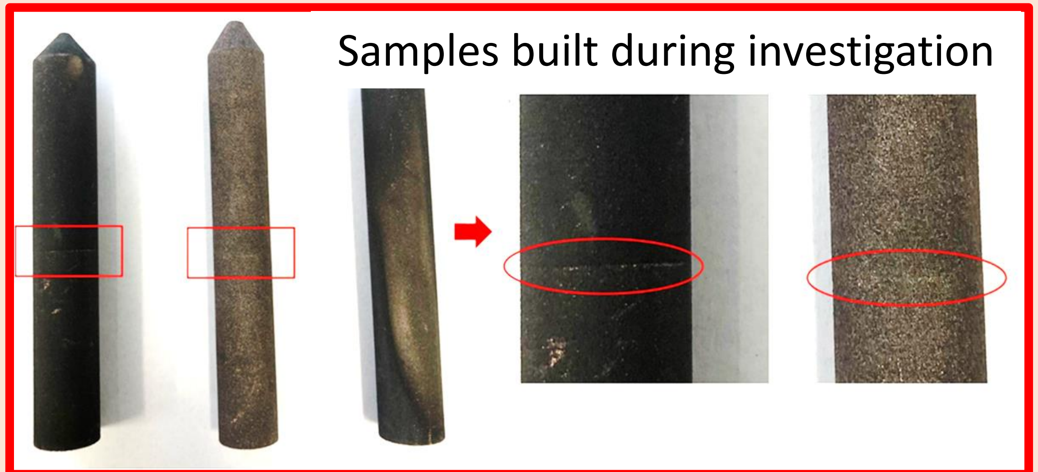


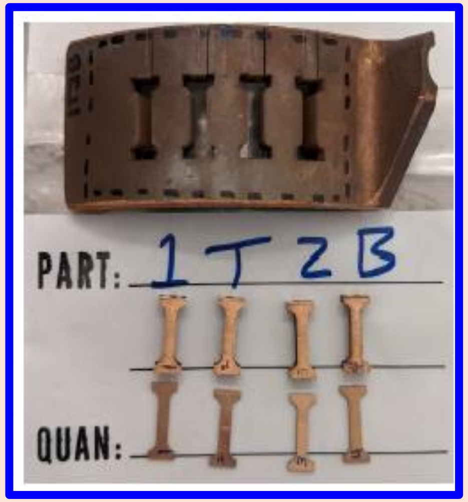
- Samples taken from un-tested chamber.
- *Tensile bar built separately as part of investigation.
- Proper HIP of chambers was confirmed.
- Porosity is evident throughout samples.
- Clear congregation of porosity around witness lines.
- Porosity reduces load bearing capacity (reduced area) and can act as stress concentrators/crack initiators.

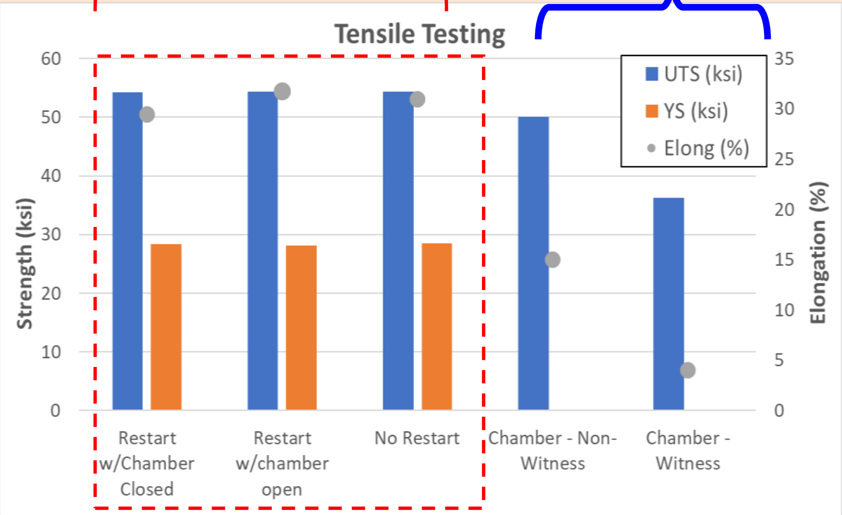
Process Investigation – Microstructure and Testing

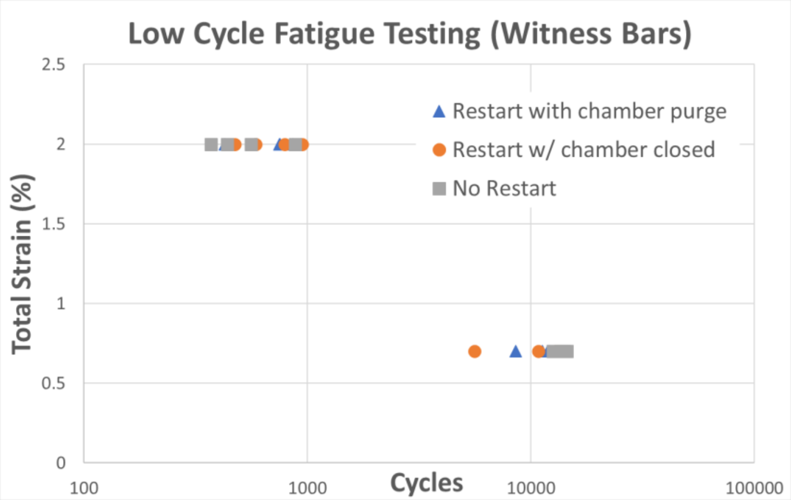
Mechanical Testing of Samples

Samples built during investigation



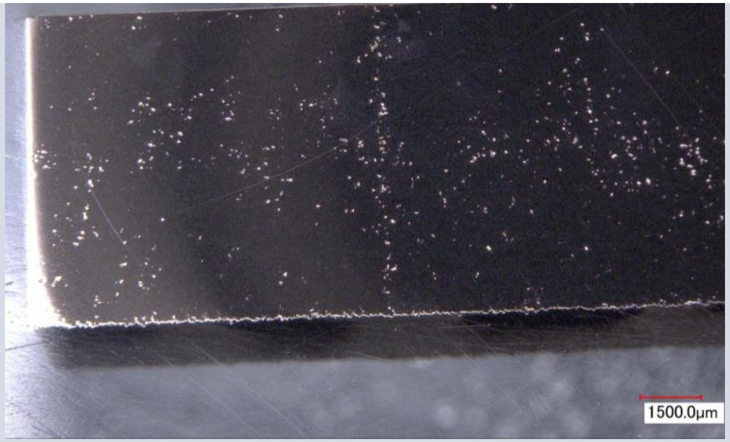






Microstructure of Sectioned Chambers

Middle Witness Line



Chamber Control

Chamber Failure Conclusions

- Chamber experienced tensile overload during hot-fire at the witness line that had a higher degree of voids.
- The L-PBF GRCop-42 chambers built under LLAMA project had higher porosity (1-2%) that congregated more at witness lines causing lack of fusion.
- Granular surfaces, unmelted particles, and irregular pores were observed in microtensile specimens (sectioned) from chambers.
- Areas affected by build interruptions must be properly evaluated and dispositioned. AM machine restarts represent a risk, and appropriate restart procedures should be developed and followed to maintain material quality.
  - Witness specimens using different types of restarts showed similar tensile strengths and LCF results.
- Build log indicated no issues with parameters, but *an issue* (parameters, lens, etc) caused the porosity and HIP did not fully close these voids.
- Demonstrates the process sensitive nature of AM parts and build interruptions need to be properly documented, fully evaluated, and properly dispositioned.

Failure Conclusions and Recommendations

- Build interruptions in GRCop-42 components do not inherently possess weakened material properties if a restart procedure is properly executed.
- Full height specimens should be built with all components to characterize the material.

- While not subject to NASA-STD-6030, this chamber provides a good case study on why it is important that AM materials used in critical applications adhere to NASA-STD-6030 standards and the need for robust process development, in-depth material evaluation, and process controls.

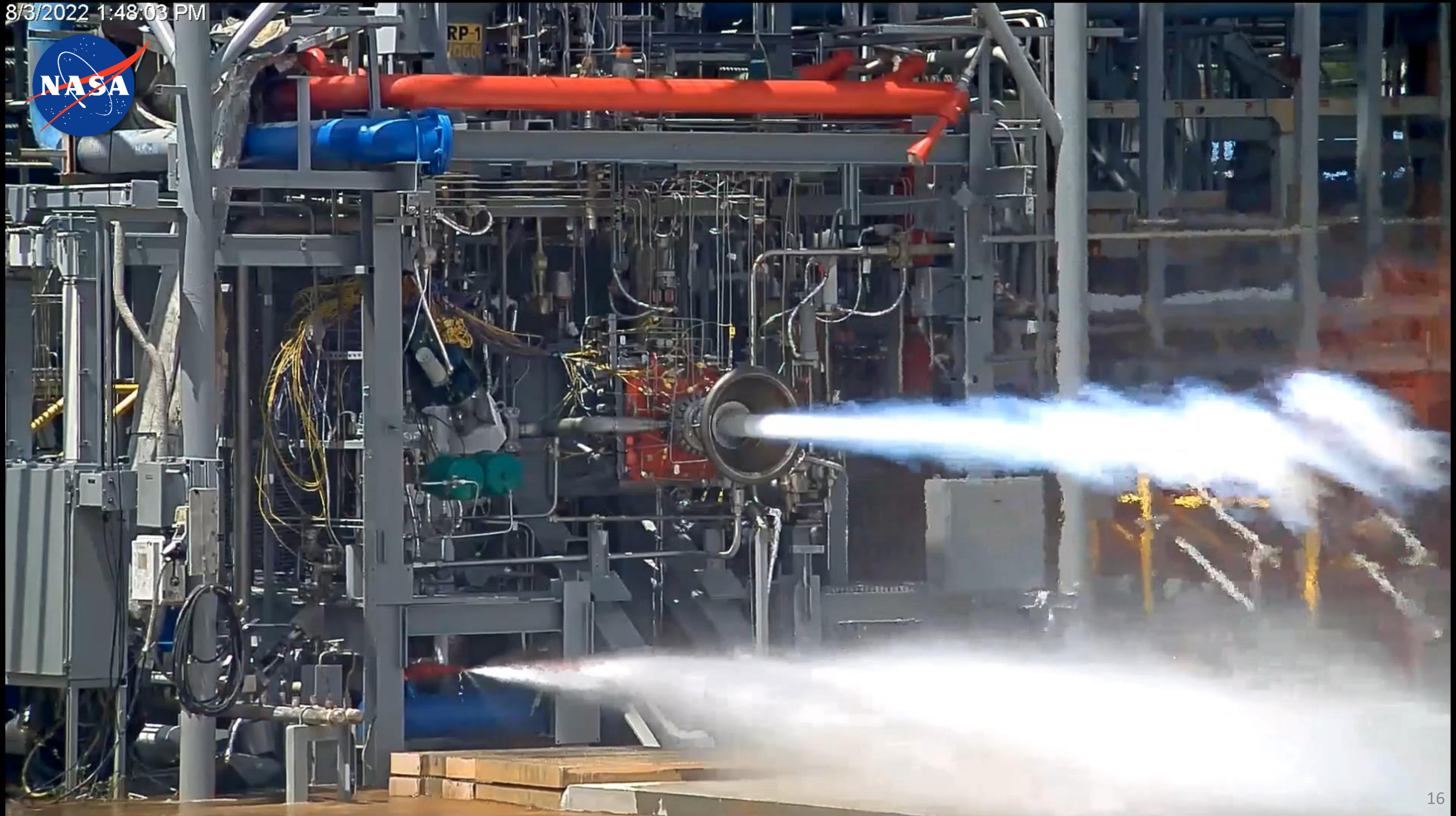

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Photo: NASA/Ben Smegelsky

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- Marissa Garcia
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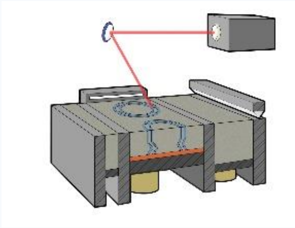
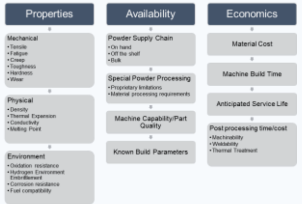
Metal Additive Manufacturing for Propulsion Applications

Editors: Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia

Chapter 1
Introduction and Applications of Additive Manufacturing for Propulsion



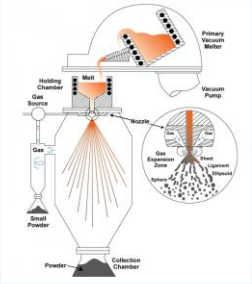
Chapter 2
Metal Additive Manufacturing Processes and Selection



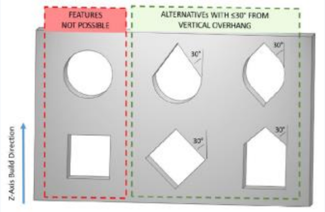
Chapter 3
Selection and Overview of Additive Manufactured Metals and Metal Alloys

Chapter 4
Microstructure and Properties of Additively Manufactured Metal Alloys

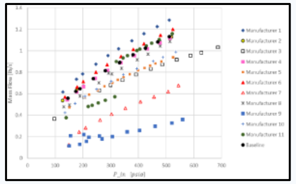
Chapter 5
Post-Processing of Metal Additively Manufactured Components



Chapter 6
Feedstock for Metal AM

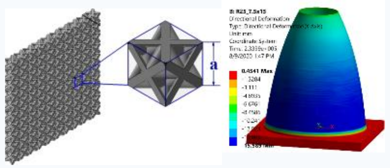


Chapter 7
Functional Design for Metal Additive Manufacturing



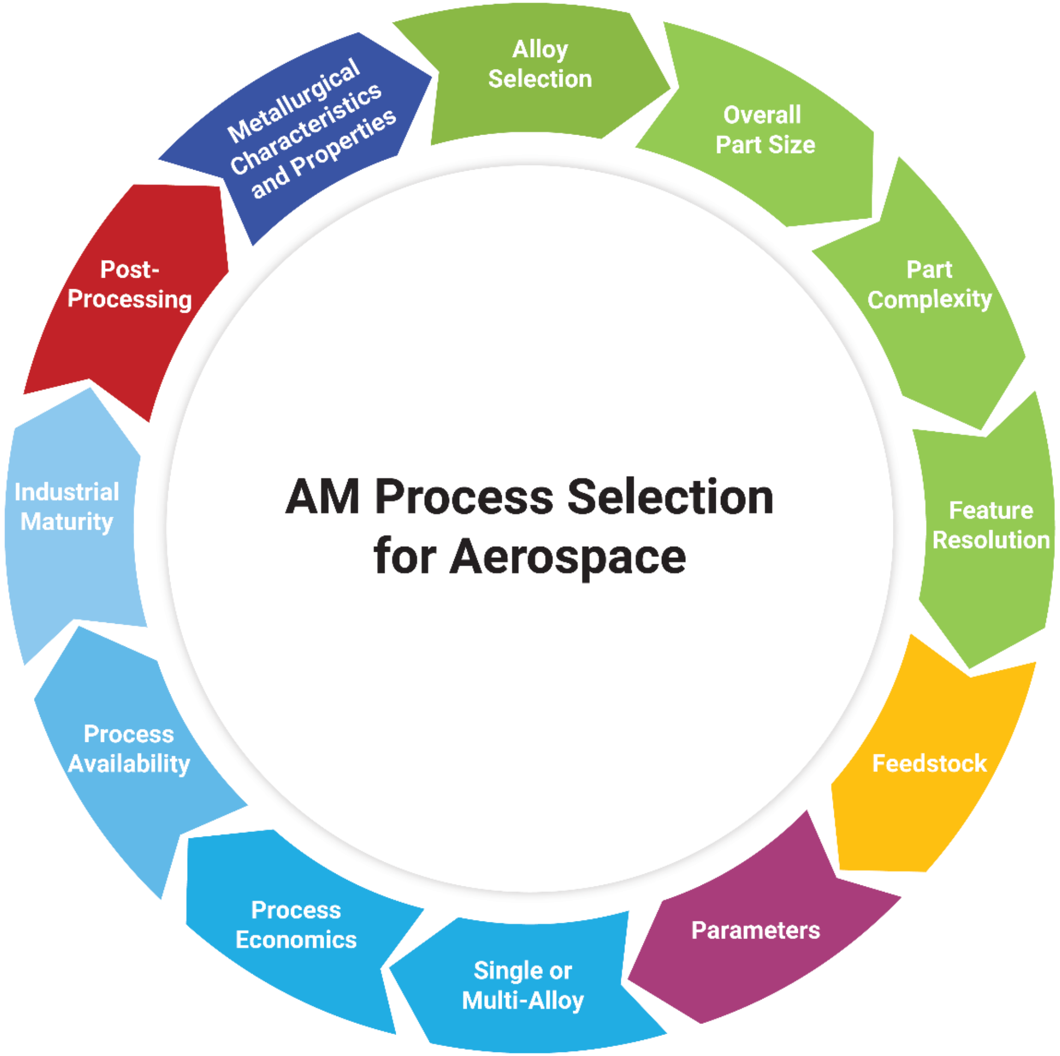
Chapter 8
Component Performance and Application Characteristics

Chapter 9
Certification of Metal Additive Manufacturing: A NASA Perspective



Chapter 10
Emerging Additive Manufacturing Technology for Propulsion

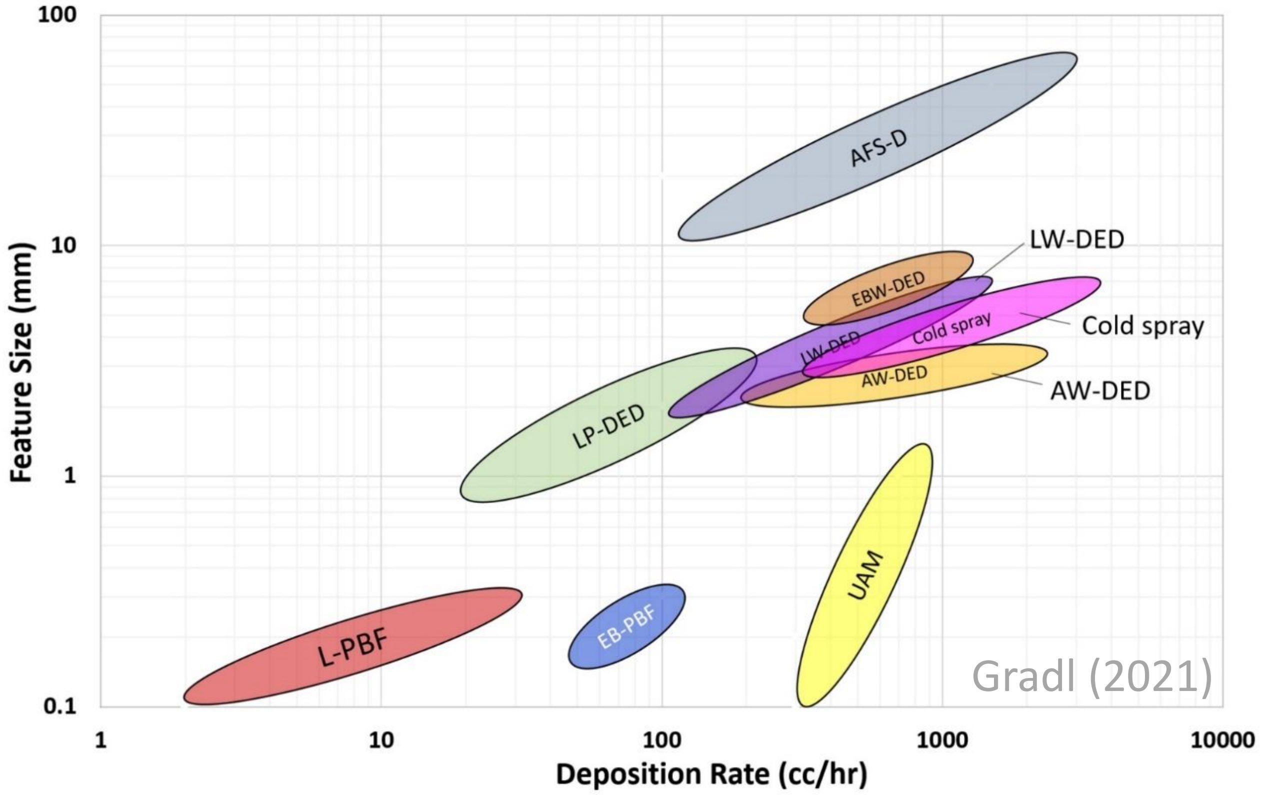
Methodical AM Process Selection

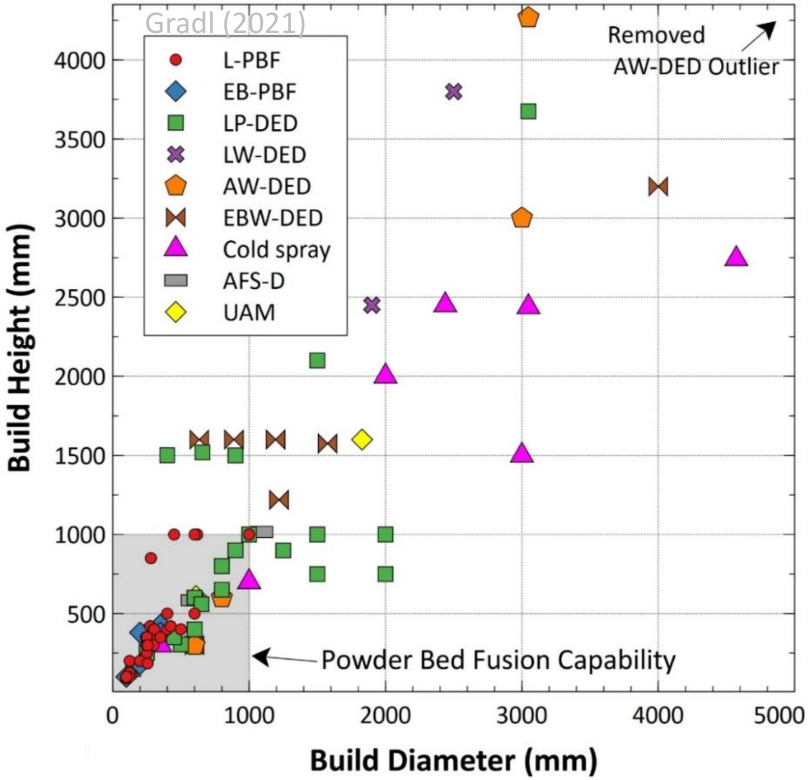


- What is the **alloy** required for the application?
- What is the **overall part size**?
- What is the **feature resolution** and internal **complexities**?
- Is it a **single alloy or multiple**?
- What are **programmatic requirements** such as cost, schedule, risk tolerance?
- What are the end-use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

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)

Various criteria for selecting AM processes



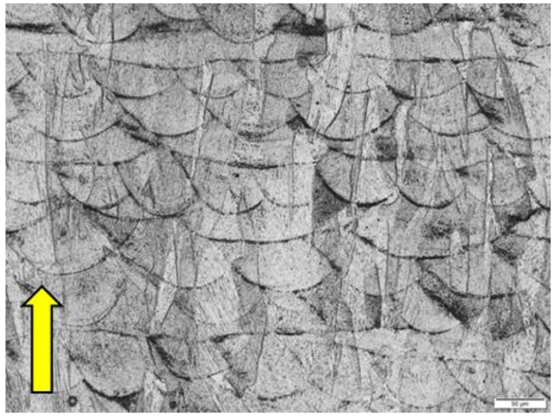


Complexity of Features | Scale of Hardware | Material Physics | Cost | Material Efficiency

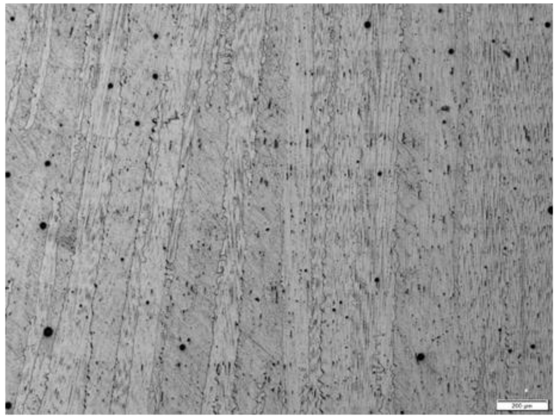
Speed of Process | Material Properties | Internal Geometry | Availability | Post Processing

- 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

Microstructure of Various AM Processes
Alloy 625 – As-Built

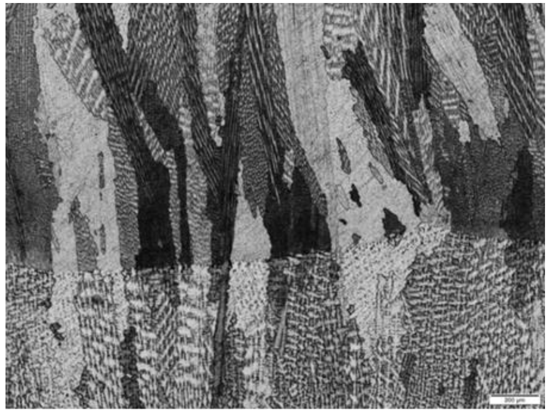


Laser Powder Bed Fusion

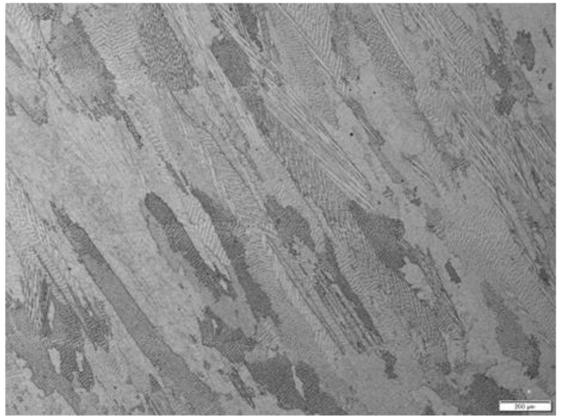


Electron Beam Powder Bed Fusion

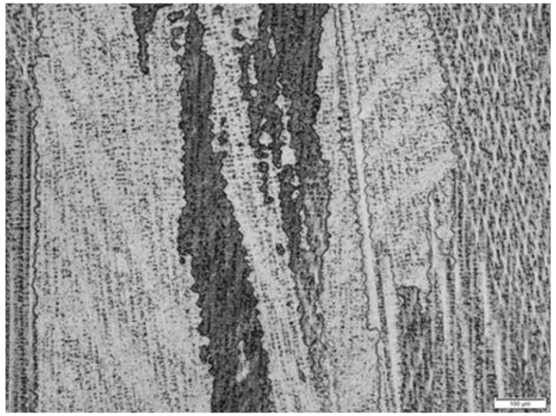
Laser Powder DED (1070 W)



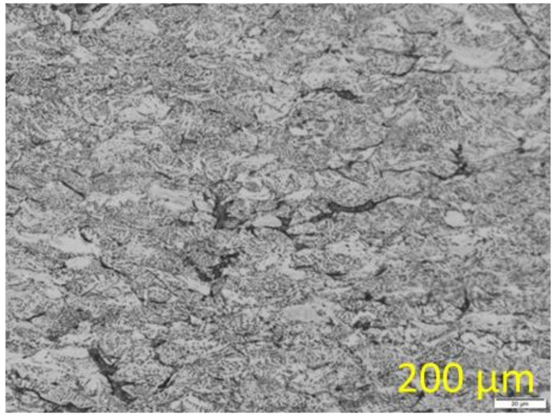
Electron Beam Wire DED



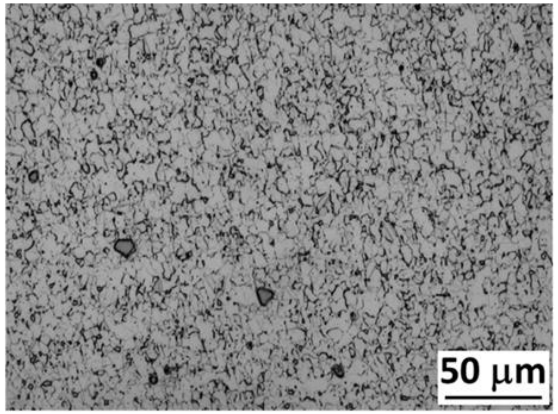
Laser Wire DED



Arc Wire DED



Cold Spray



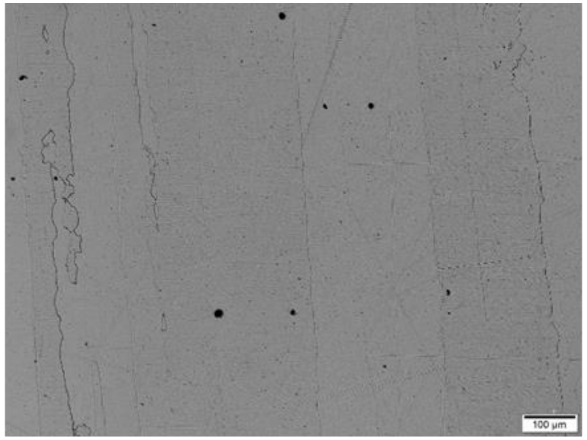
Additive Friction Stir Deposition

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

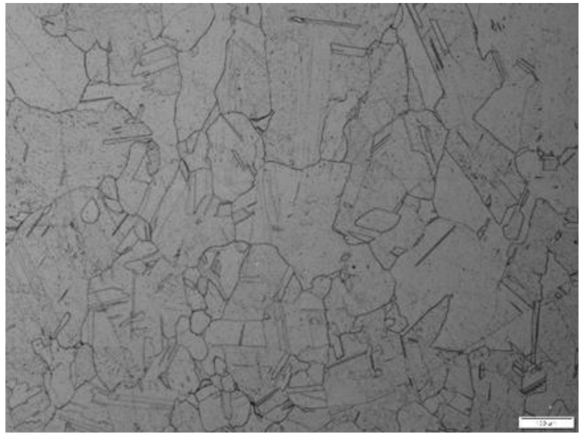
- Gamon, A., Arrieta, E., Gradl, P.R., Katsarelis, C., Murr, L.E., Wicker, R.B., Medina, F., 2021. Microstructure and hardness comparison of as-built Inconel 625 alloy following various additive manufacturing processes. Results in Materials 12. https://doi.org/10.1016/j.rinma.2021.100239
- Gradl, P.,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

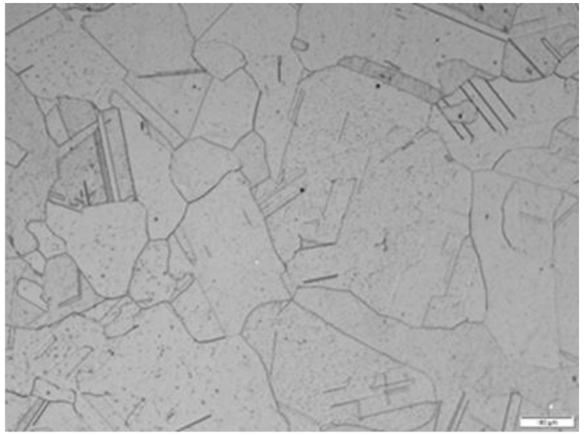
Laser Powder Bed Fusion



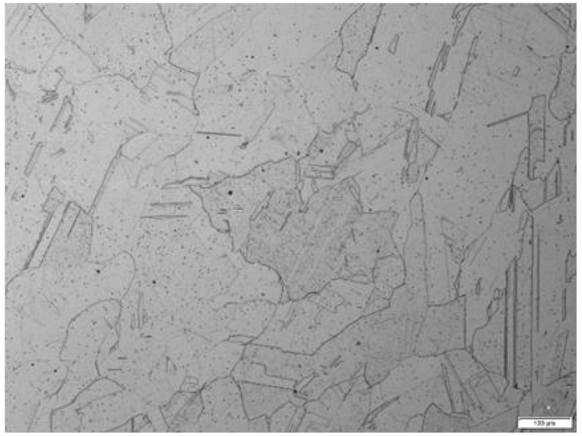
Electron Beam PBF



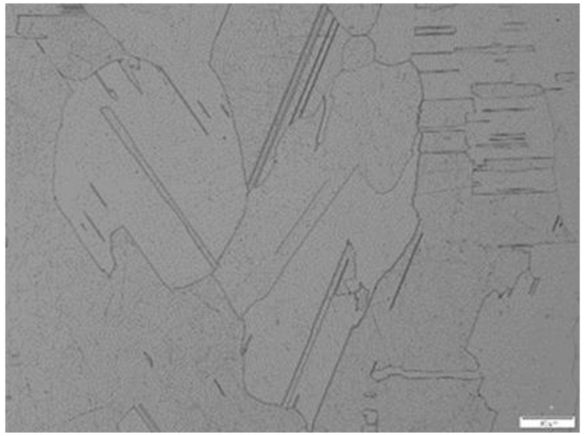
Laser Powder DED (1070 W)



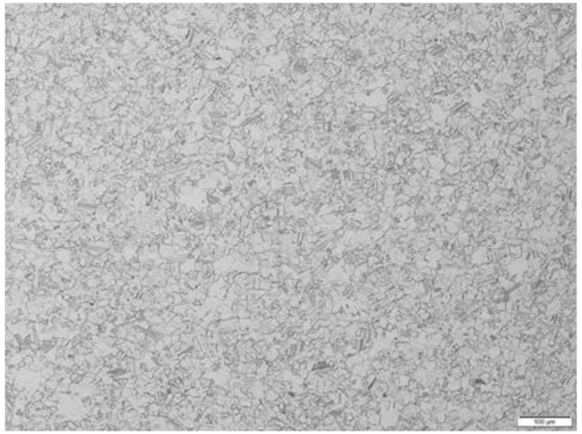
Electron Beam Wire DED



Laser Wire DED



Arc Wire DED



Cold Spray

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NASA's AM Property Database Development – List of Materials 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

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

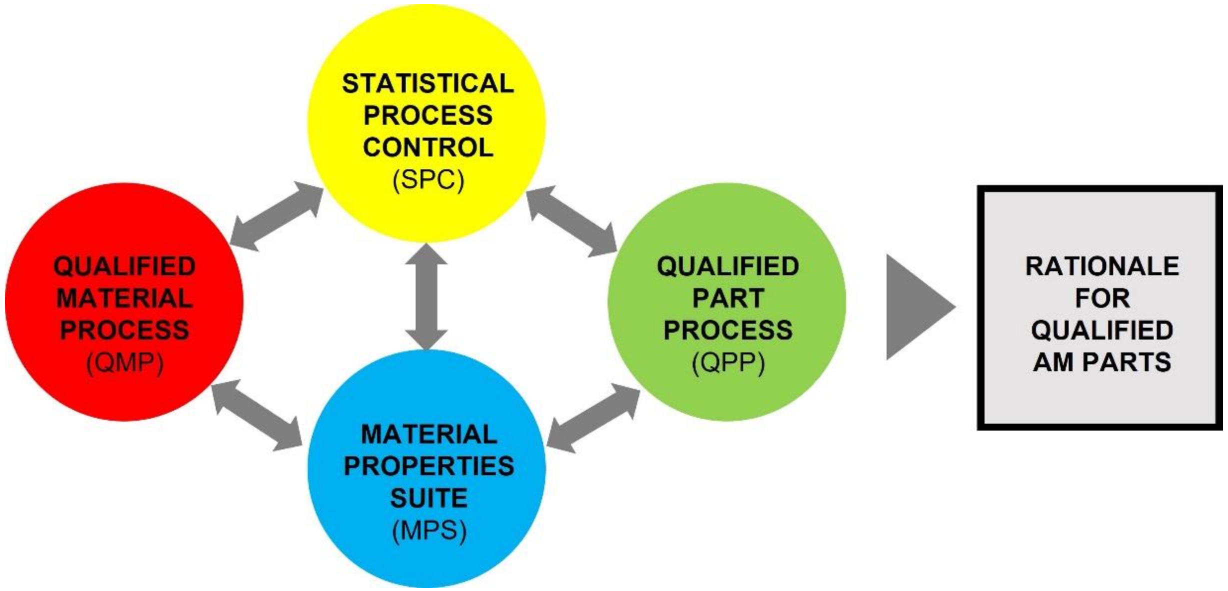

GRX-810 L-PBF

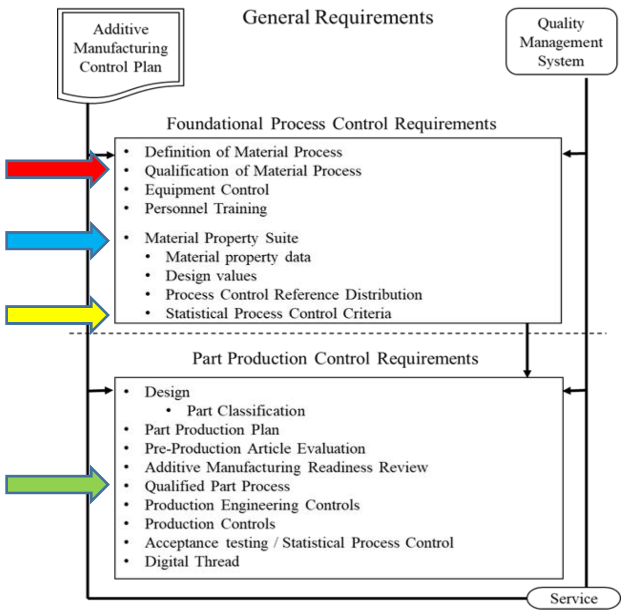

C103 L-PBF

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

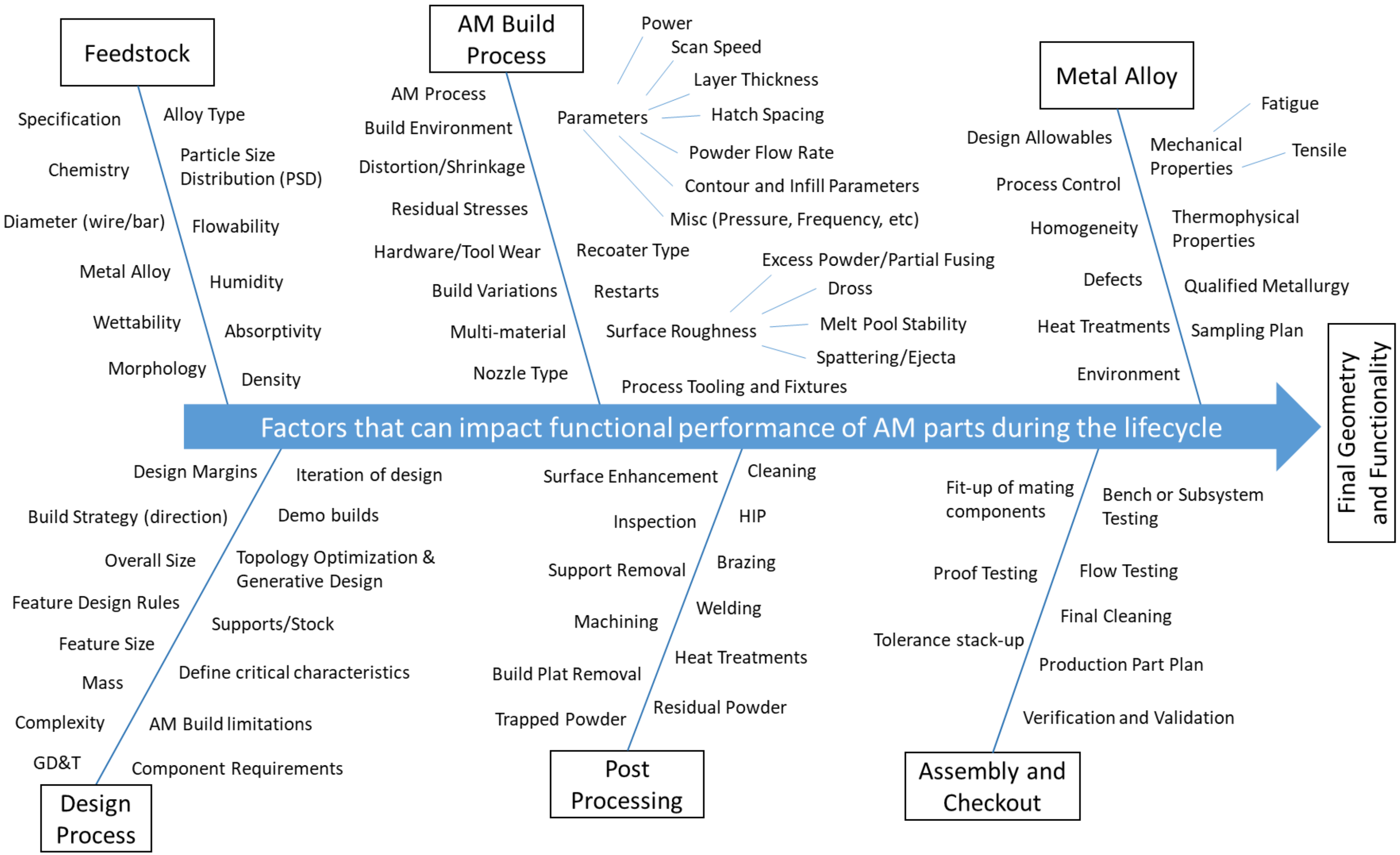
Certification and Standards (NASA-STD-6030)

- General Requirements
  - Additive Manufacturing Control Plan (AMCP) and Quality Management System (QMS)
  - Backbone that defines and guides the engineering and production practices
  - Approach is heavily rooted in metallurgical understanding and respecting the evolving and meticulous AM process
- Foundational Process Control Requirements
  - Includes the requirements for AM processes that provide the basis for reliable part design and production
- Part Production Control Requirements
  - Includes design, assessment controls, plans (PPP), preproduction articles and AM production controls



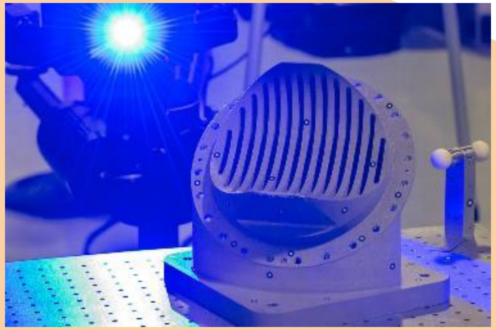


The Challenges with AM Processes



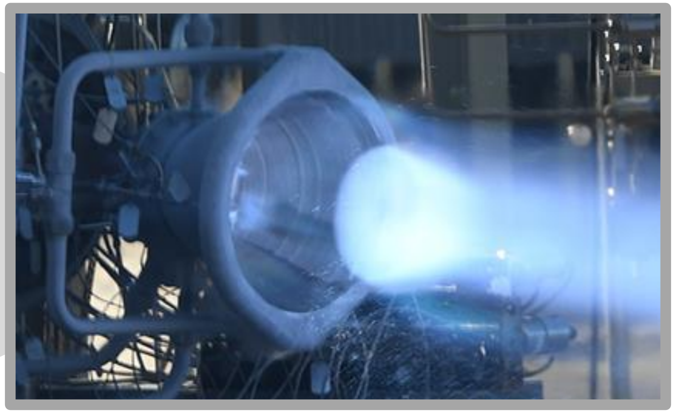
There are a lot of inputs and steps in the AM lifecycle that must go right to meet the expected geometry

Industrial Maturity and TRL of AM Processes


L-PBF


Cold spray

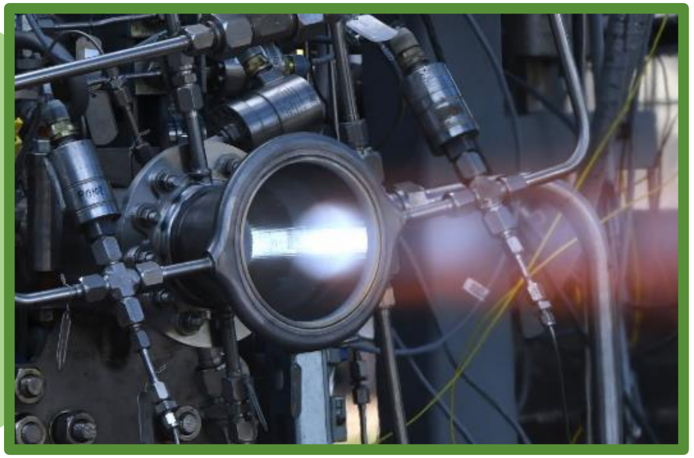
LP-DED




L-PBF

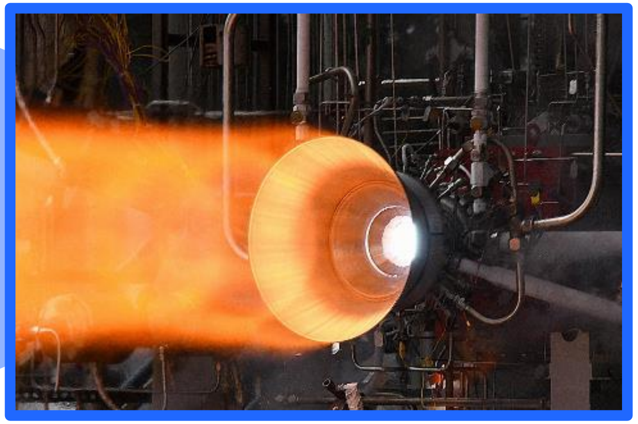

AW-DED


LW-DED



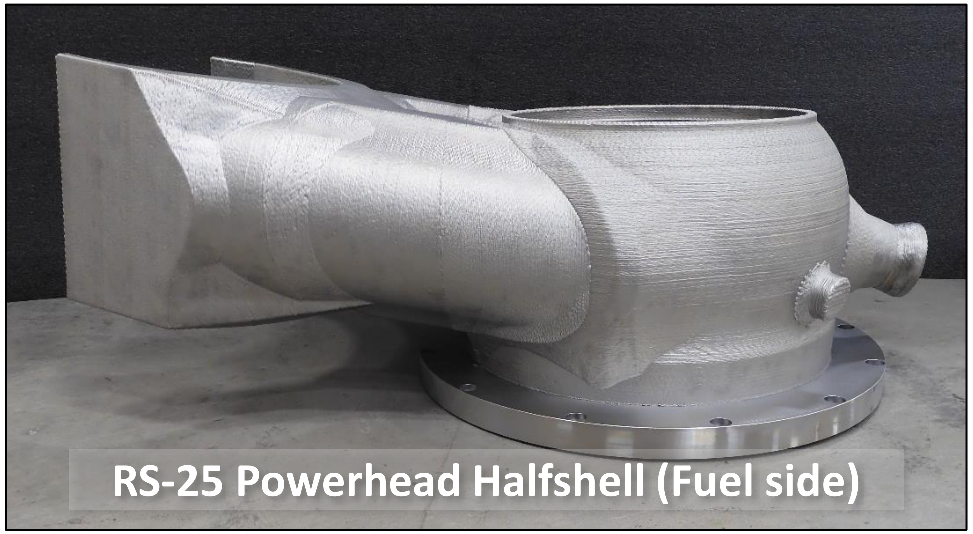

L-PBF

EBW-DED



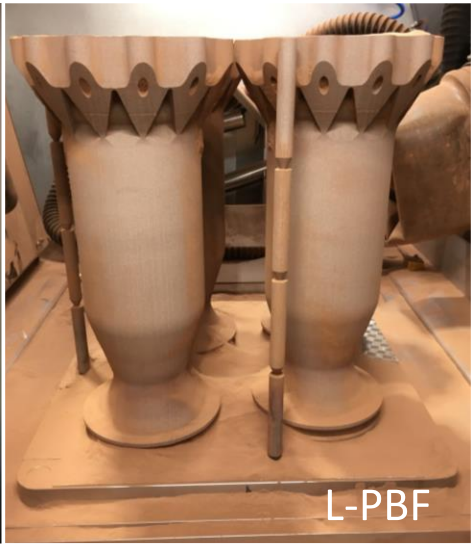
Over 100,000 sec of accumulated hot-fire time on chambers, nozzles, injectors

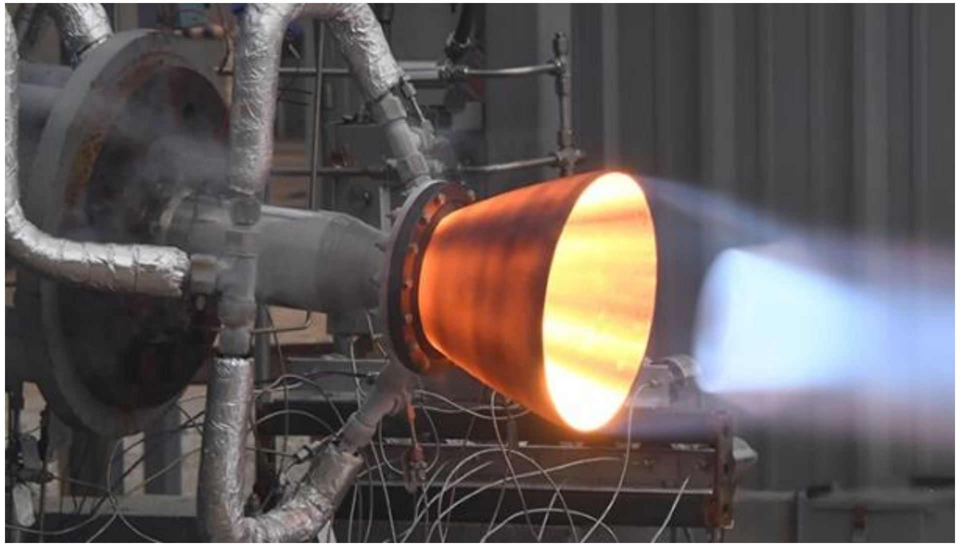
NASA HR-1 Components Fabricated using LP-DED



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).





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