Metal Additive Manufacturing for Aerospace Applications

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Overview of Presentation

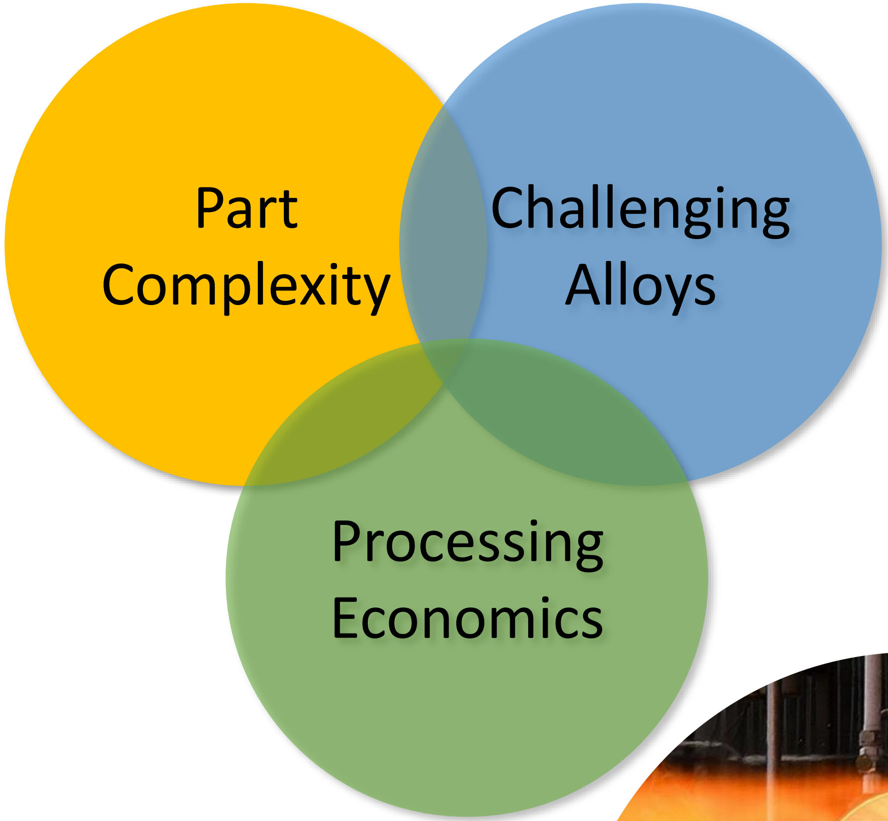
- Why additive manufacturing?
- AM Processes and Selection
- Large Scale AM Development
- Maturity of AM for Rocket Engines
- Gaps in Technology
- Summary

The Case for Additive Manufacturing in Propulsion

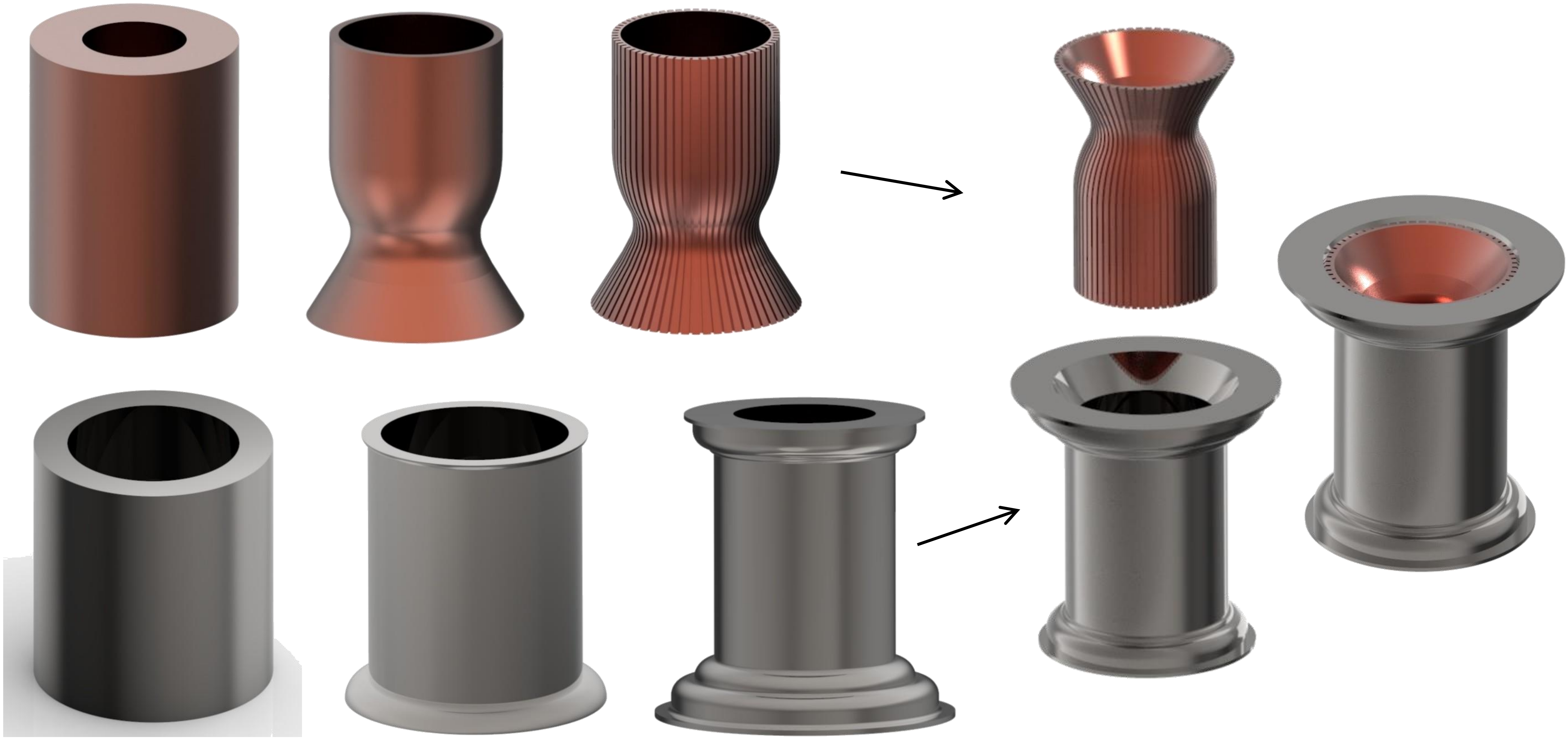
- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%

- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities.

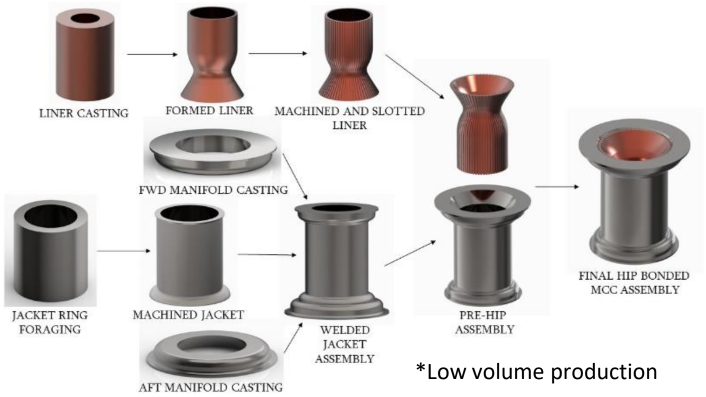
- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing.



Traditional Manufacturing…Forging to final assembly



A rocket combustion chamber case study for AM

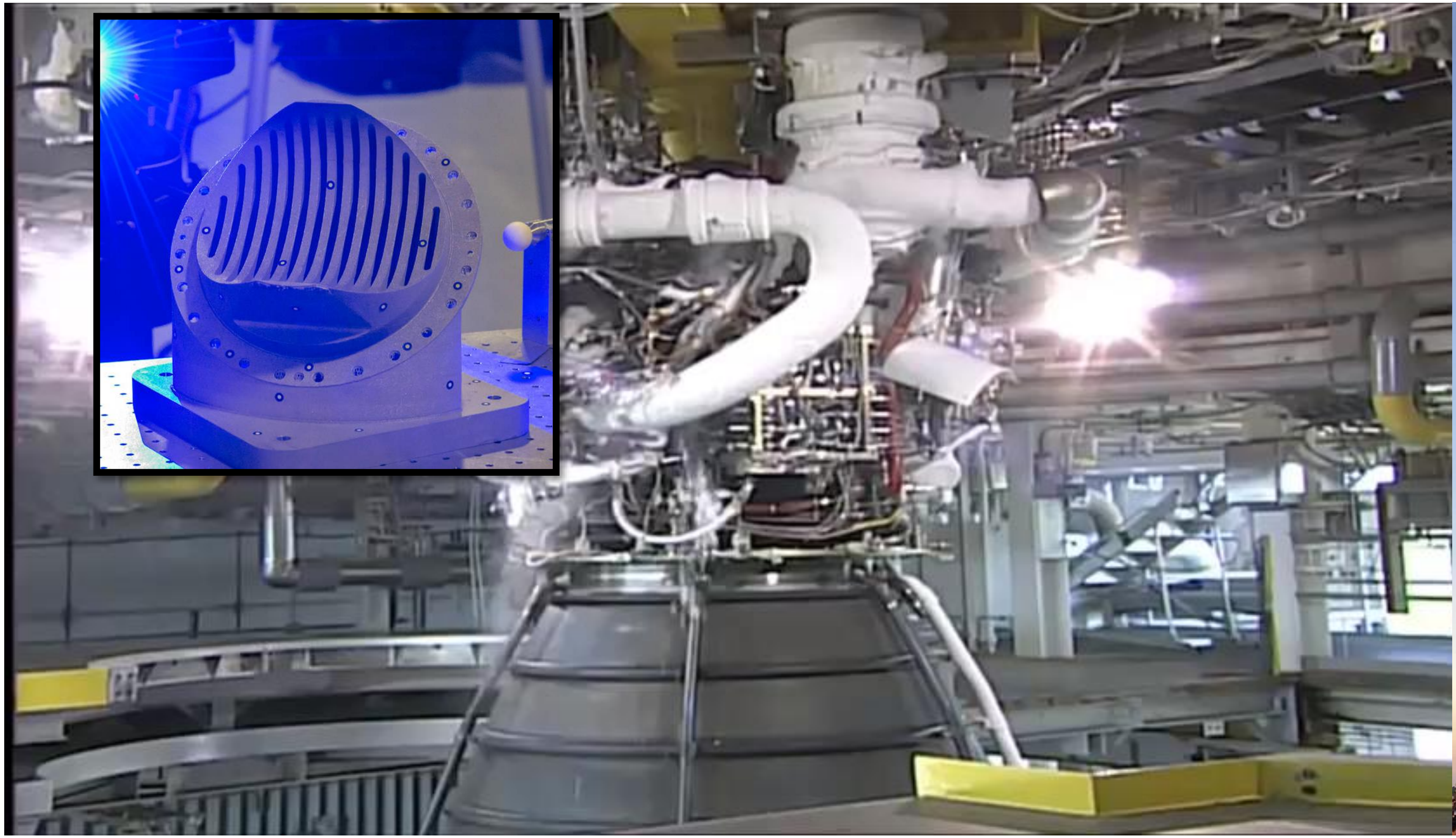


*Low volume production

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)

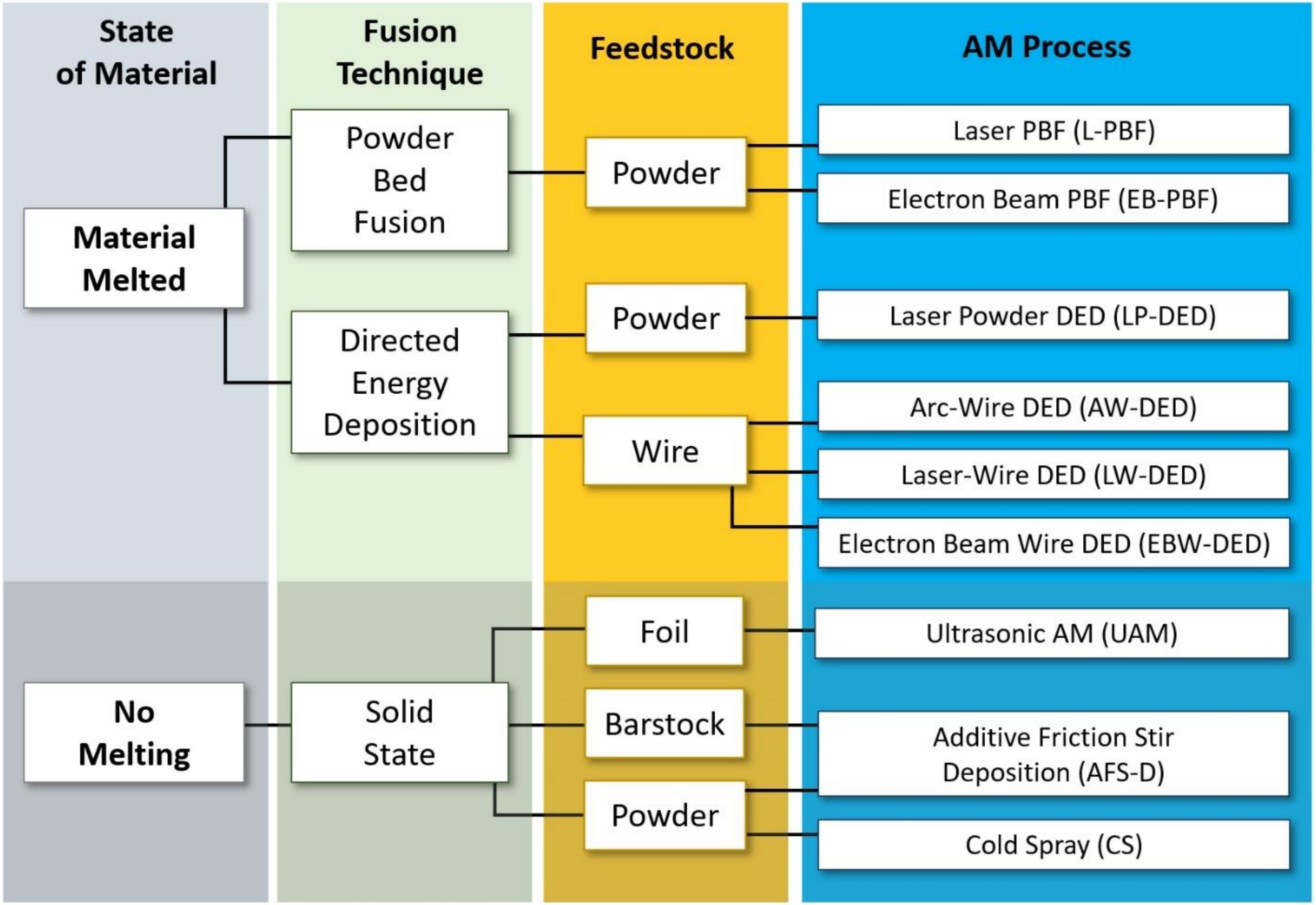


Successful hot-fire testing of full-scale additive manufacturing (AM) Part to be flown on SLS RS-25

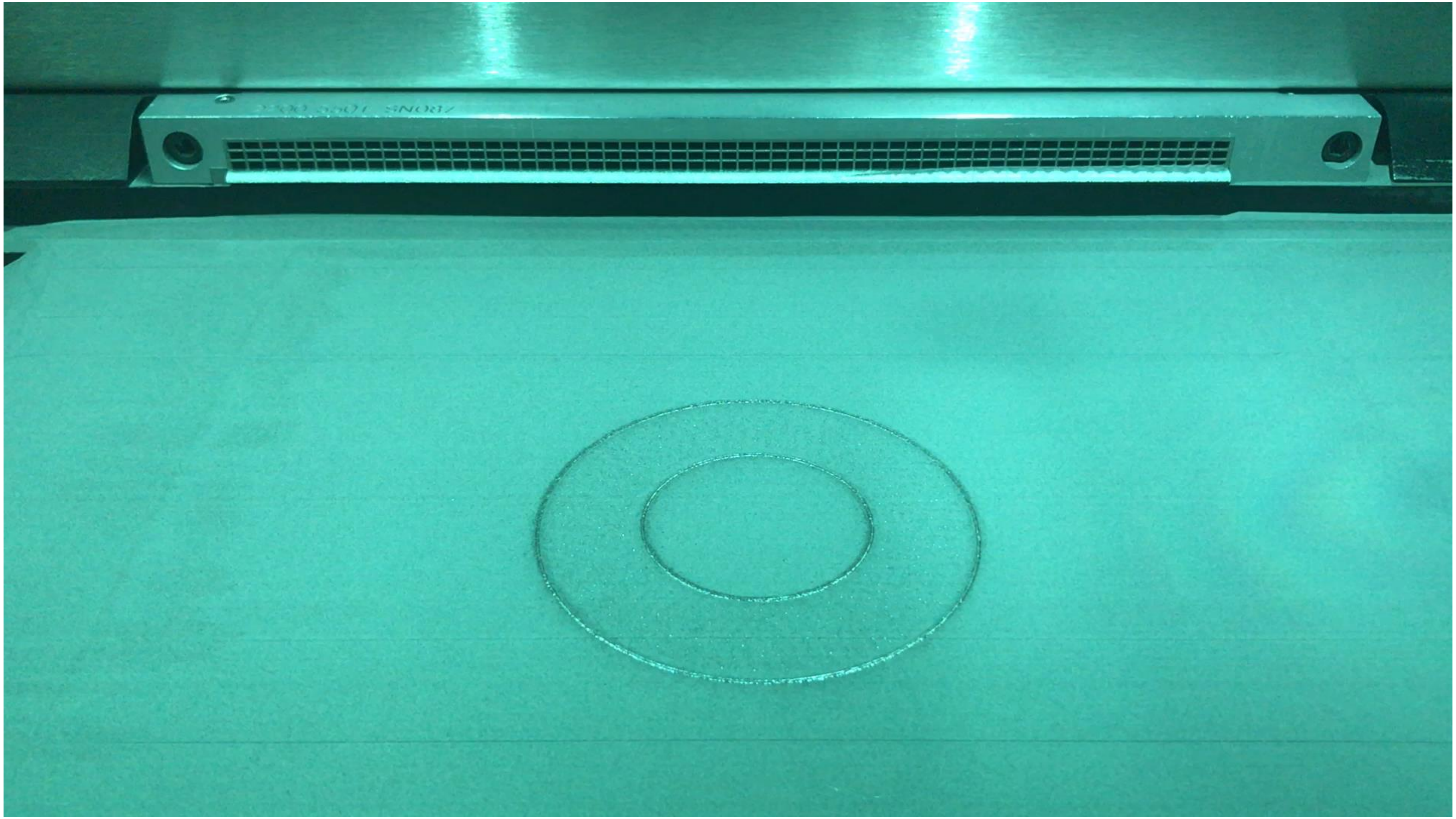
RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from <u>127 welds to 4 welds</u>

Ref: Andy Hardin, Steve Wofford/ NASA MSFC

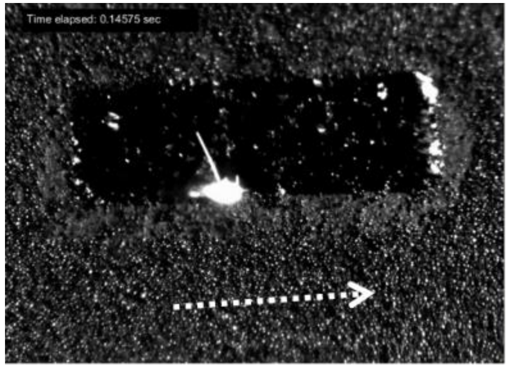
Various Metal AM Processes



Laser Powder Bed Fusion (L-PBF)

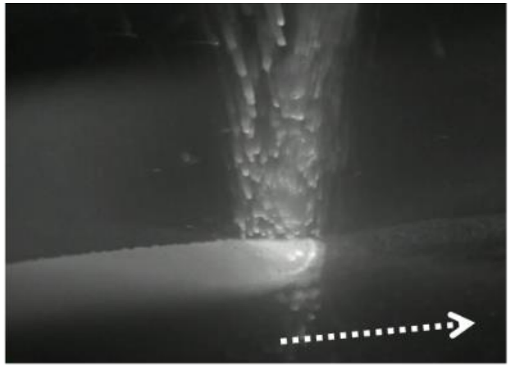


AM Processes for various applications

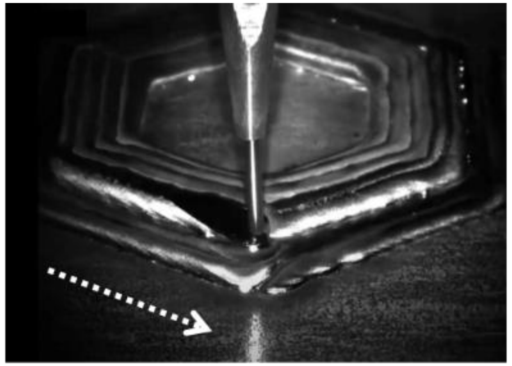


Laser Powder Bed Fusion

Electron Beam Powder Bed Fusion

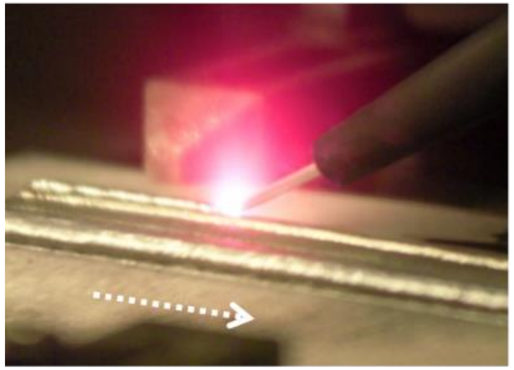


Laser Powder DED

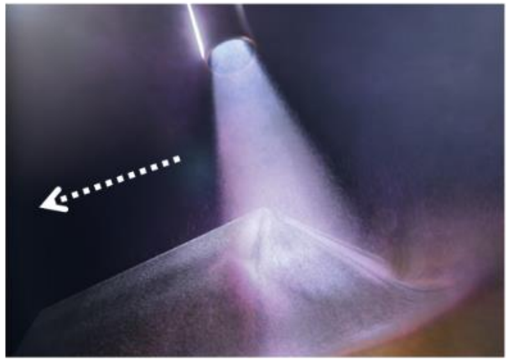


Laser Wire DED

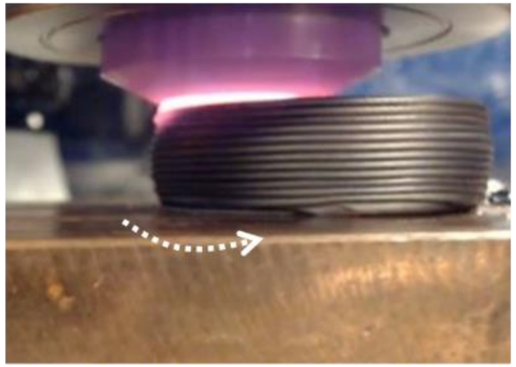
Arc Wire DED



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: 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].*

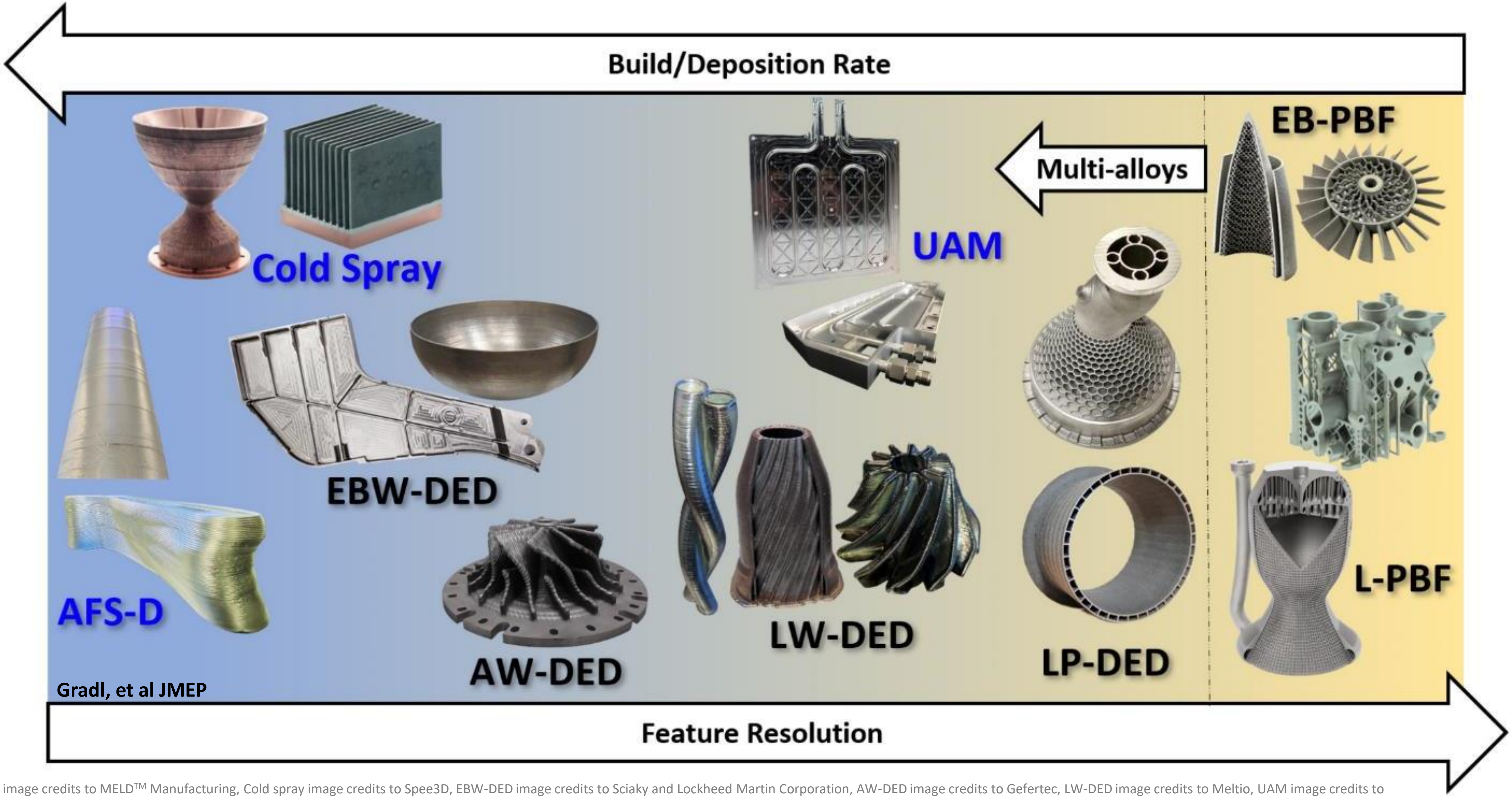
Reference: Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

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?

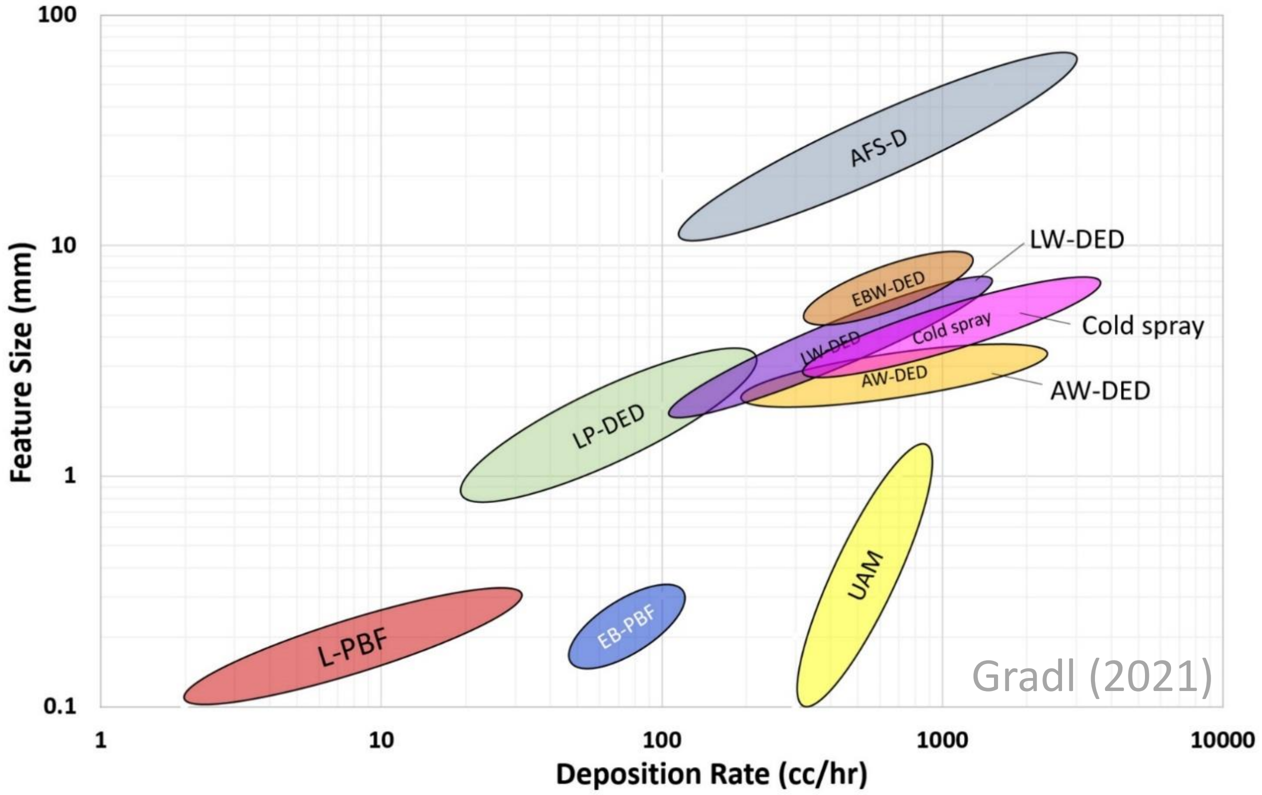
Reference: Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

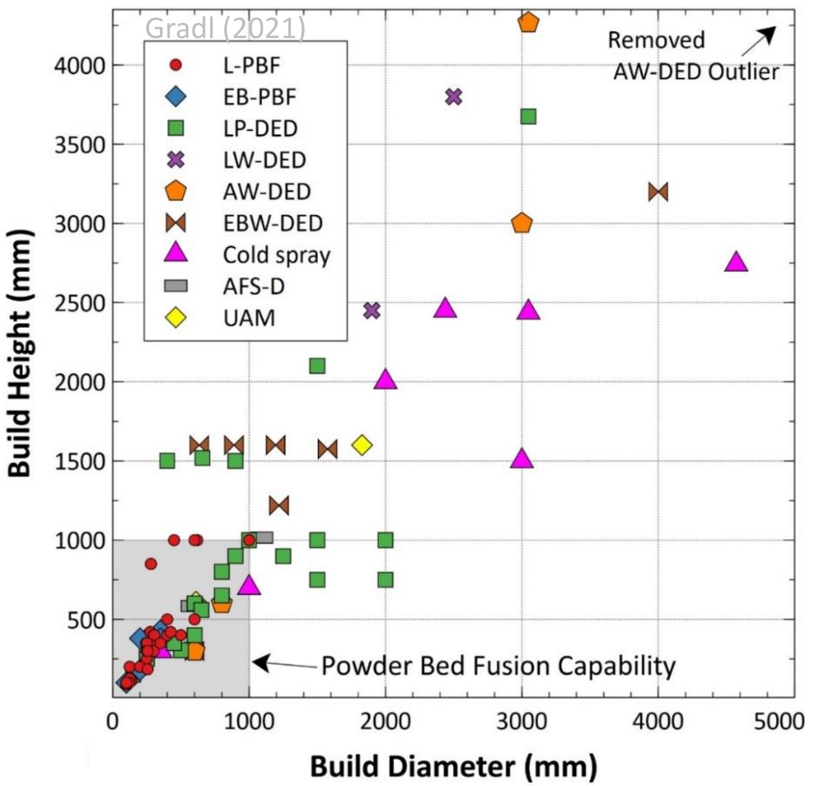
Criteria and Comparison Various Metal AM Processes



CREDITS: AFS-D image credits to MELD[TM] 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

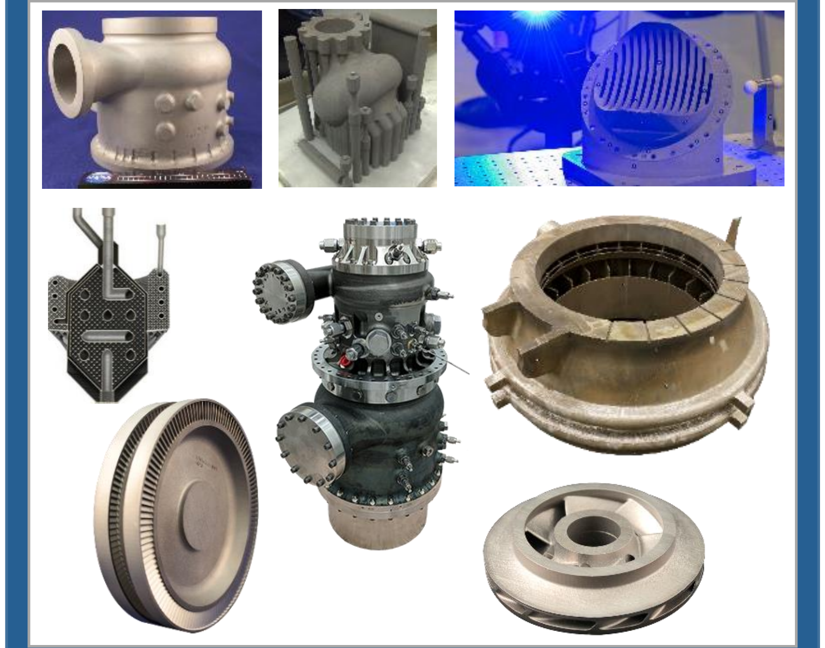
References:

- 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

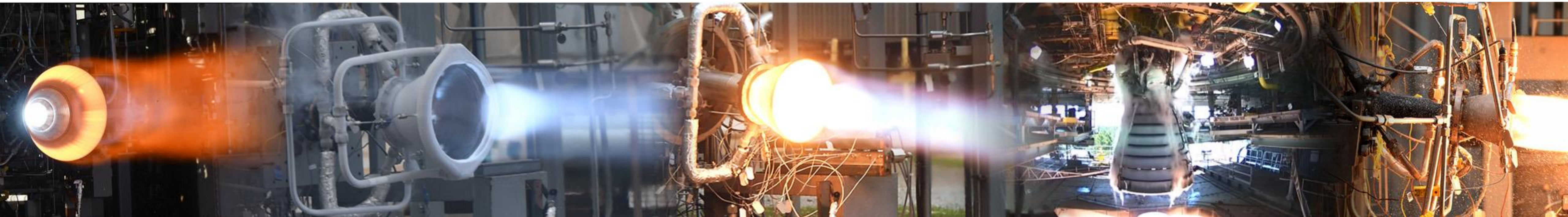
Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

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

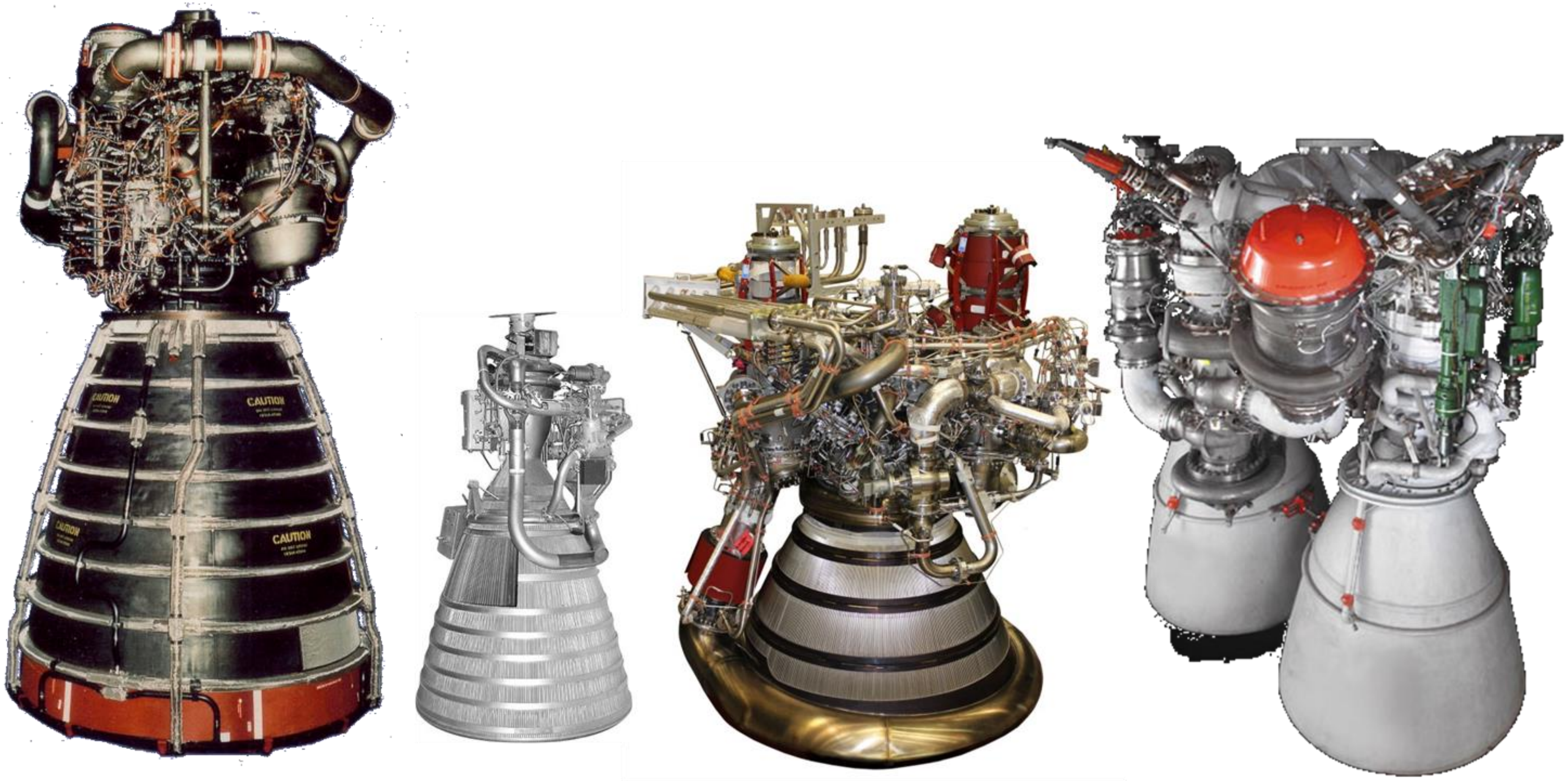


EXPLORE MOON to MARS

Large Scale Additive Manufacturing for Rocket Nozzles

NASA

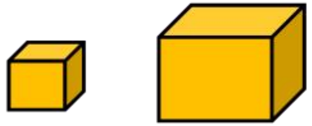
SSME/RS-25 | RL-10A-4 | J-2X, Regen Only | RD-180



90″ | 46″ | 70″ | 56″

Nozzle Exit Dia.

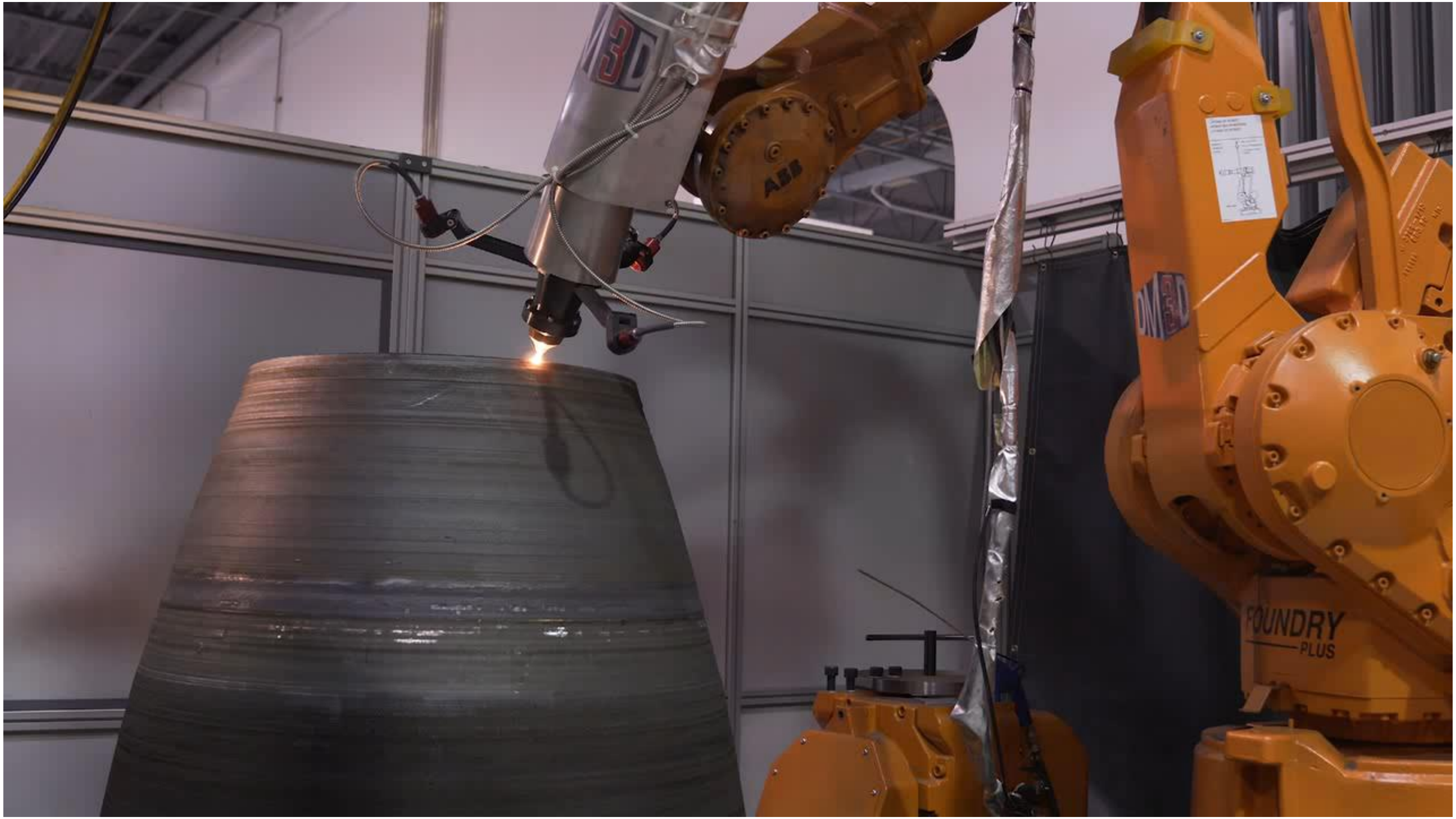
L-PBF Build Boxes



10x10x10   15.5x24x19

(inches)

Laser Powder Directed Energy Deposition (DED)



Laser Powder Directed Energy Deposition (LP-DED) Large Scale Nozzles

1.52 m diameter and 1.78 m height with integral channels
90 day deposition

2.41 m dia and 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

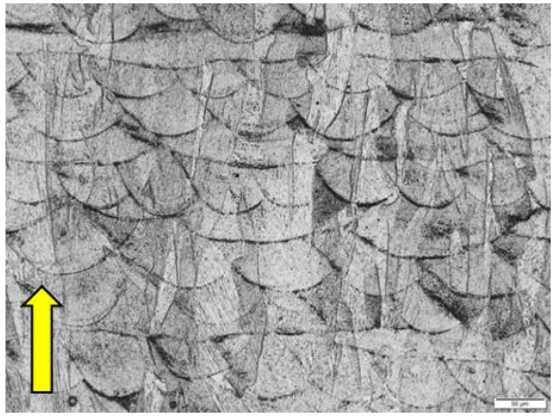
Part in Service
- Assembly
- Validation / Testing
- Qualified Metallurgy
- Part Production Plan

Qualification

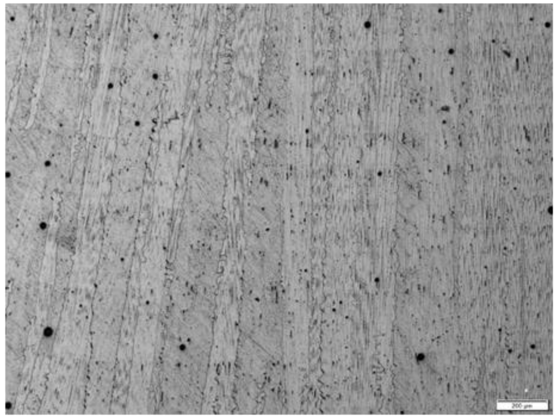
Proper AM process selection requires an integrated evaluation of all process lifecycle steps

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

Microstructure of Various AM Processes
Alloy 625 – As-Built

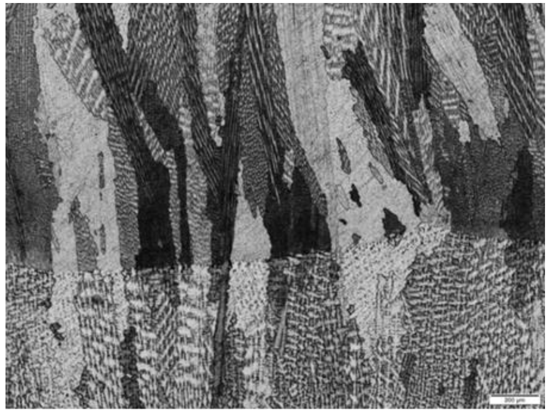


Laser Powder Bed Fusion

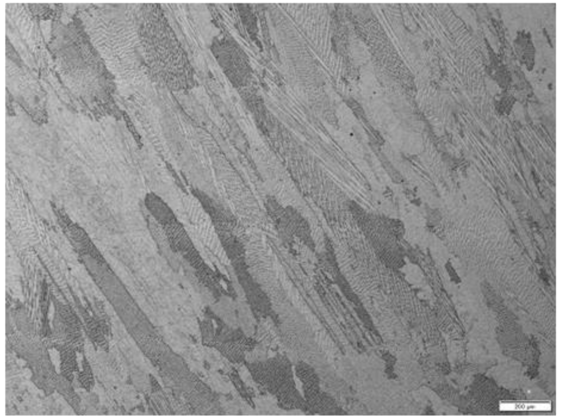


Electron Beam Powder Bed Fusion

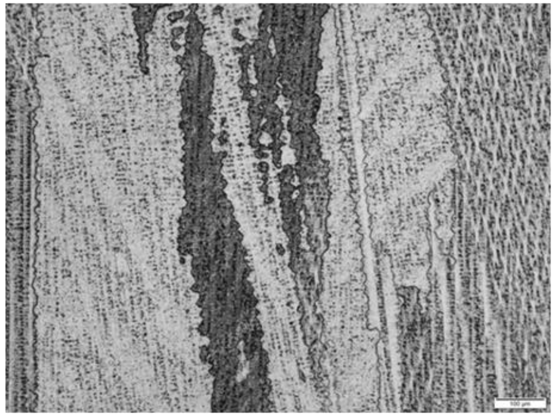
Laser Powder DED (1070 W)



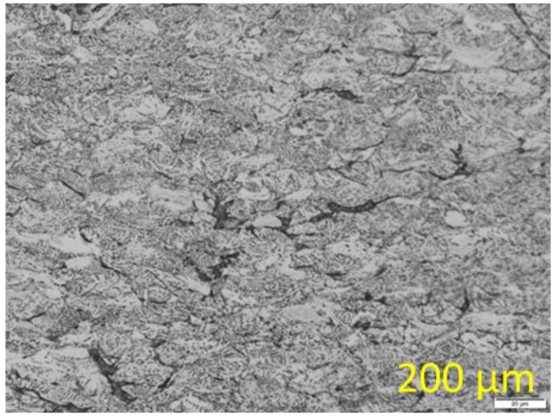
Electron Beam Wire DED



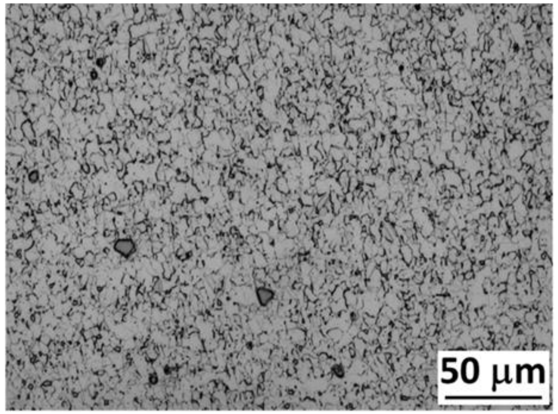
Laser Wire DED



Arc Wire DED



Cold Spray



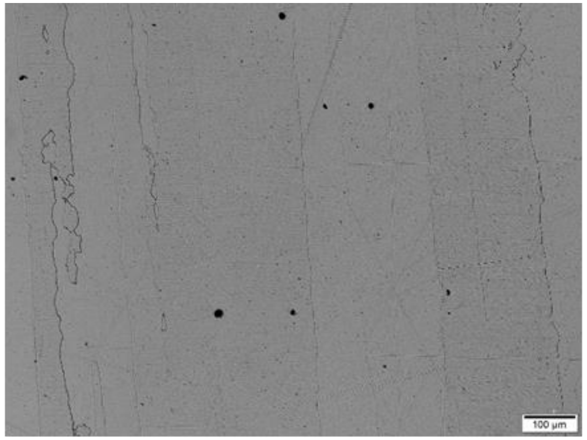
Additive Friction Stir Deposition

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

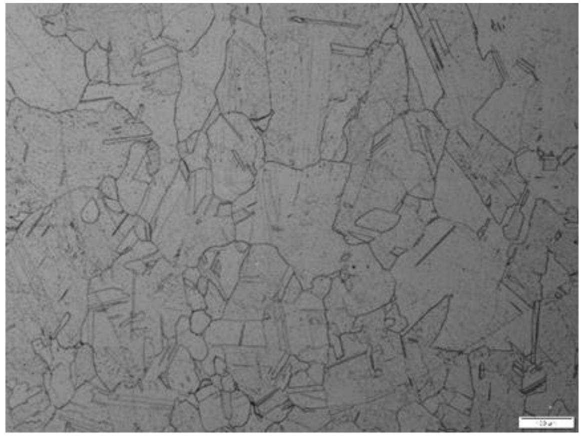
- Gamon, A., Arrieta, E., Gradl, P.R., Katsarelis, C., Murr, L.E., Wicker, R.B., Medina, F., 2021. Microstructure and hardness comparison of as-built Inconel 625 alloy following various additive manufacturing processes. Results in Materials 12. https://doi.org/10.1016/j.rinma.2021.100239
- Gradl, P.,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

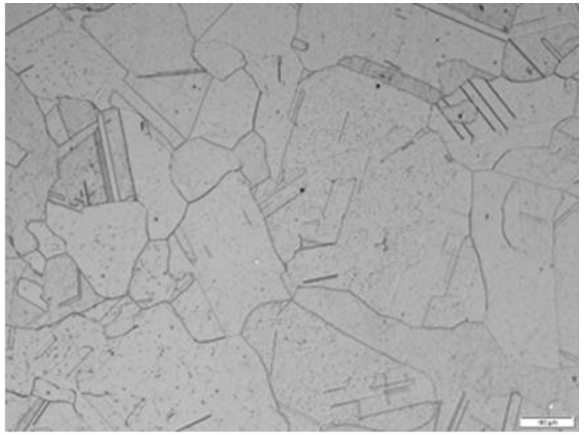
Laser Powder Bed Fusion



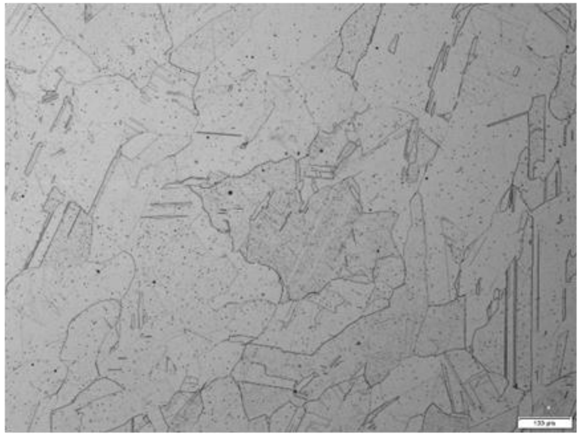
Electron Beam PBF



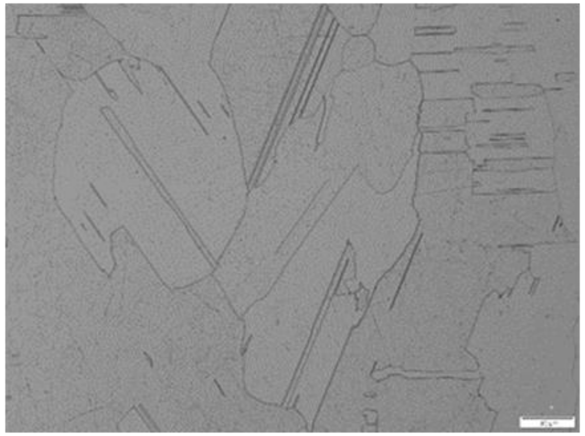
Laser Powder DED (1070 W)



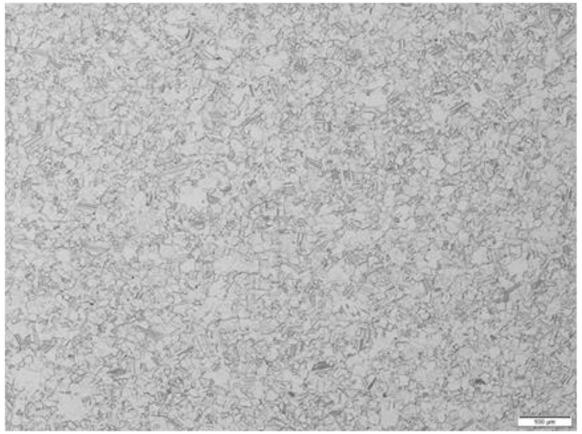
Electron Beam Wire DED



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
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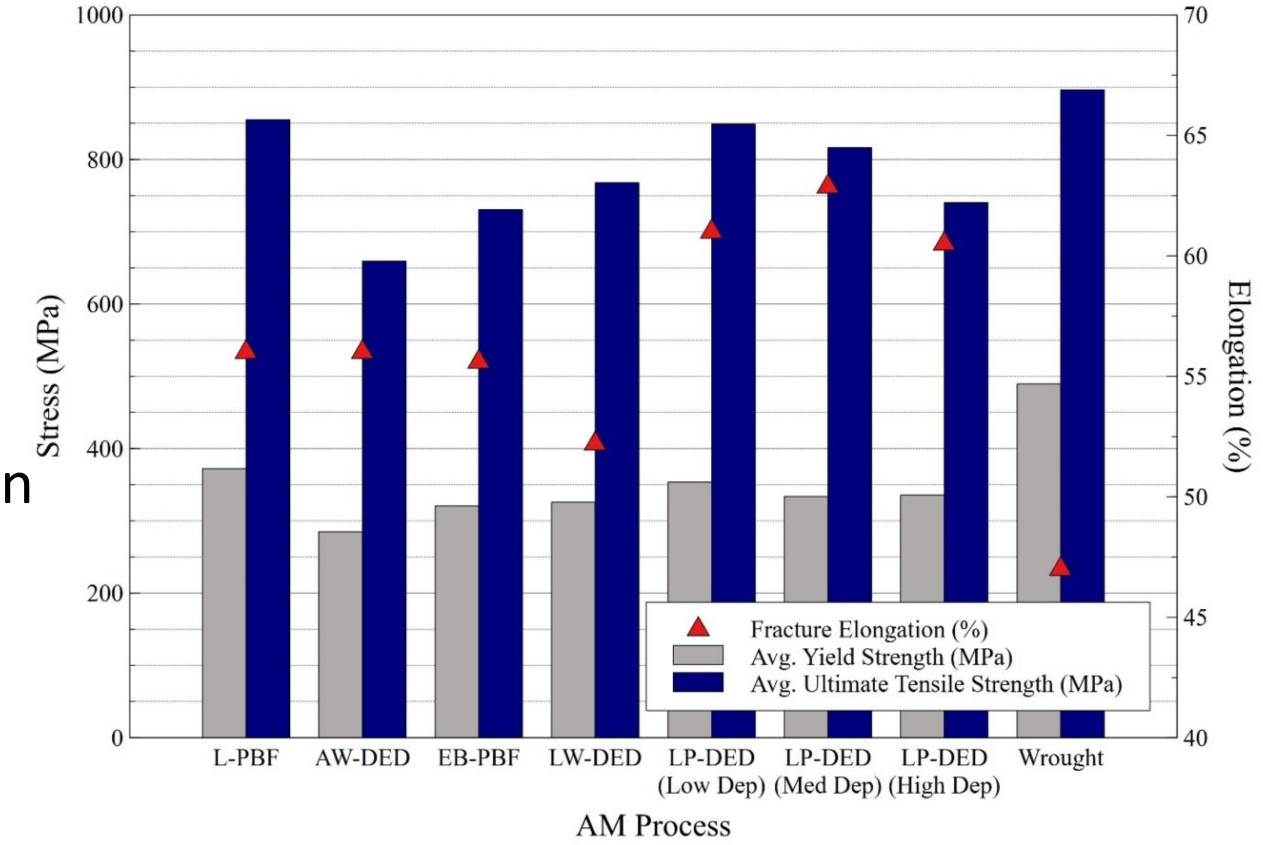
Material Properties for Various AM Processes

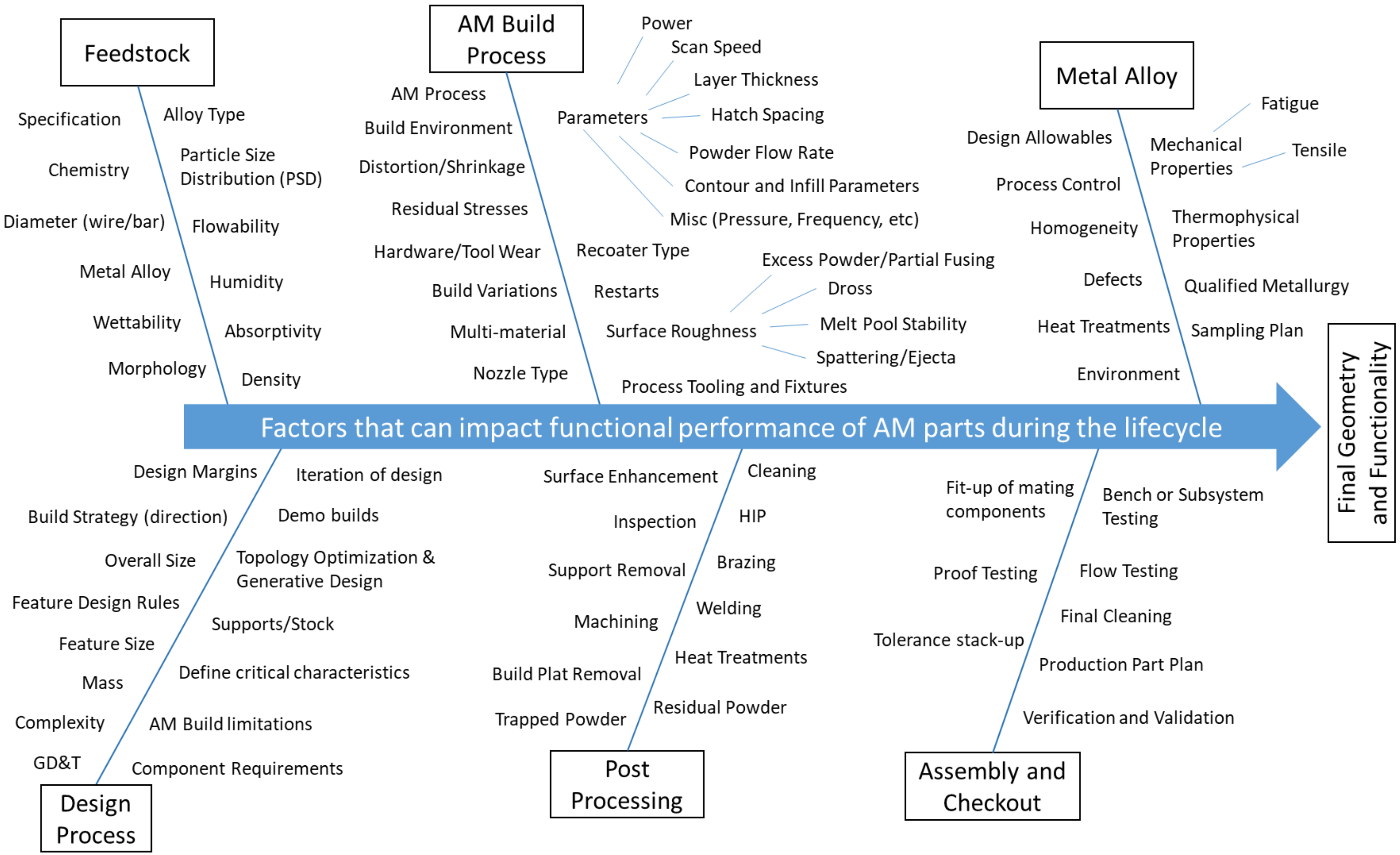
- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Cold spray….), the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build.
- Each AM process results in different grain distributions, precipitates, and porosity, 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, Heat Treated per AMS 7000 Room Temperature UTS



*Not design data and provided as an example only

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

Challenges in AM

- Surface Texture
- Repeatability of the process (across designs, machines, facilities…)
- Inspection of components
- Residual stresses and distortion
- Properties of alloys and common usage (databases)
  - Anisotropy based on build direction
  - Differences between processes
  - Mechanical, thermophysical, texture, etc…
- Design of AM parts and systematic application of AM
  - Education of AM for proper infusion
  - Understand of the entire lifecycle
- Standards and certification of process

AM Mechanical Property Database

- Obtained material samples from L-PBF and LP-DED vendors with full traceability
- Characterization of as-built samples and evolution through heat treatments to select optimal heat treatment cycle (HIP baselined)
  - Partnership with Auburn NCAME
- After appropriate heat treatment cycle, complete temperature dependent tensile and fatigue testing
- Partial data set is published as Appendix in AIAA book
  - 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
- Future goal to publish all data and characterization in a handbook and raw data uploaded to selected database (potentially MAPTIS)

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

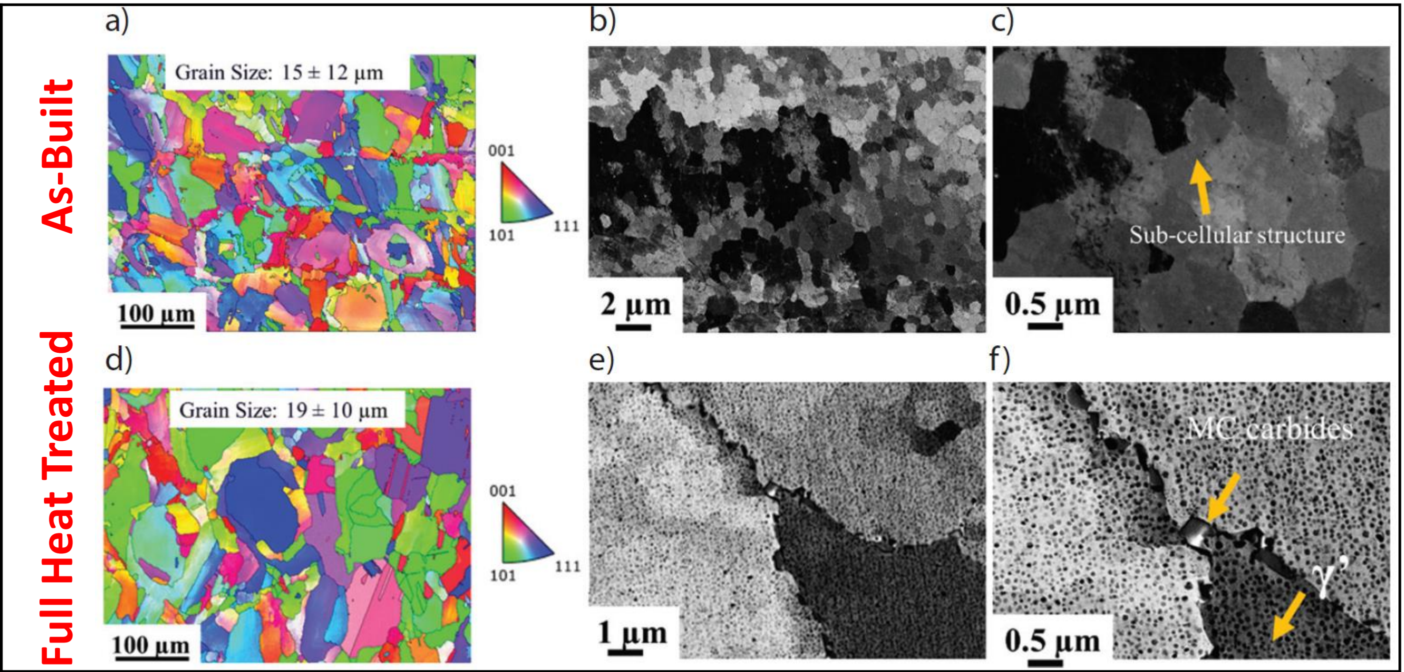
Material	Process
Monel K500	LP-DED
Monel K500	L-PBF
GRCop-42	L-PBF
GRCop-42	LP-DED
GRCop-84	L-PBF
C-18150	L-PBF
Ti6Al-4V	L-PBF
Ti6Al-4V	LP-DED
Ti6Al-4V	LW-DED
Ti6Al-4V	EBW-DED
Ti6242	L-PBF
Ti6242	LP-DED
GRX-810	L-PBF
GRX-810	LP-DED
Haynes 214-ODS	L-PBF
C-103	LP-DED

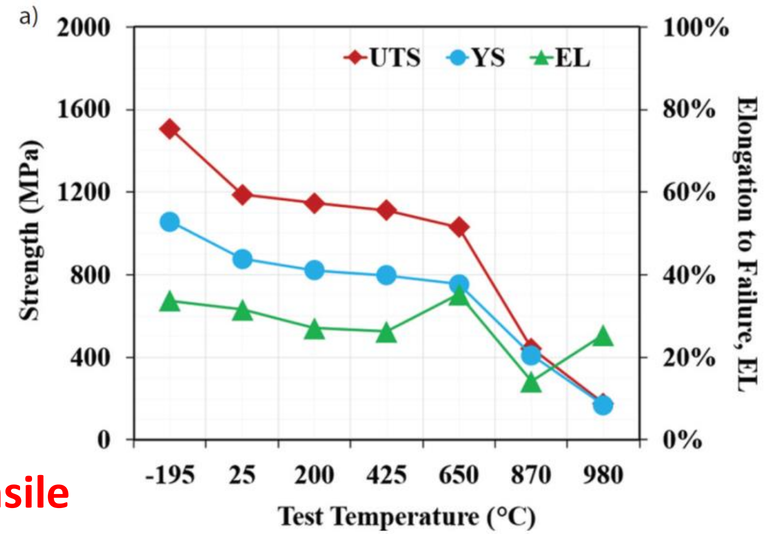
55+ Alloys in characterization

Data example of Haynes 282 L-PBF

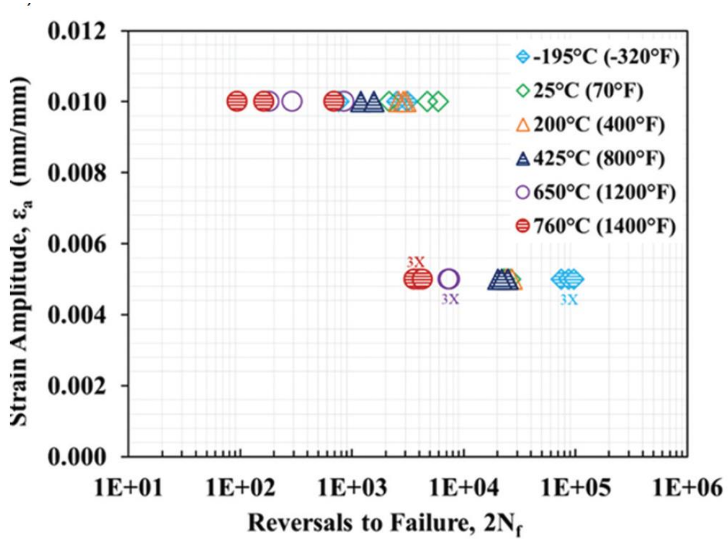
Material	Power (W)	Layer Height (mm)	Scan Speed (mm/s)	Hatch Distance (mm)
Haynes 282	285	0.04	960	0.13

Procedure (Designation)	Temperature (°C)	Time (hrs)	Cooling
Stress Relief (SR)	1065	1.5	Furnace cool
HIP [2]	1162/103 MPa	3.5	Furnace cool
Solution Annealed (SOL)	1135	1	Argon quench
Double Step Aging (AGE)	1010	2	Furnace cool at 10°C/min
	788	8	2 bar Argon gas at 20°C/min





Tensile



LCF

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

AM Thermophysical Property Database

- Identical samples and heat treatments determined for mechanical testing also complete thermophysical testing
  - CTE, thermal diffusivity, specific heat, thermal conductivity
  - Comparison of data to select alloys wrought form
  - Data tested in partnership with LSU

TABLE 1-1 COEFFICIENTS OF THERMAL EXPANSION (CTE) OF THE ALLOYS (10^{-6}/K)

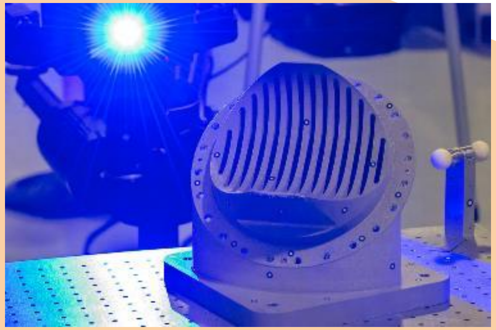
Temp. (°C)		100	200	300	400	500	600	700	800	900	1000
Material	Process										
GRCop-42	L-PBF	14.7	16.2	16.7	17.1	17.7	18.2	18.7	19.4	20.2	/
GRCop-84	L-PBF	/	/	/	/	/	/	/	/	/	/
C-18150	L-PBF	/	/	/	/	/	/	/	/	/	/
Inconel 625	L-PBF	11.5	12.8	13.3	13.6	13.9	14.3	14.9	15.5	16	16.4
Inconel 625	LP-DED	12.1	12.6	13.1	13.5	13.8	14	14.6	15.2	15.6	16.1
Inconel 718	L-PBF	12.6	13.9	14.2	14.5	14.8	15.1	15.6	16.4	17.5	17.8
Inconel 718	LP-DED	12.7	13.9	14.4	14.7	15	15.3	15.7	16.7	17.9	18.2
Inconel 939	L-PBF	11.4	12.4	12.9	13.3	13.7	14.0	14.6	15.1	16.0	11.4
HastelloyX	L-PBF	13	14	14.3	14.7	14.9	15.3	15.8	16.1	16.4	16.8
HastelloyX	LP-DED	12.6	14	14.5	14.8	15	15.4	15.9	16.2	16.5	16.8
Haynes 214	L-PBF	12.4	13.7	14.1	14.4	14.7	15.0	15.5	16.4	17.5	/
Haynes 230	L-PBF	11.1	12.4	12.9	13.3	13.7	13.9	14.6	15.2	15.7	11.1
Haynes 230	LP-DED	11.6	12.6	13.1	13.4	13.7	13.9	14.5	15	15.5	16.1
Haynes 282	L-PBF	/	11.5	12.3	12.9	13.3	13.6	14.3	14.9	16	17.3
SS 316L	LP-DED	14.4	16.1	16.7	17.1	17.4	17.8	18.1	18.5	18.8	19.1
15-5, H900	LP-DED	9.7	10.5	10.9	11.3	11.6	11.9	9.7	9.8	11.1	/
15-5, H1150	LP-DED	10.9	11.9	12.5	12.9	13.2	13.2	12.6	12.5	13.3	14.4

TABLE 2-8 TESTED THERMAL PROPERTY RESULTS OF INCONEL 939 (L-PBF)

Temp. (°C)	Density (g/cm^3)	Specific Heat J/(gK)	STD	Thermal Diffusivity mm^2/s	STD	Thermal Conductivity W/(mK)	STD
25	8.03	0.607	0.036	2.94	0.07	14.4	0.8
100	8.01	0.606	0.040	3.14	0.07	15.0	1.2
200	7.98	0.518	0.095	3.38	0.09	14.6	2.7
300	7.95	0.665	0.044	3.72	0.09	19.9	1.2
400	7.92	0.679	0.041	4.00	0.05	23.3	3.9
500	7.89	0.705	0.037	4.30	0.06	24.4	1.4
600	7.86	0.760	0.046	4.62	0.16	27.5	1.7
700	7.82	0.791	0.052	4.85	0.18	29.9	1.9
800	7.79	0.852	0.052	4.88	0.13	32.2	1.9
900	7.75	0.916	0.058	4.98	0.22	35.2	2.2
1000	7.71	1.059	0.085	5.04	0.33	41.4	3.2

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

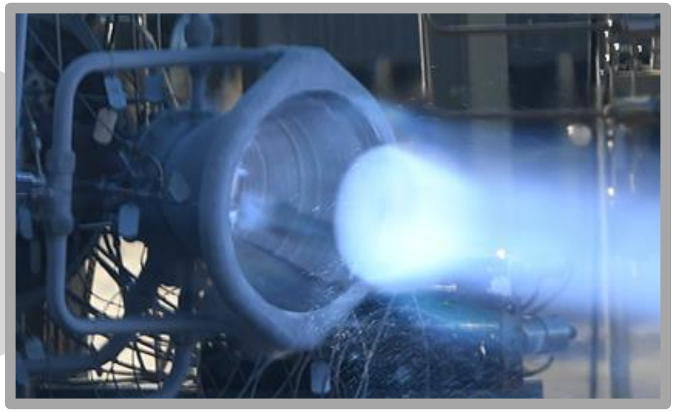
Industrial Maturity and TRL of AM Processes



L-PBF

Cold spray

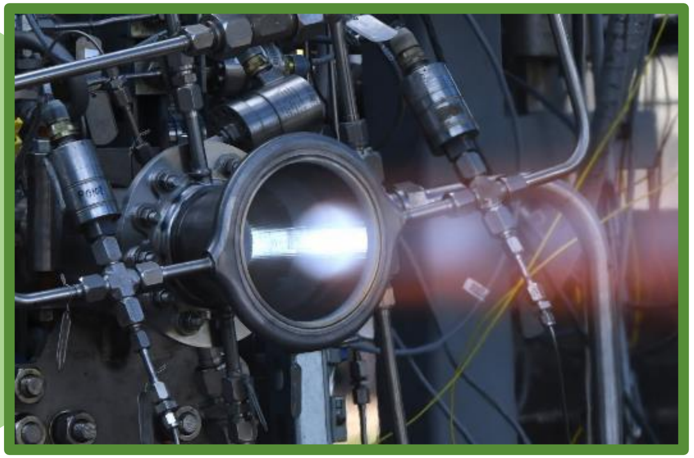
LP-DED



L-PBF

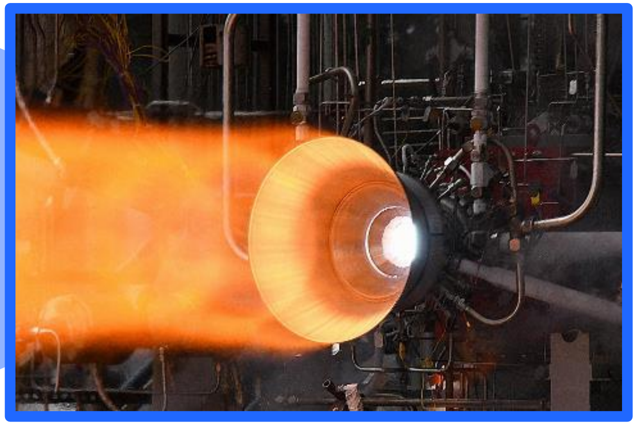
AW-DED

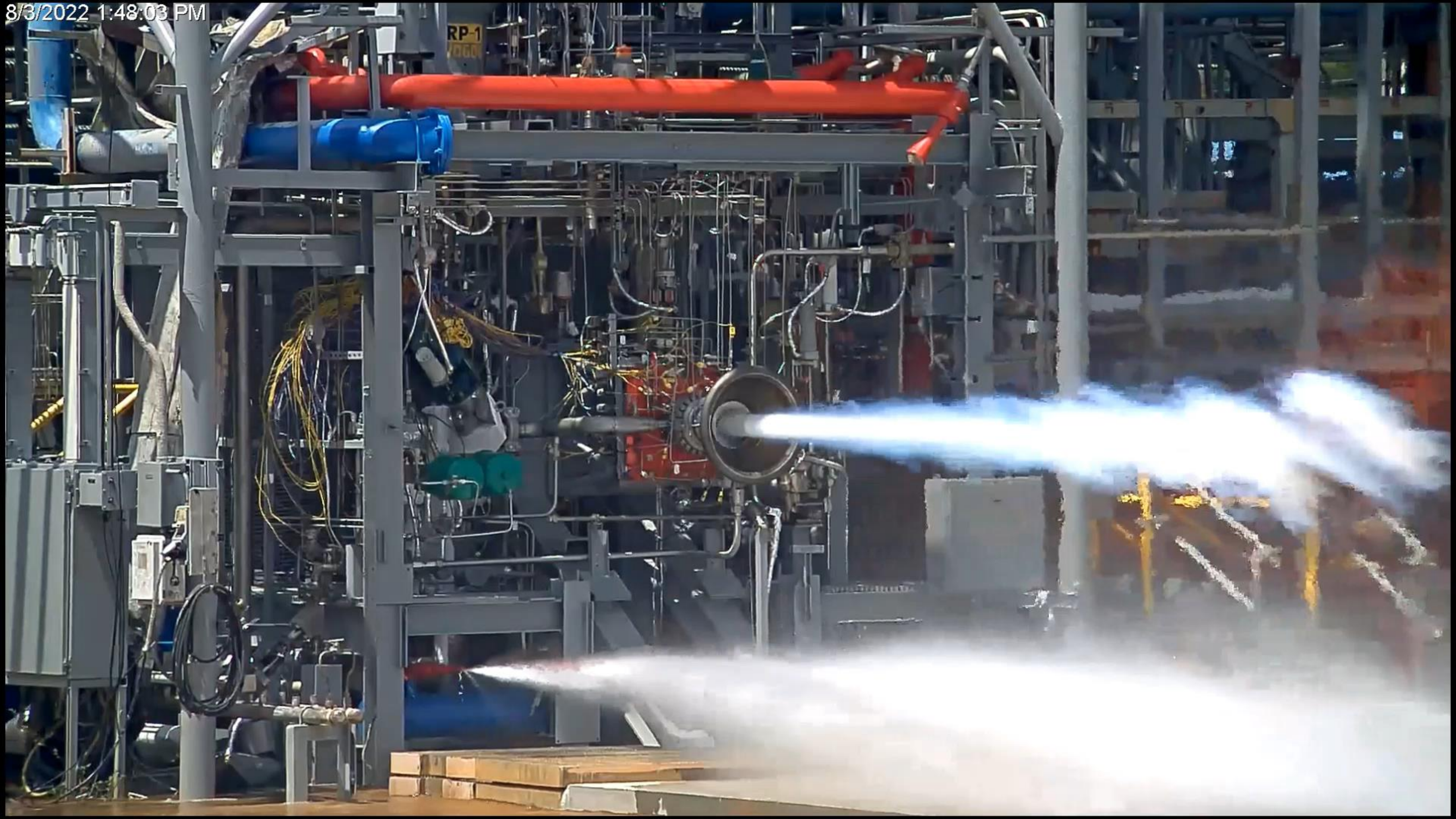
LW-DED



L-PBF

EBW-DED

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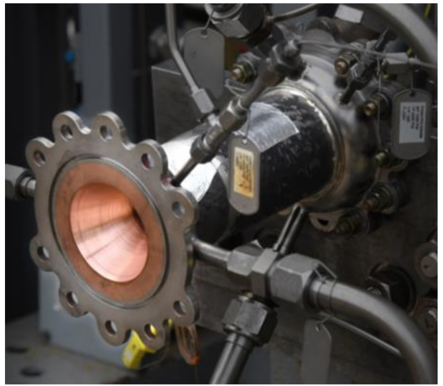
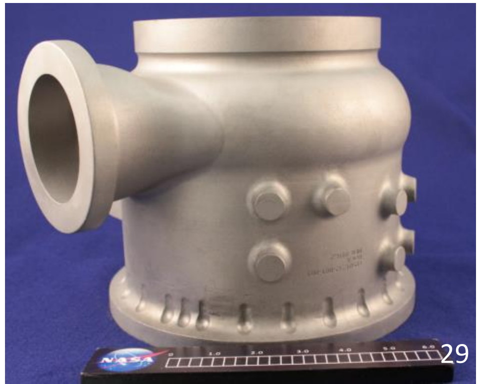
RP-1

Summary

- Various AM processes have matured for rocket propulsion applications each with unique advantages and disadvantages.
- AM is <u>not a solve-all</u>; consider trading with other manufacturing technologies and use <u>only</u> 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.





NASA led book on Metal Additive Manufacturing

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.

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Photo: NASA/Ben Smegelsky

Emerging Areas of Development for Metal AM

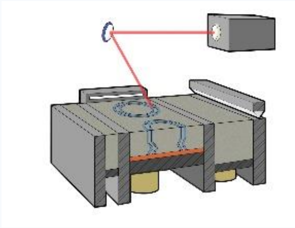
- Maturing each of the AM processes and understanding of microstructure, properties, build limitations, and methods for design and post-processing.
- Ongoing development for large scale AM using DED and other processes.
- Continuous hot-fire and component testing to advance various combustion chambers, 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.

AIAA SHAPING THE FUTURE OF AEROSPACE

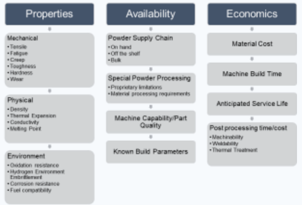
Metal Additive Manufacturing for Propulsion Applications

Editors: Paul Gradl, Chris Protz, Chance Garcia, Omar Mireles

Chapter 1
Introduction and Applications of Additive Manufacturing for Propulsion



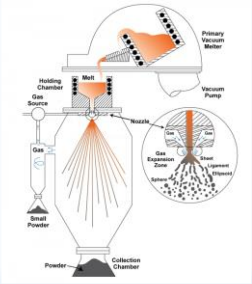
Chapter 2
Metal Additive Manufacturing Processes and Selection



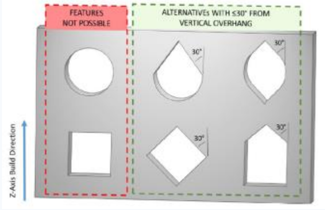
Chapter 3
Selection and Overview of Additive Manufactured Metals and Metal Alloys

Chapter 4
Microstructure and Properties of Additively Manufactured Metal Alloys

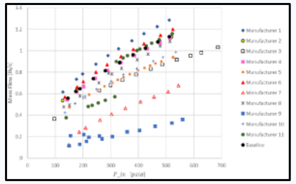
Chapter 5
Post-Processing of Metal Additively Manufactured Components



Chapter 6
Feedstock for Metal AM

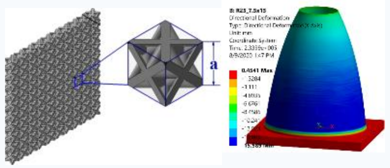


Chapter 7
Functional Design for Metal Additive Manufacturing



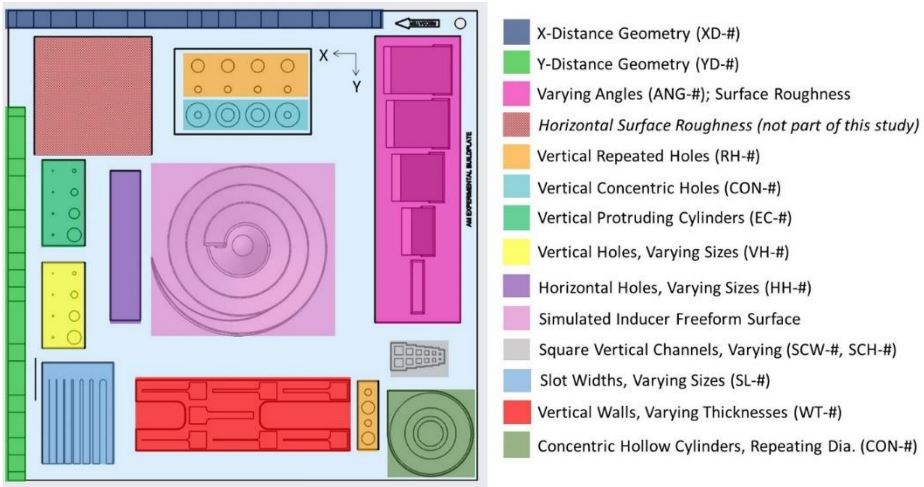
Chapter 8
Component Performance and Application Characteristics

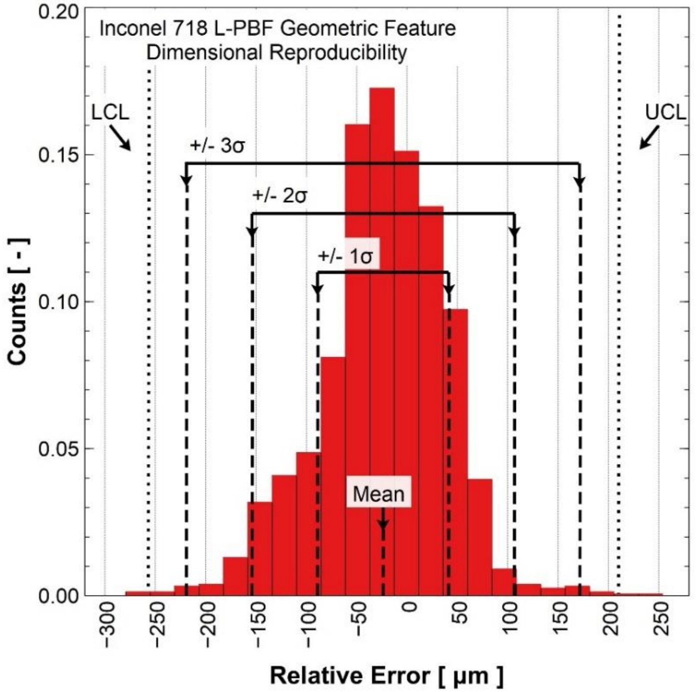
Chapter 9
Certification of Metal Additive Manufacturing: A NASA Perspective

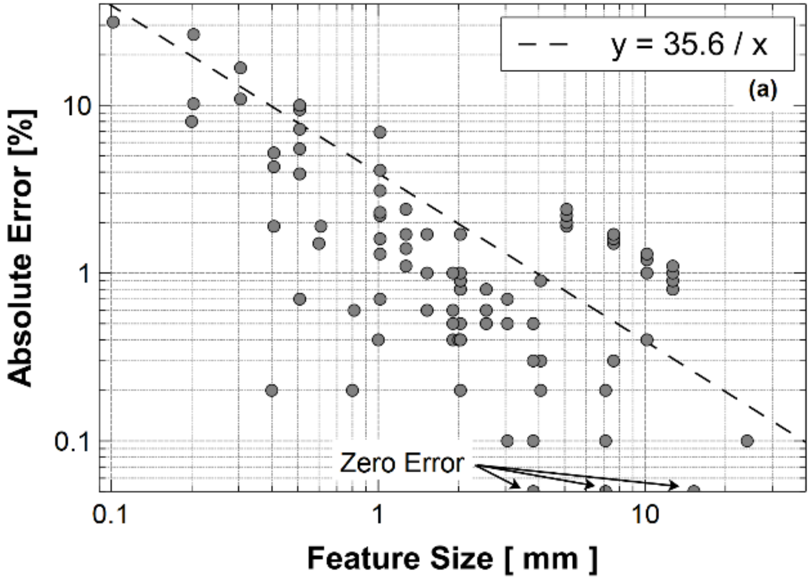


Chapter 10
Emerging Additive Manufacturing Technology for Propulsion

Detailed Study on L-PBF Geometric Reproducibility – Inconel 718







- Upper and lower control limits of +0.009" / -0.010" (mean error 0.0009")
- Relative error decreases inversely with feature size.
- Features sized at 0.004 inches (0.1 mm) failed to build for thin walls and slots
- Features sized at 0.008 inches (0.1 mm) failed to build for horizontal holes
- Features sized at 0.008 inches (0.02 mm) had high variability for thin walls, slots, and extruded cylinders

Gradl, P.R., Tinker, D.C., Ivester, J., Skinner, S.W., Teasley, T., Bili, J.L., 2021. Geometric Feature Reproducibility for Laser Powder Bed Fusion (L-PBF) Additive Manufacturing with Inconel 718. Additive Manufacturing 47, 102305. https://doi.org/10.1016/j.addma.2021.102305

Overview of Database

- A few alloys have been matured with significant property development at NASA MSFC (Inco 718, Inco 625, GRCop-42/84)
- Other alloys are of interest to include in component trades for development as well as AM modeling efforts, but limited data is available
- As AM parts increase complexity, process modeling is being evolved to help successful builds, but detailed data required
- Under the NASA Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project, Auburn is under contract to establish public-private partners to engage industry in cost sharing
- A current task under this development is to complete an initial database of key properties to help with the initial trades and modeling efforts supporting the program
  - While many of the alloys of interest and have been characterized by various companies, a majority of the data is proprietary and not accessible

Approach

- While we are not specifically limiting materials, we are trying to focus on many of the current alloys that have been matured across industry and of interest across various components and NASA. We are working to establish the following:
  - A fundamental understanding of the build process and material using some best practices from MSFC-SPEC-3717 (along with MSFC-STD-3716)
  - Characterization and evolution of the materials during heat treatments
  - Recommending heat treatment schedules
  - Complete basic mechanical and thermophysical property testing
    - Tensile from -320F through 1800F +
    - Low Cycle Fatigue at various strains from -320F through 1600F
    - High cycle fatigue testing as allows at various strains
    - Thermal conductivity, CTE
    - Others as available
  - Document results to make available for component trades, modeling efforts internal to NASA
  - Publish open reports/journals/articles on properties, heat treatments, and make data available to industry and research community to build upon

Key Properties - Minimum

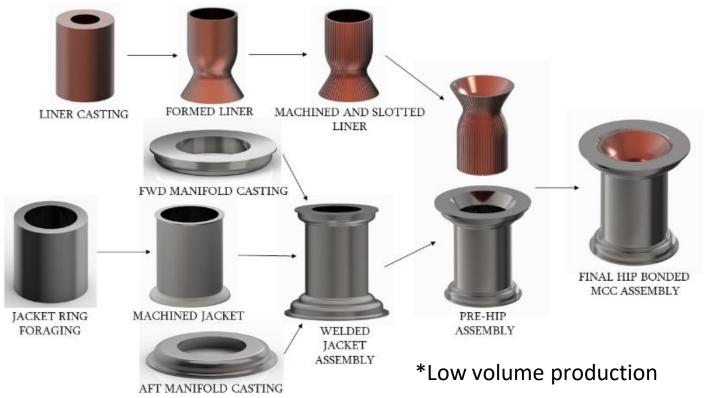
Tensile - # specimens at each						
-320 F	**70 F**	**400 F**	**800 F**	**1200 F**	**1600 F**	**1800 F**
6	6	6	6	6	6	6
	Total	42				

LCF - # specimens at each ; Various Strain Ranges						Varies for each alloy	
-320 F	**70 F**	**400 F**	**800 F**	**1200 F**	**1600 F**	**Strain Amplitude**	**Strain Rate**
3	3	3	3	3	3	1.00%	1.00%
3	3	3	3	3	3	0.70%	1.00%
	3					0.50%	1.00%
	3					0.30%	1.00%
	3					0.20%	1.00%
	Total	45					
						R=-1	
						Triangular	

Test conditions depend on alloy, trying to keep general comparisons as much as feasible

- Additional samples used for heat treatment evolution and characterization a well as metallography and SEM
- Min 2 samples for conductivity and CTE
- Additional samples used for more testing of Tensile, LCF, HCF, other properties

A rocket combustion chamber case study for AM



*Low volume production

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