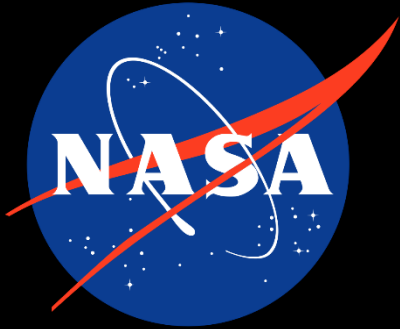


Statement A: Approved for public release; distribution is unlimited.



EXPLORE MOON *to* MARS

Introduction to Additive Manufacturing for Propulsion Systems

Paul R. Gradl, Omar R. Mireles
National Aeronautics and Space Administration (NASA)

5 December 2022
JANNAF LPS



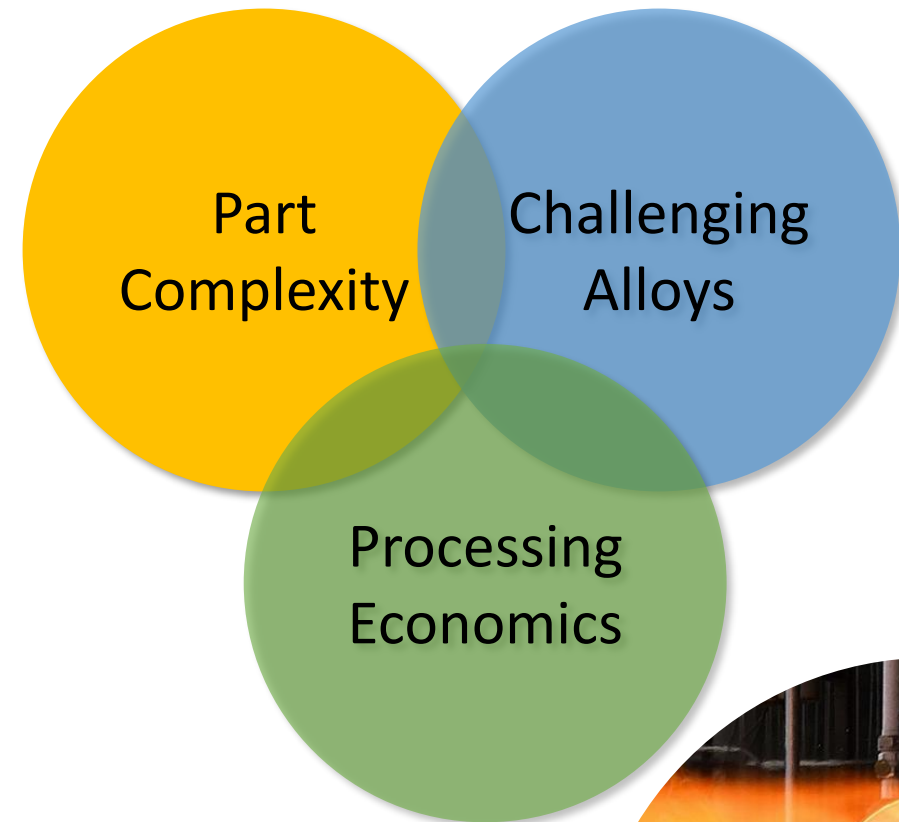
- Introduction / Use Cases
- Metal AM Process Selection
- Overview of AM Materials & Microstructure
- Metal AM Feedstock
- AM Post-Processing
- Design for AM (DfAM)
- Certification of Metal AM



The Case for Additive Manufacturing in Propulsion

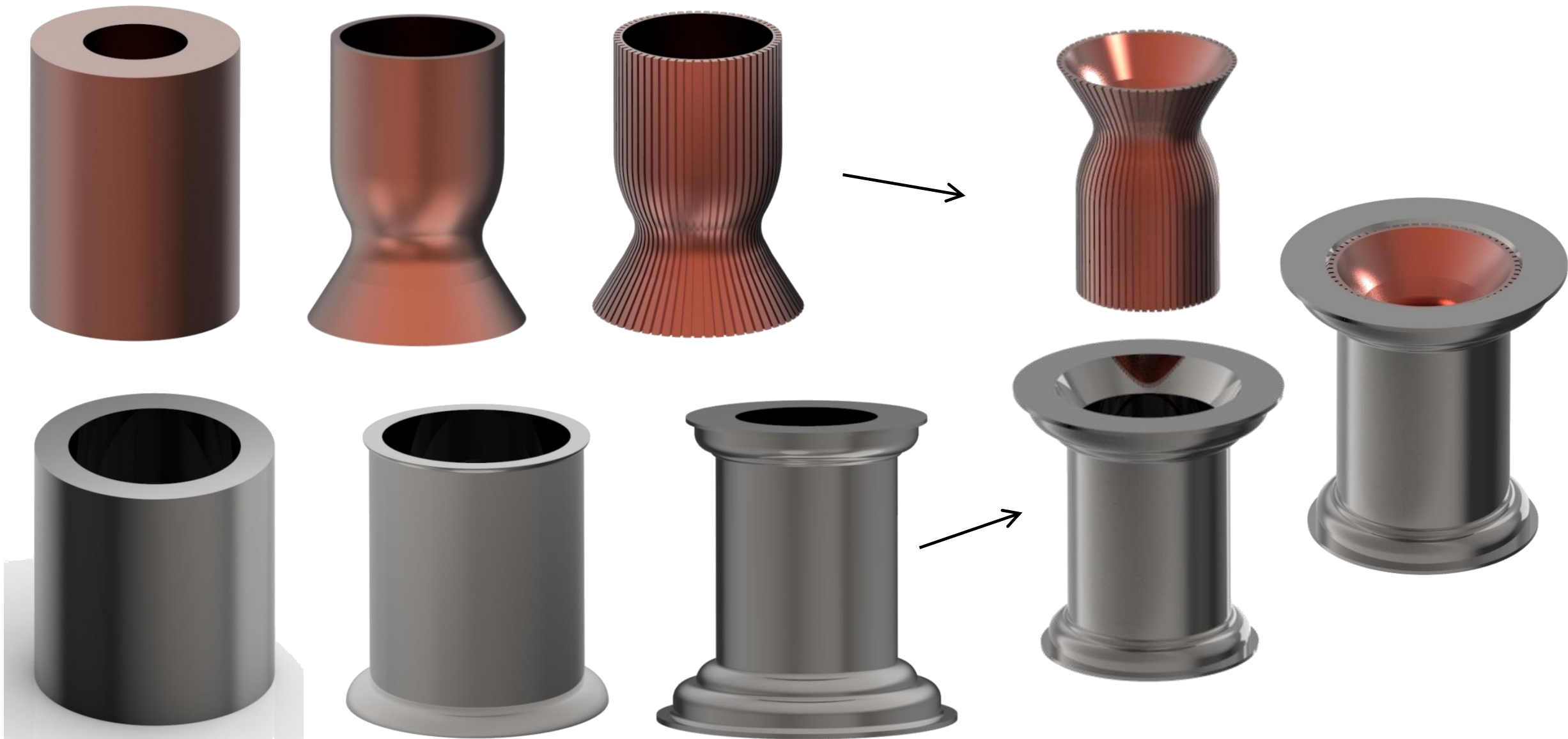


- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
 - Lead times reduced by 2-10x
 - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new designs, part consolidation, 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.

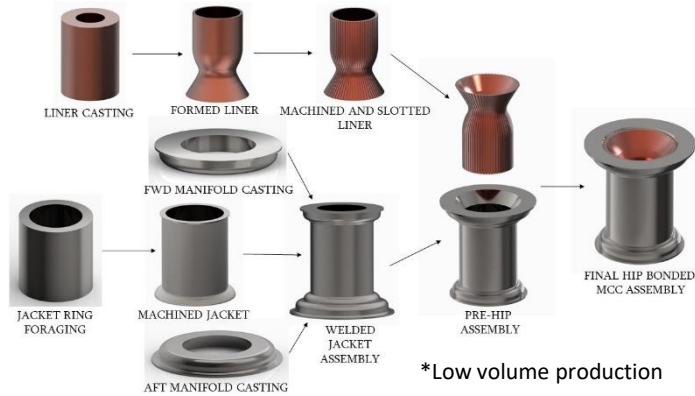




Traditional Manufacturing...Forging to final assembly



A rocket combustion chamber case study for AM

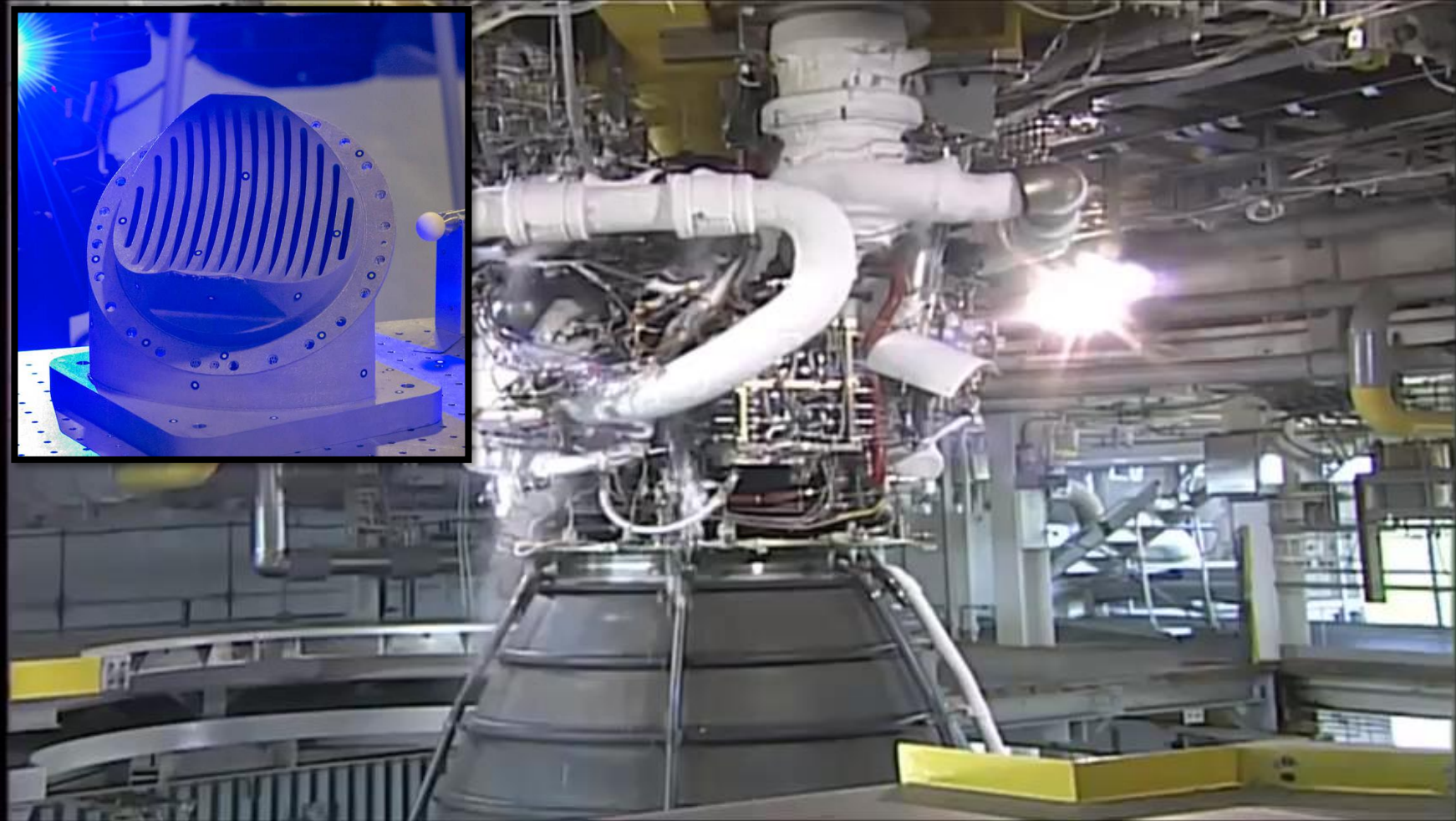
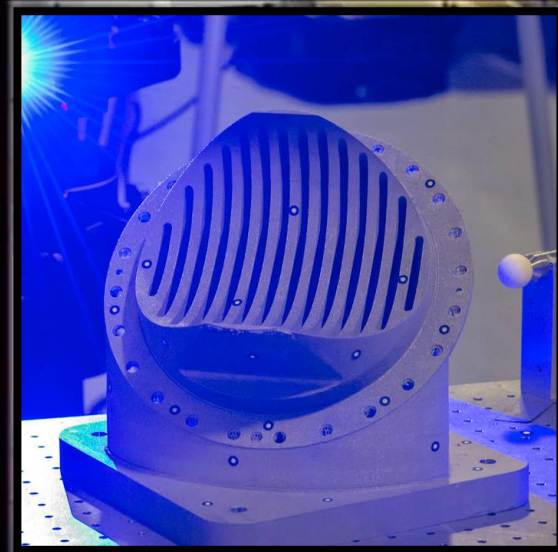


Category	Traditional Manufacturing	Initial AM Development	Evolving AM Development
Design and Manufacturing Approach	Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly	Four-piece assembly using multiple AM processes; limited by AM machine size. Two-piece L-PBF GRCo-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 GRCo-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 127 welds to 4 welds**



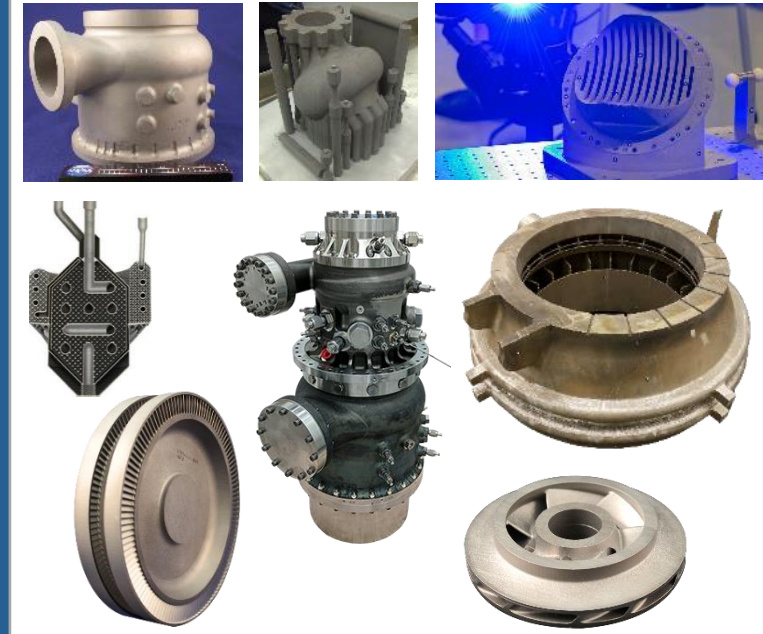
Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines



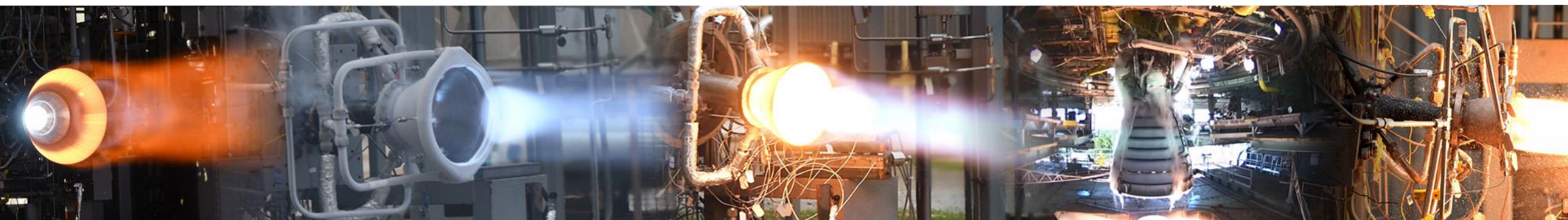
Laser Powder Bed Fusion (L-PBF)
Copper Alloys combined with other
AM processes to provide bimetallic



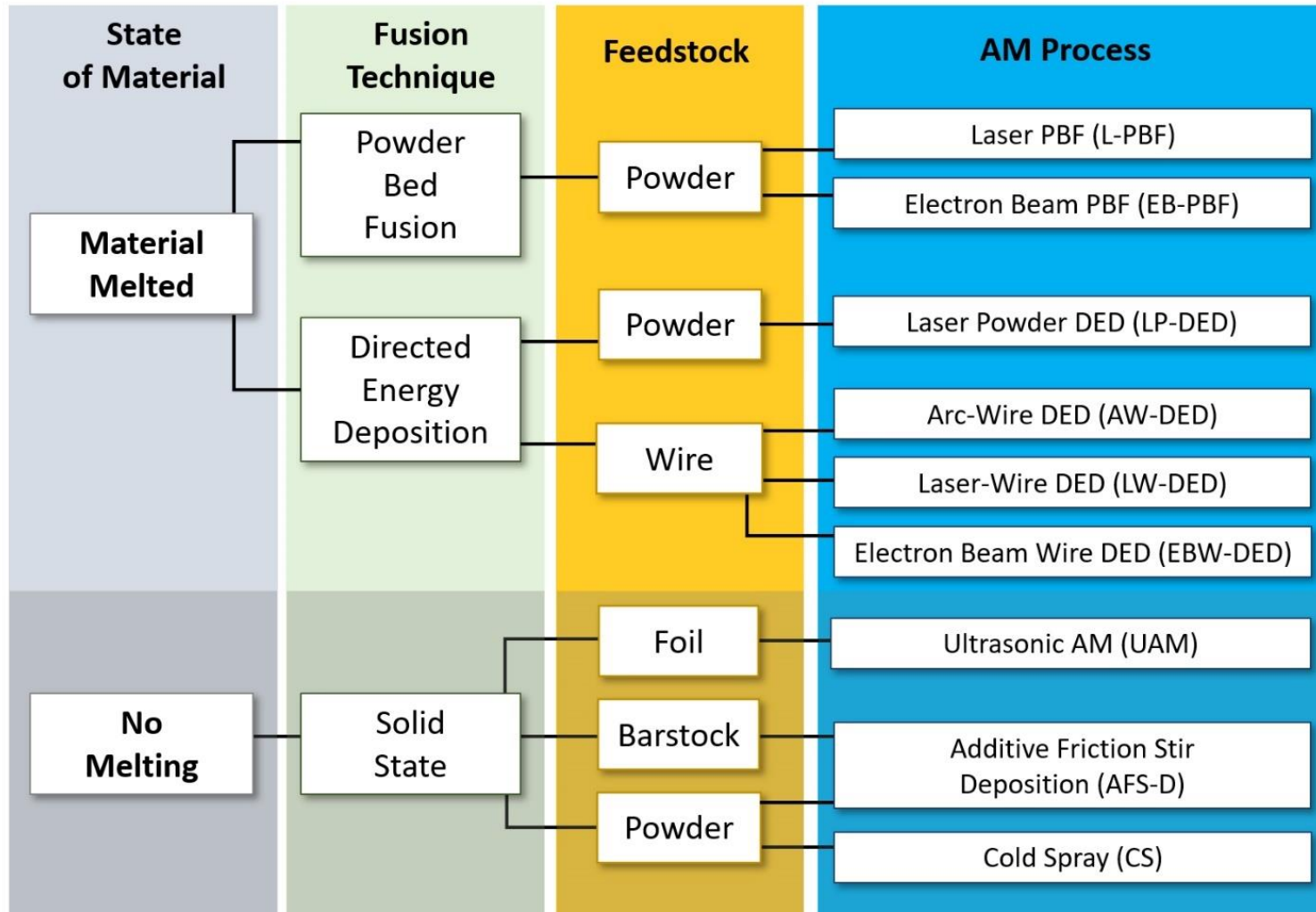
Directed Energy Deposition



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

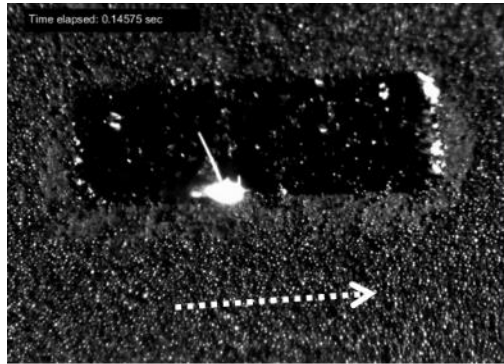


Various Metal AM Processes

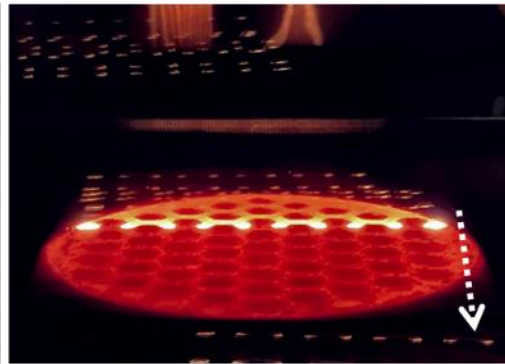


Many AM processes exist and must be traded (along with traditional techniques) to optimize

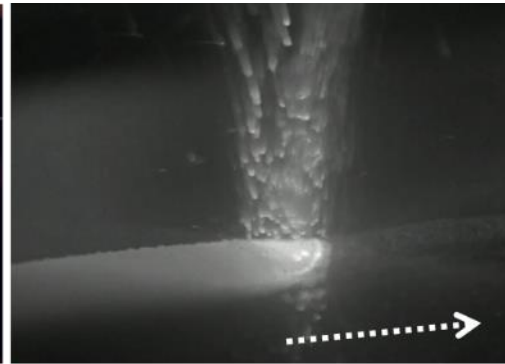
AM Processes for various applications



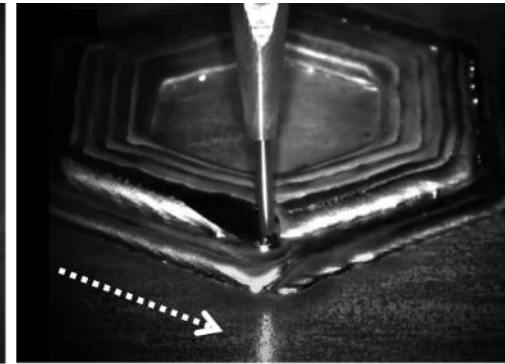
Laser Powder Bed Fusion



Electron Beam Powder Bed Fusion



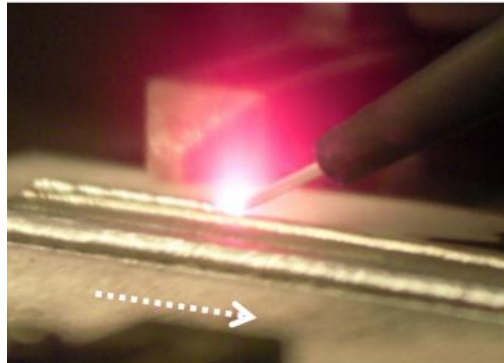
Laser Powder DED



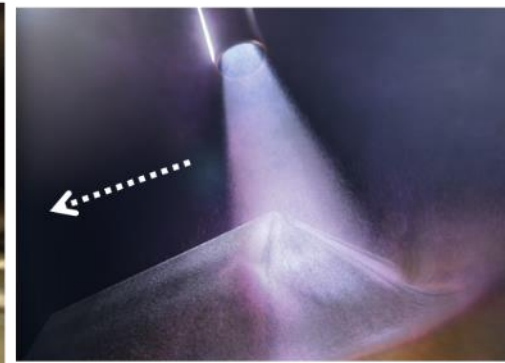
Laser Wire DED



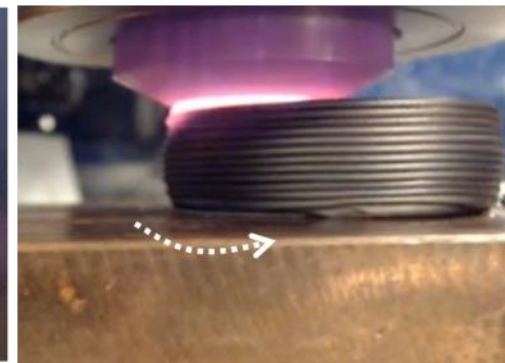
Arc Wire DED



Electron Beam Wire DED



Cold Spray



Additive Friction Stir Deposition



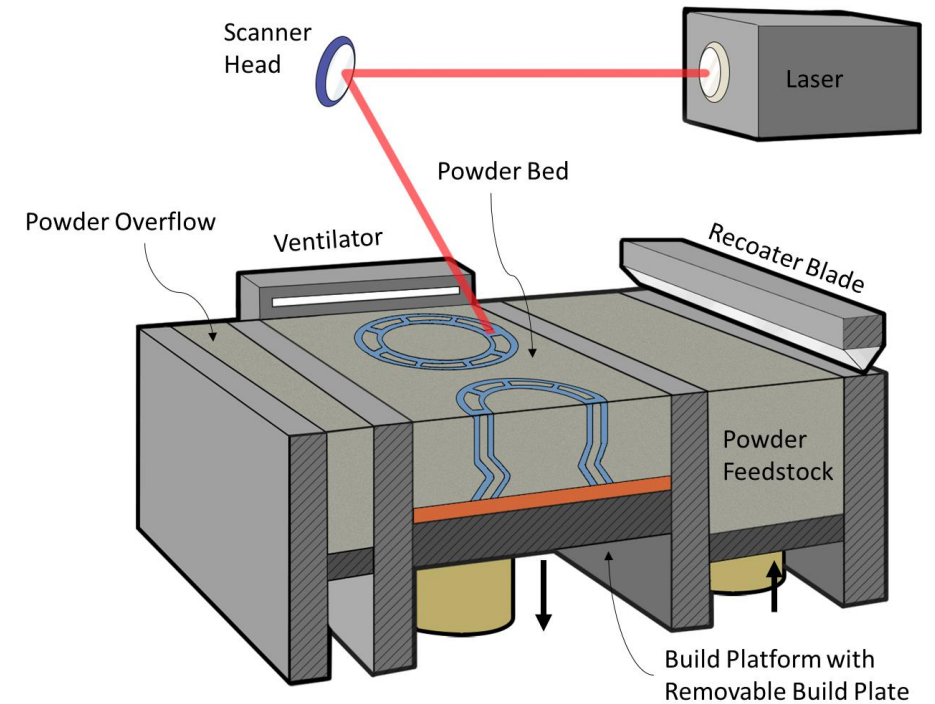
Ultrasonic Additive Manufacturing

**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: Formlloy], 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].

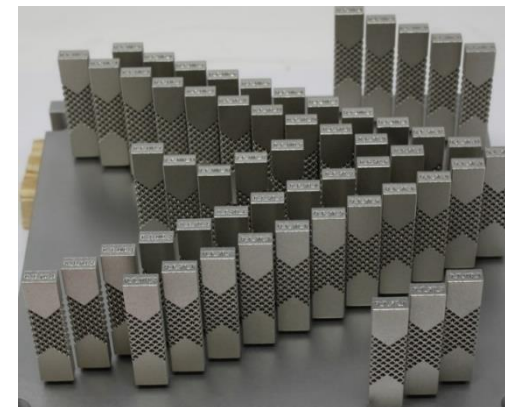
- **Laser Powder Bed Fusion (L-PBF)**

- Basic Process: Layer-by-layer powder-bed approach where desired features are melted using a laser and solidify.
- Advantages: High feature resolution, complex internal designs such as cooling channels.
- Disadvantages: Scale limited and does not provide a solution for all components.

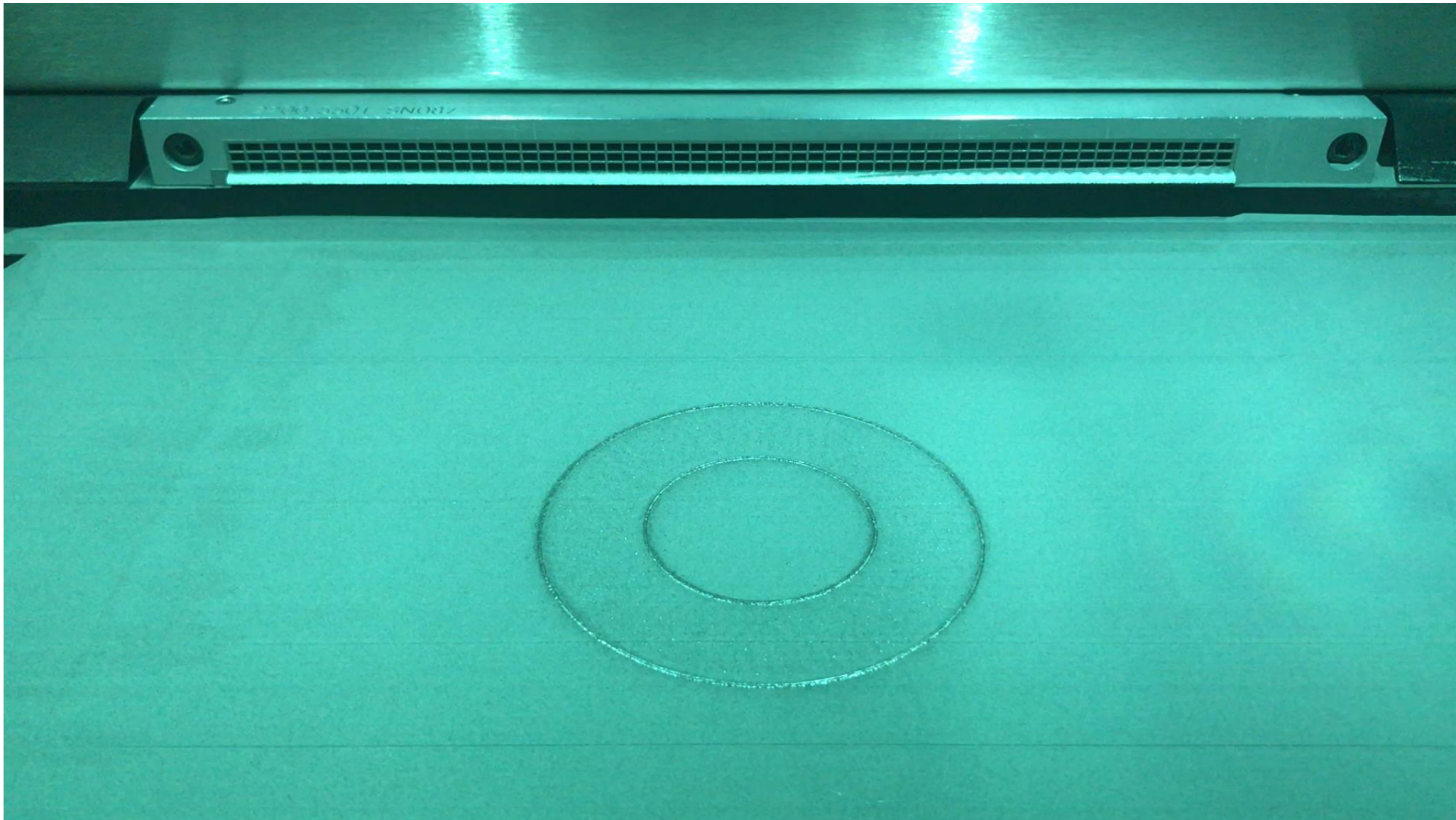


- **Electron Beam Melting**

- Basic Process: Similar to L-PBF but uses an electron beam.
- Advantages: Performed in-near vacuum, which is useful for reactive materials such as Ti6A4V.



Laser Powder Bed Fusion (L-PBF)





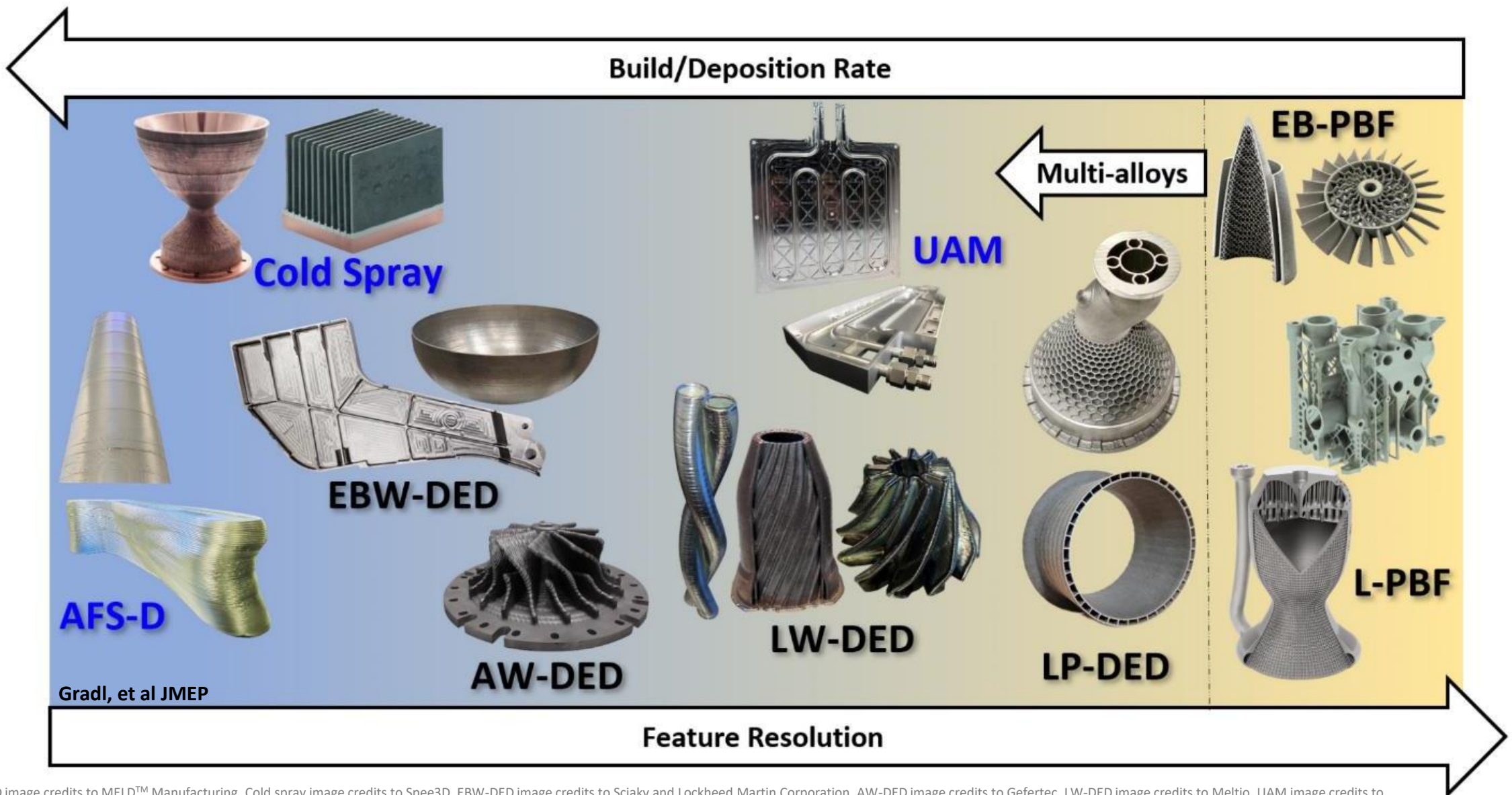
Methodical AM Process Selection



- 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?

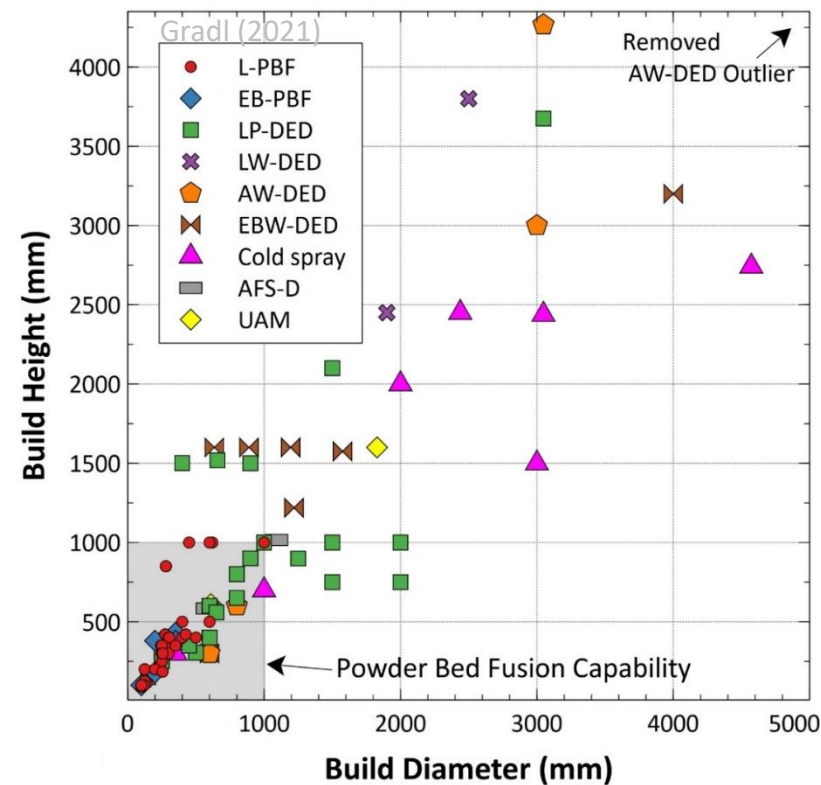
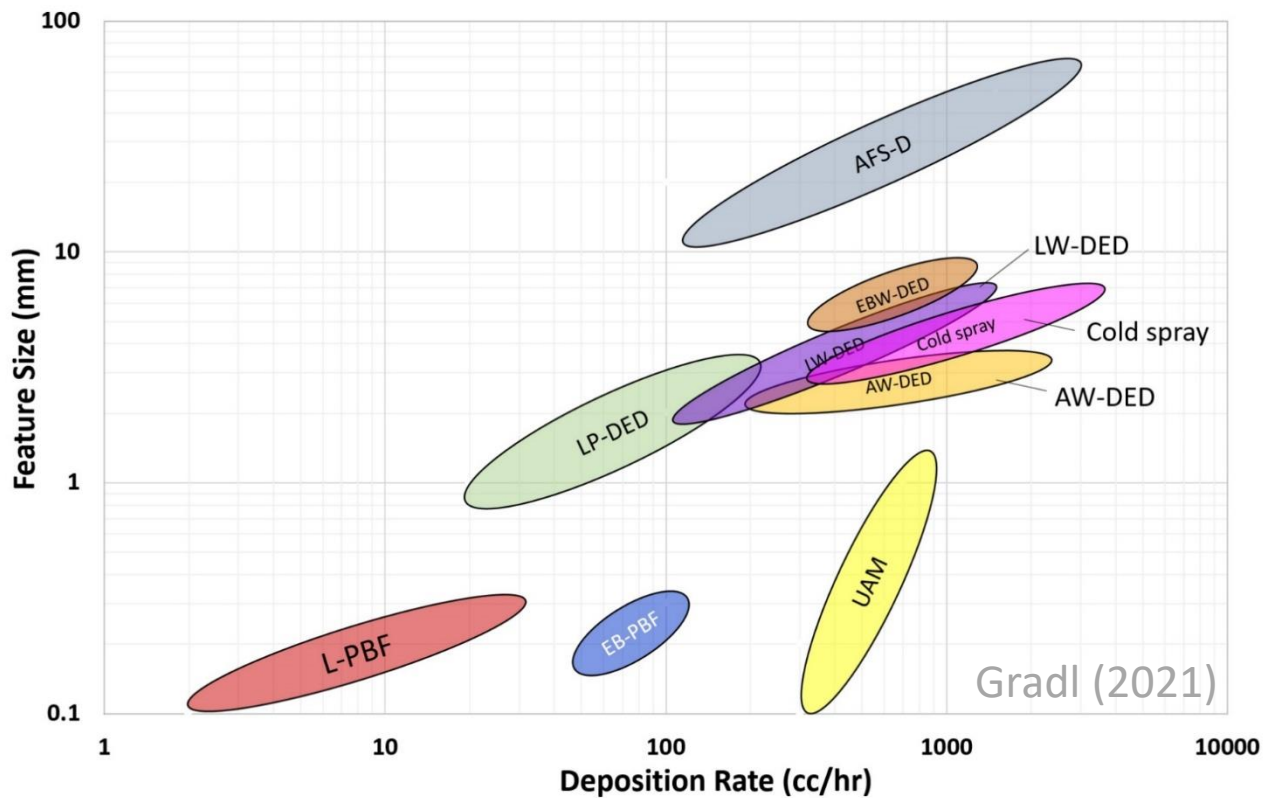


Criteria and Comparison Various Metal AM Processes





Various criteria for selecting AM techniques



Complexity of Features

Scale of Hardware

Material Physics

Cost

Material Efficiency

Speed of Process

Material Properties

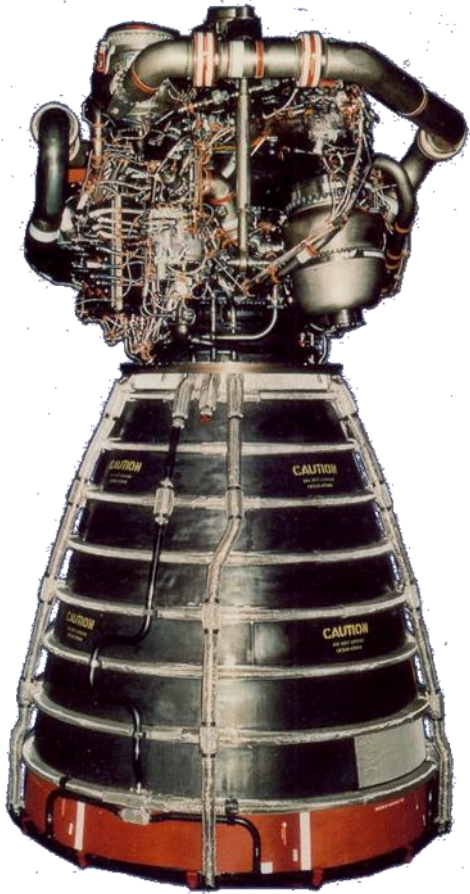
Internal Geometry

Availability

Post Processing

Large Scale Additive Manufacturing for Nozzles

SSME/RS-25



90"

RL-10A-4



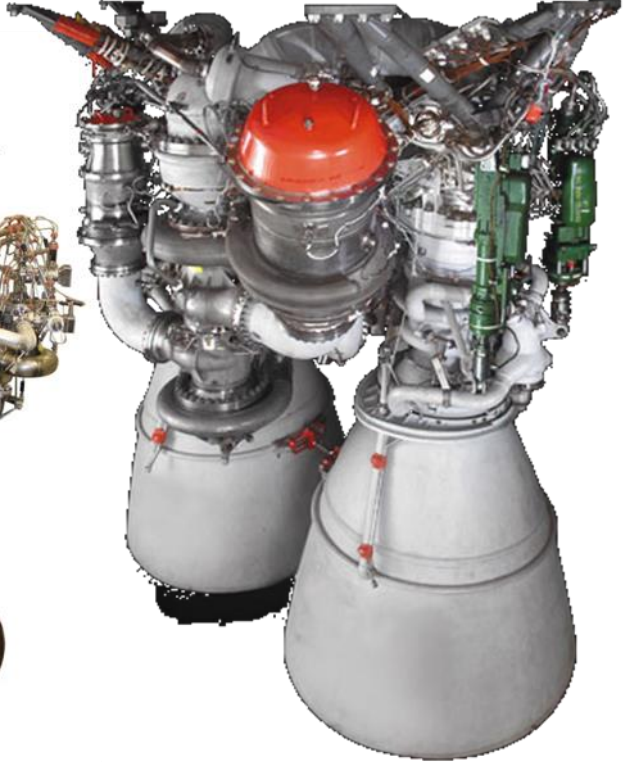
46"

J-2X, Regen Only



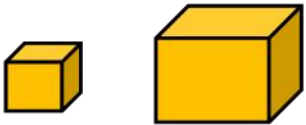
70"

RD-180



56"

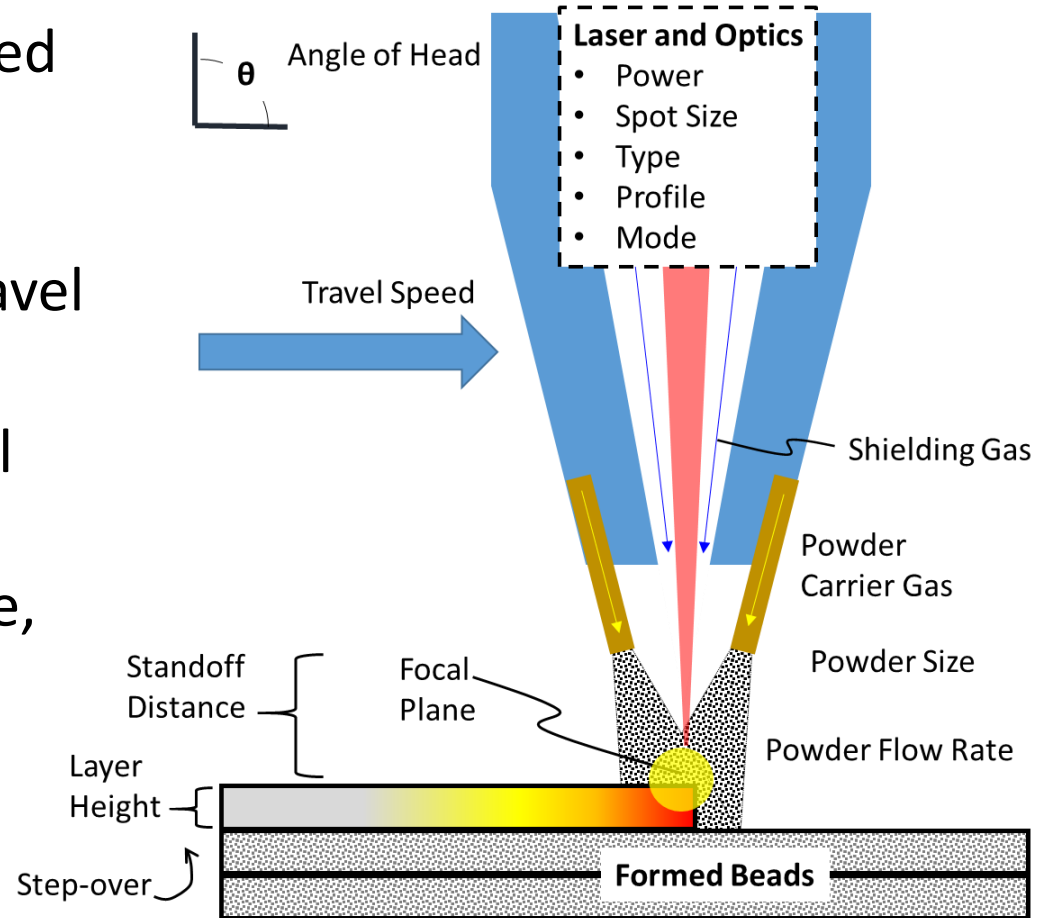
L-PBF Build Boxes



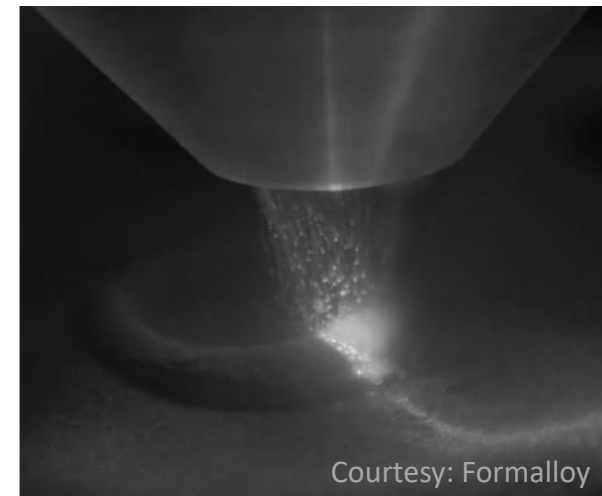
10x10x10 15.5x24x19
(inches)

Nozzle Exit Dia.

- Powder and laser beam path (sometimes optics) integrated into deposition head
- Basic parameters include power, powder feedrate, travel speed
- Additional geometry control for layer height, step over (hatching), standoff distance, angle of head and trunnion table
- Can vary spot size



AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl , Protz, Mireles, Garcia (unreleased)



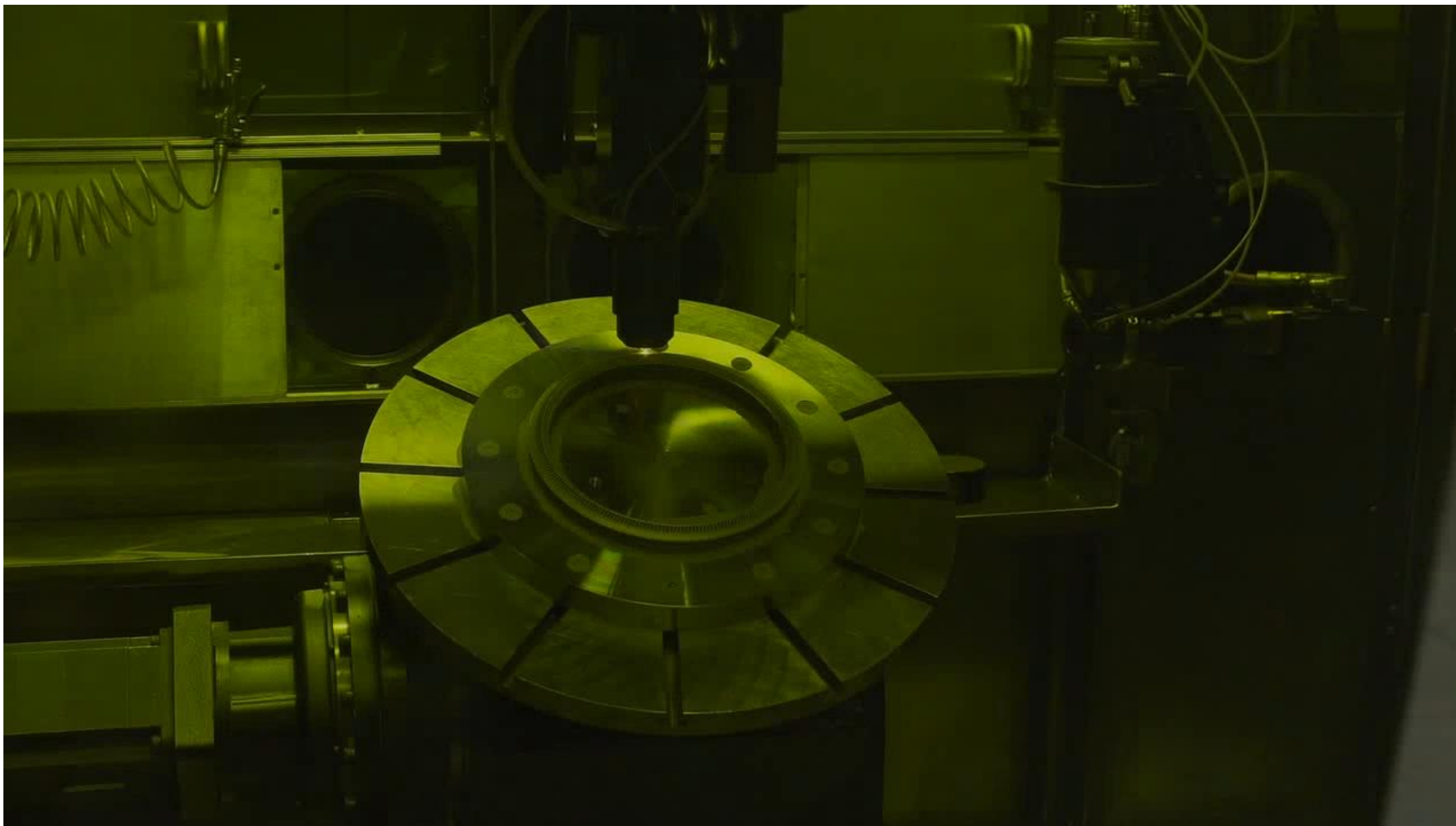


Laser Powder Directed Energy Deposition (DED)

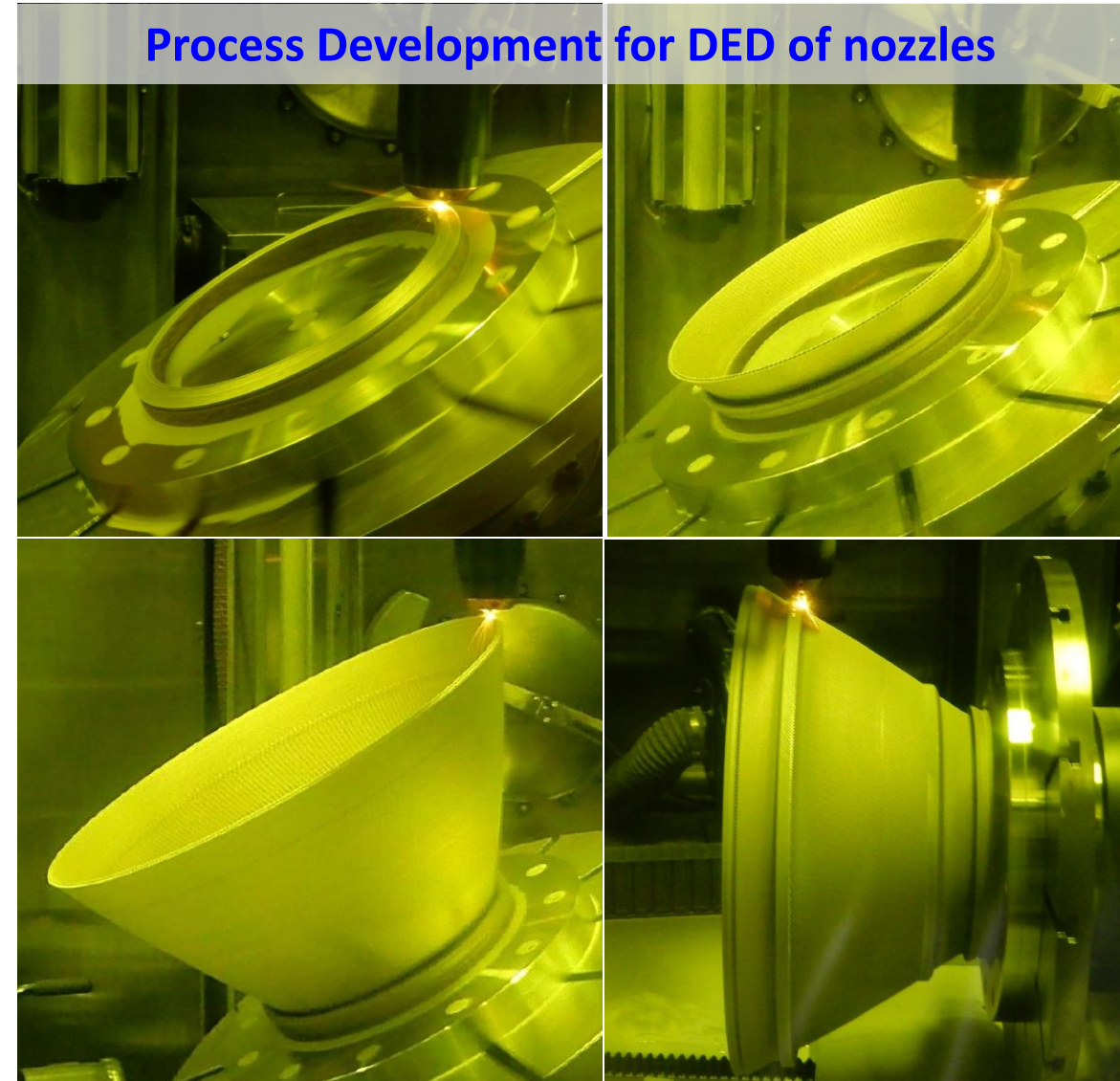
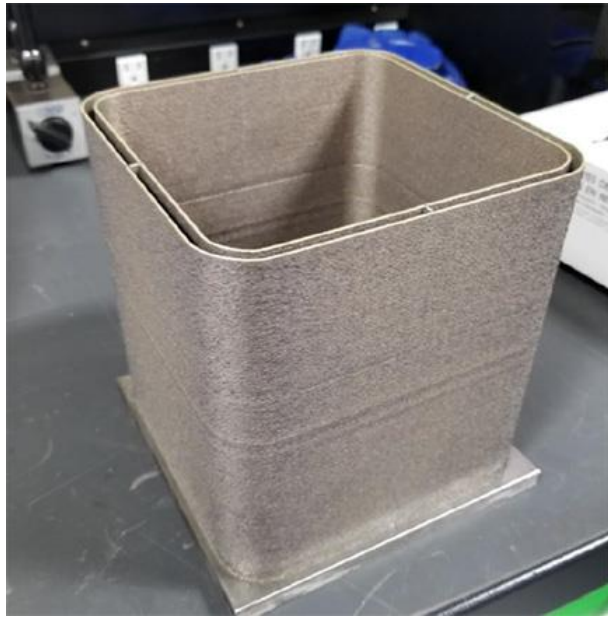




Example of LP-DED with small features



Large-scale Thin Wall Deposition of Nozzles





LP-DED Large Scale Nozzle Development



NASA HR-1
60" (1.52 m) diameter and 70" (1.78 m) height with integral channels
90 day deposition



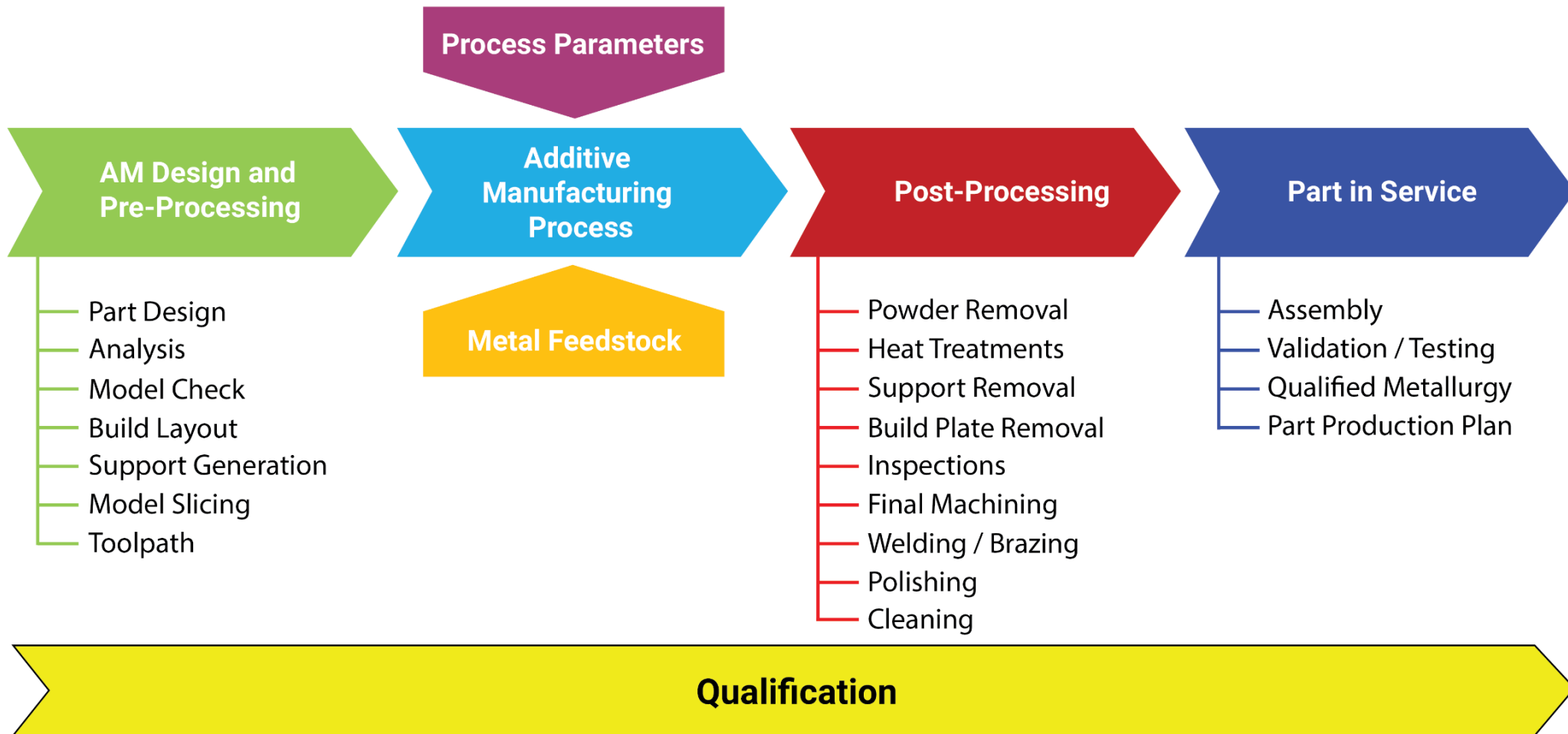
JBK-75

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

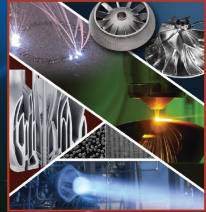
Reference: P.R. Gradl, T.W. Teasley, C.S. Protz, C. Katsarelis, P. Chen, Process Development and Hot-fire Testing of Additively Manufactured NASA HR-1 for Liquid Rocket Engine Applications, in: AIAA Propuls. Energy 2021, 2021: pp. 1–23. <https://doi.org/10.2514/6.2021-3236>.



Additive Manufacturing Typical Process Flow



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



Metal Additive Manufacturing for Propulsion Applications

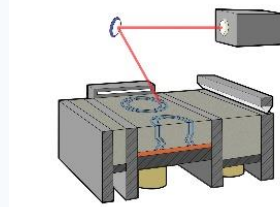


Editors: Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia



Chapter 1

Introduction and Applications of Additive Manufacturing for Propulsion



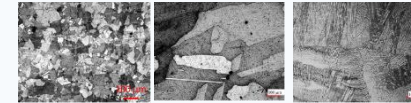
Chapter 2

Metal Additive Manufacturing Processes and Selection

Properties	Availability	Economics
<ul style="list-style-type: none"> Mechanical Thermal Chemical Electrical Other 	<ul style="list-style-type: none"> Powder Supply Chain On-hand Off-hand Stock 	<ul style="list-style-type: none"> Material Cost Machine Build Time Anticipated Service Life
<ul style="list-style-type: none"> Physical Density Thermal Expansion Conductivity Welding Point 	<ul style="list-style-type: none"> Special Powder Processing Regulatory Assistance Material processing requirements 	<ul style="list-style-type: none"> Post processing/finishing Heat-treatability Chemical Treatment
<ul style="list-style-type: none"> Environment Operator Assistance Hygiene Environment Contamination Material Traceability 	<ul style="list-style-type: none"> Machine Capability/Part Quality Known Build Parameters 	

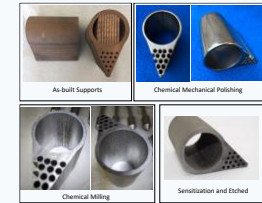
Chapter 3

Selection and Overview of Additive Manufactured Metals and Metal Alloys



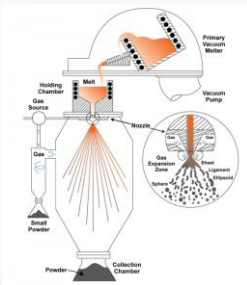
Chapter 4

Microstructure and Properties of Additively Manufactured Metal Alloys



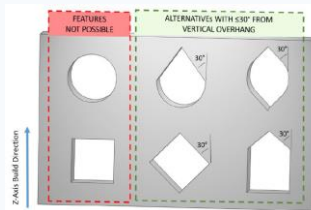
Chapter 5

Post-Processing of Metal Additively Manufactured Components



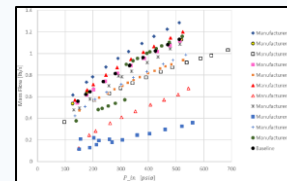
Chapter 6

Feedstock for Metal AM



Chapter 7

Functional Design for Metal Additive Manufacturing



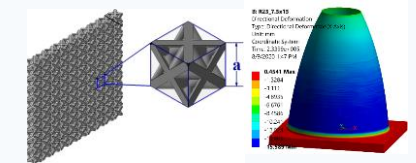
Chapter 8

Component Performance and Application Characteristics



Chapter 9

Certification of Metal Additive Manufacturing: A NASA Perspective

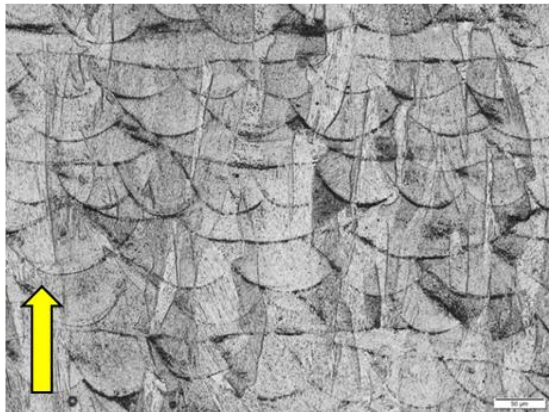


Chapter 10

Emerging Additive Manufacturing Technology for Propulsion

Microstructure of Various AM Processes

Alloy 625 – **As-Built**



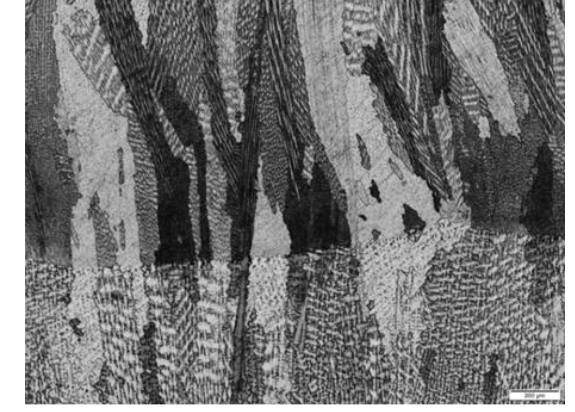
Laser Powder Bed Fusion



Electron Beam Powder Bed Fusion



Laser Powder DED (1070 W)



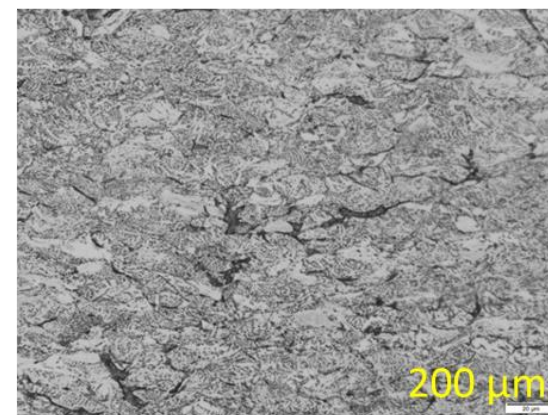
Electron Beam Wire DED



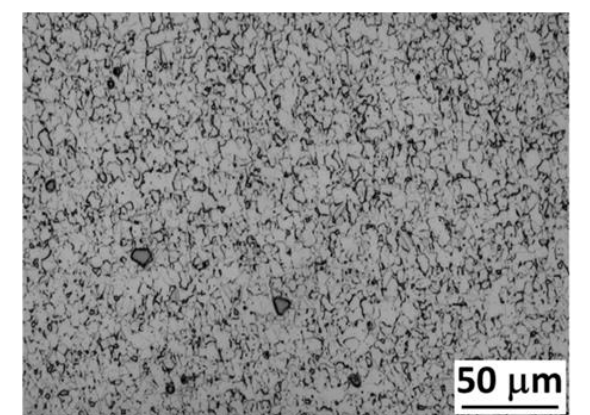
Laser Wire DED



Arc Wire DED



Cold Spray



Additive Friction Stir Deposition

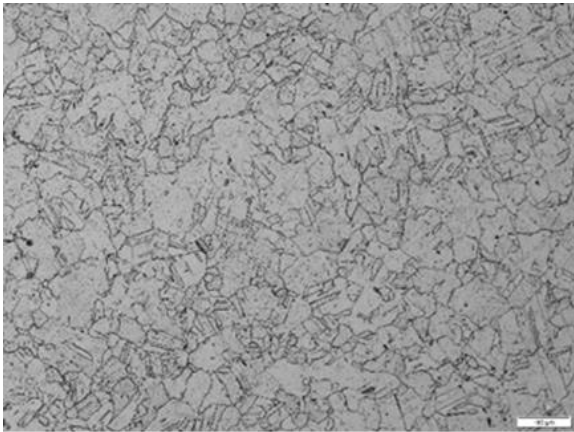
Each AM process results in different grain structures, which ultimately influence properties

- 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

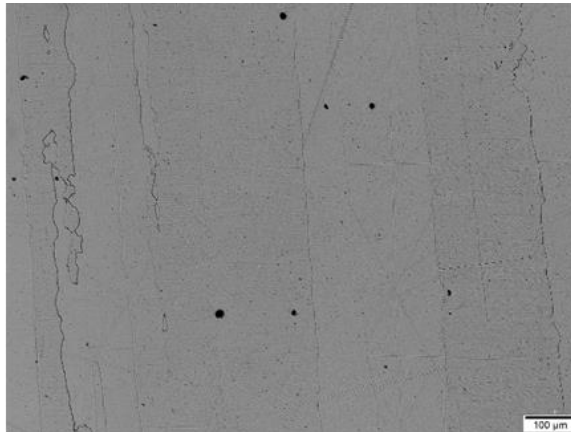


Microstructure of Various AM Processes

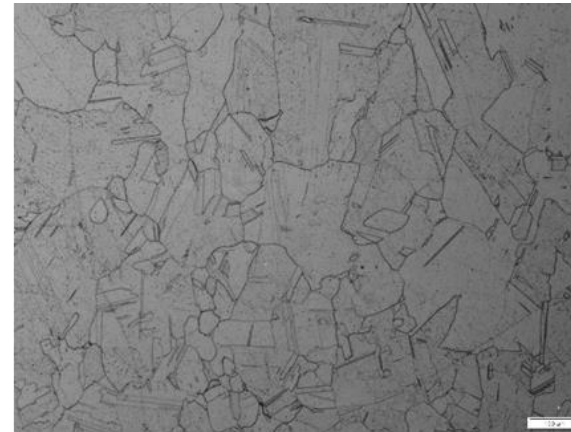
Alloy 625 – Stress Relief, HIP, Solution per AMS 7000



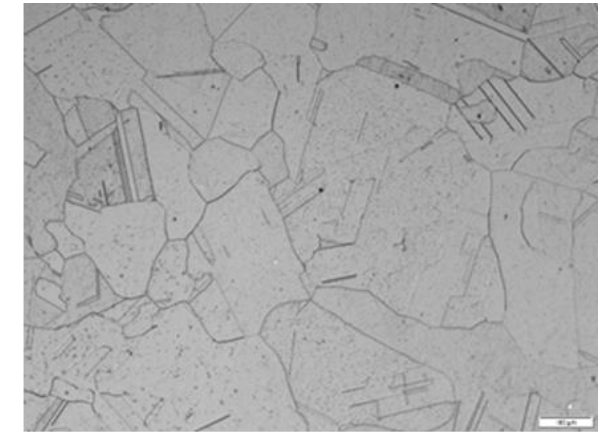
Laser Powder Bed Fusion



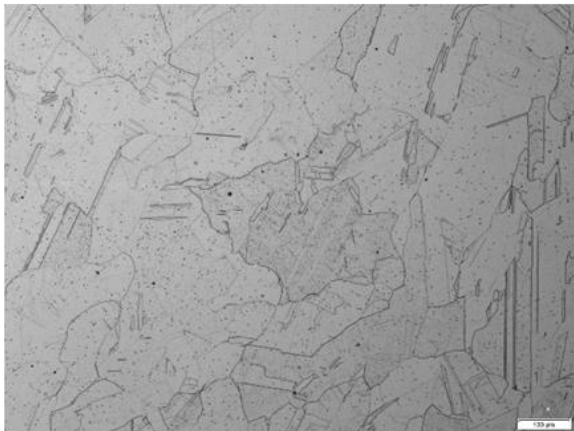
Electron Beam PBF



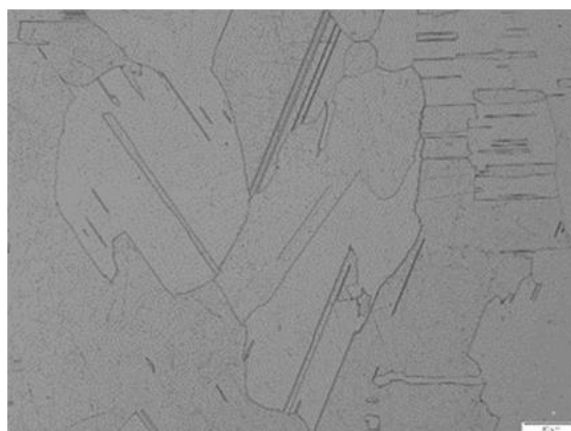
Laser Powder DED (1070 W)



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>

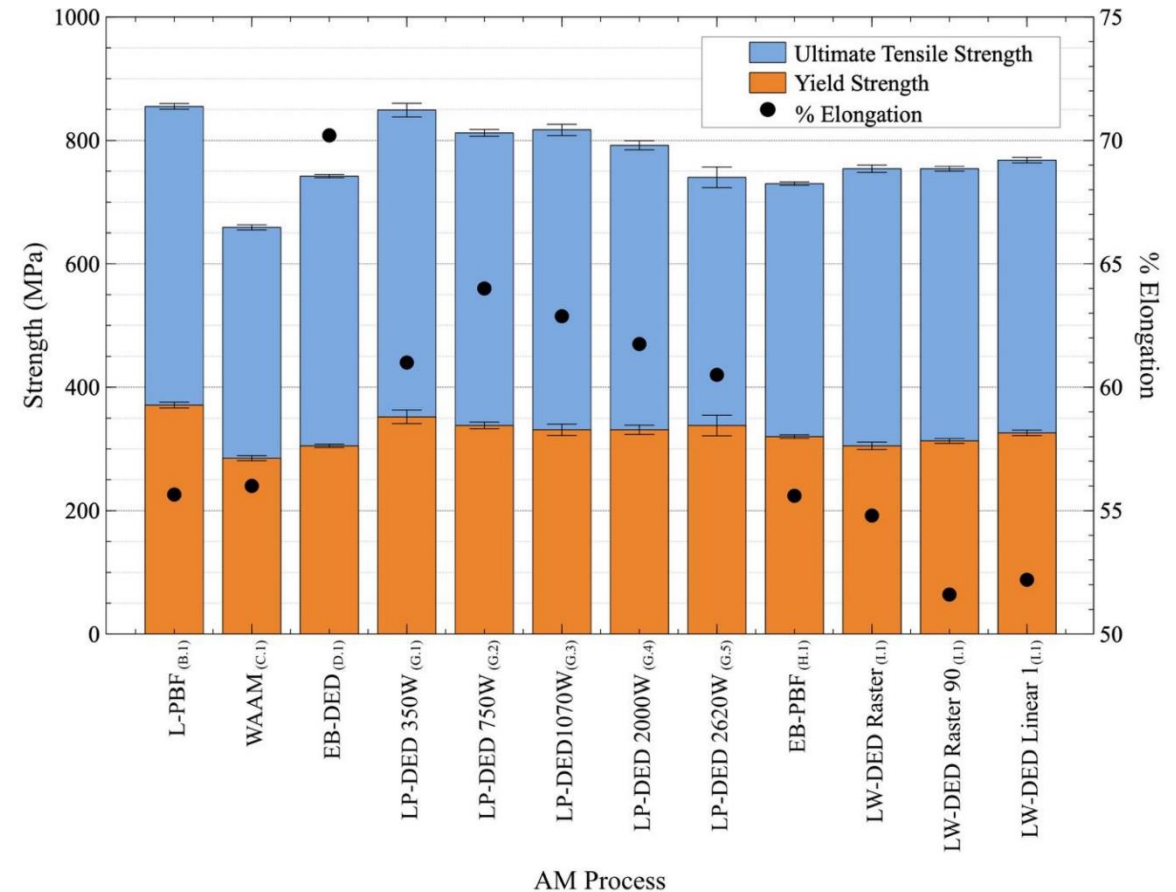


Material Properties for Various AM Processes



- 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.

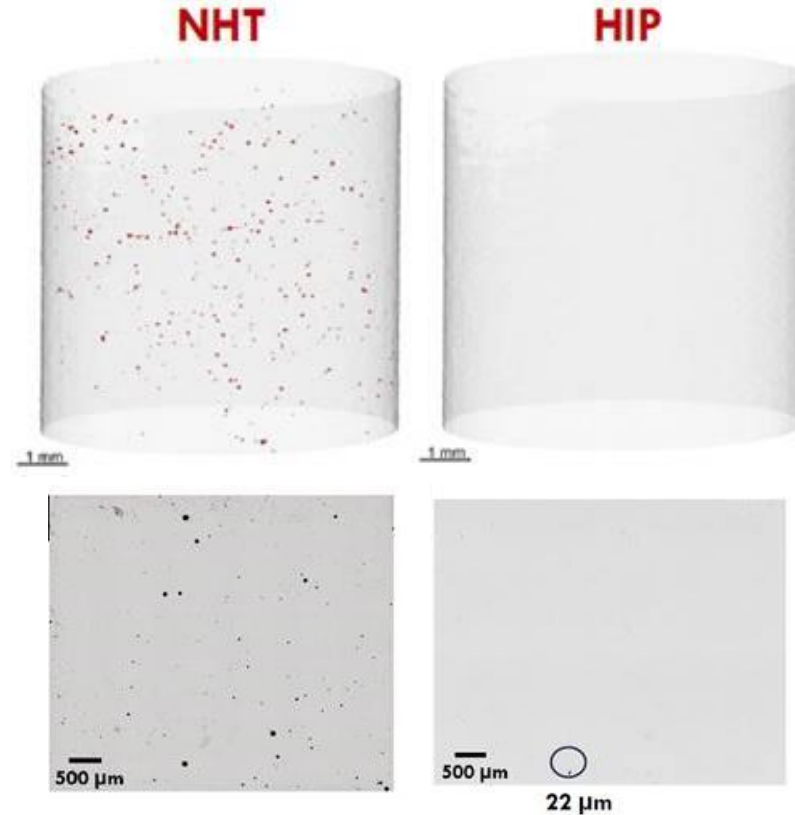
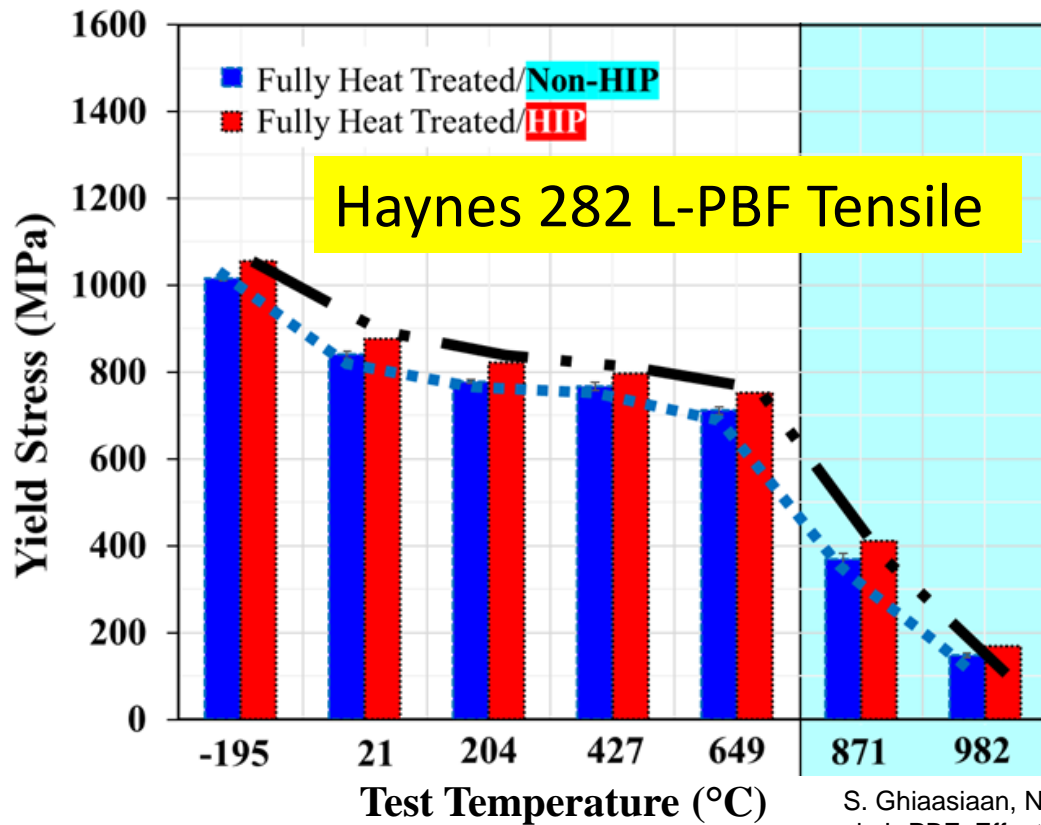
Alloy 625, Heat Treated per AMS 7000 Room Temperature UTS



***Not design data and provided as an example only**

Why baseline HIP?

- NASA has baselined HIP for data generation (per NASA 6030).
- HIP does add process time and cost but can improve performance of alloys for tensile and fatigue based on comparison studies.



S. Ghiaasiaan, N. Ahmad, P. Gradl, S. Shao, N. Shamsaei: Additively Manufactured Haynes 282 via L-PBF: Effect of Post-processing on Mechanical Properties at Different Temperatures



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

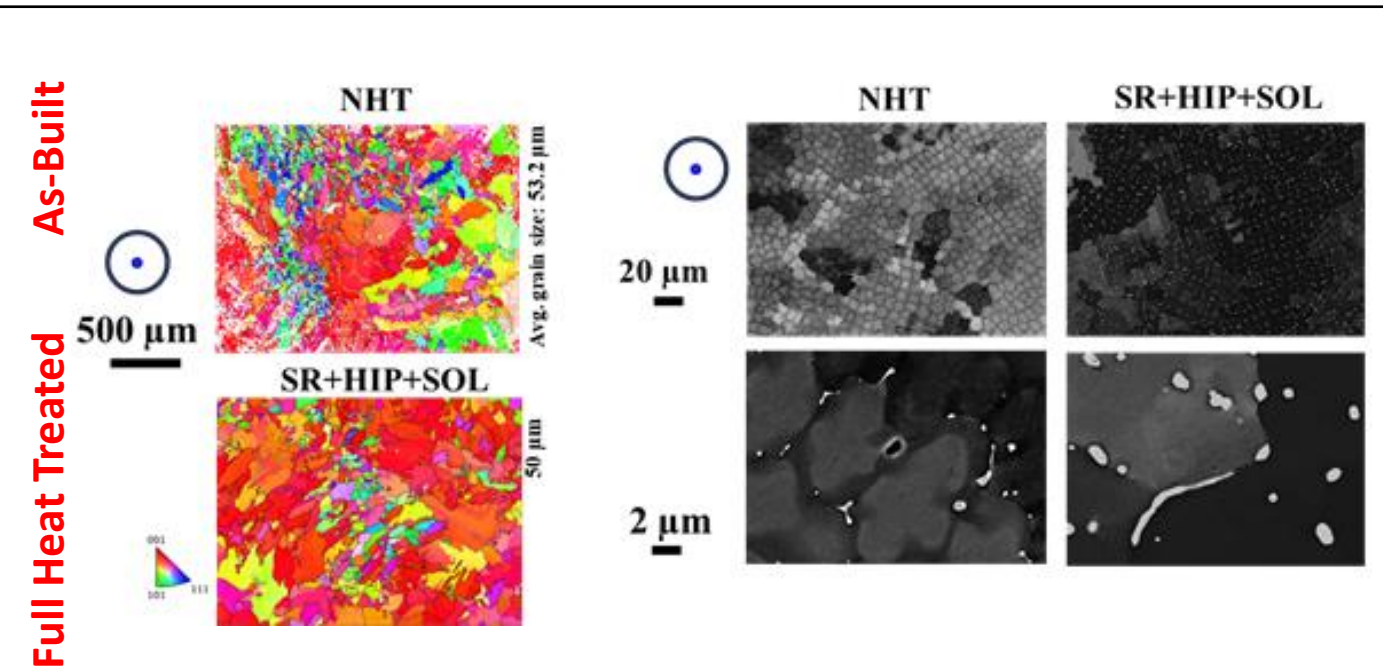


Data example of Haynes 230 LP-DED



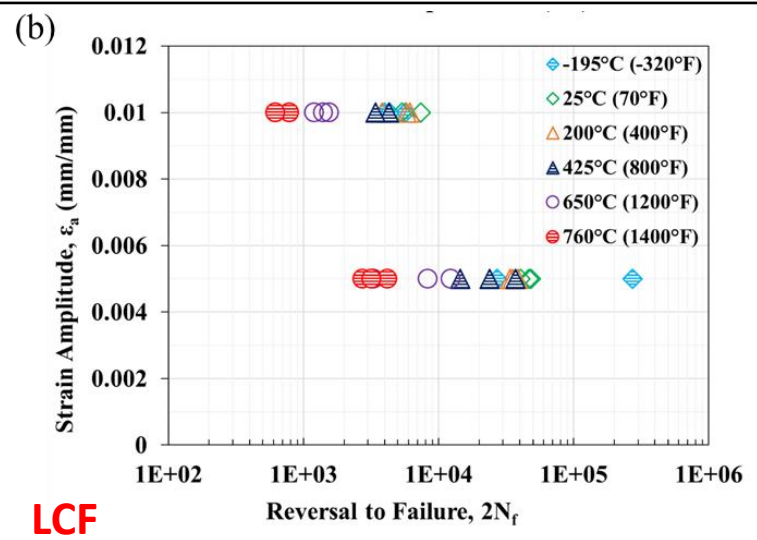
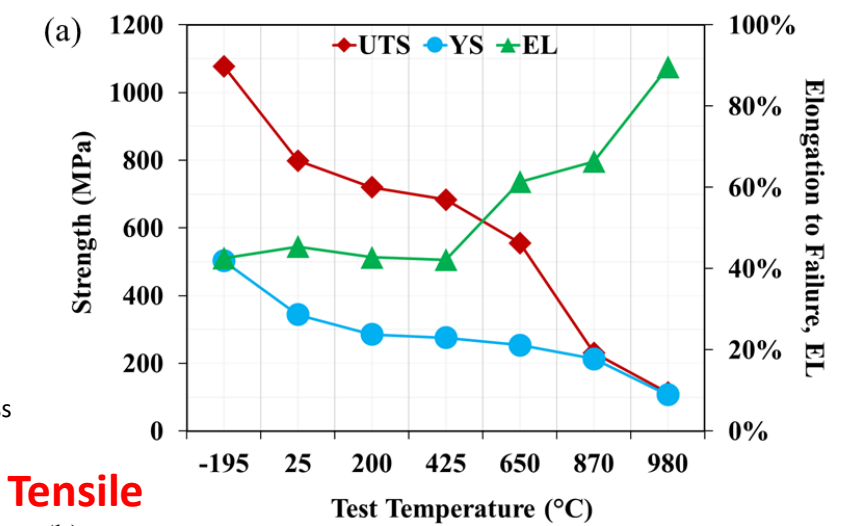
Power (W)	Layer height (μm)	Travel speed (mm/min)	Powder feed rate (g/min)
1070	381	1016	19.10

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



[2] HIP per ASTM F3301

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





New Alloy Development to Improve Performance



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



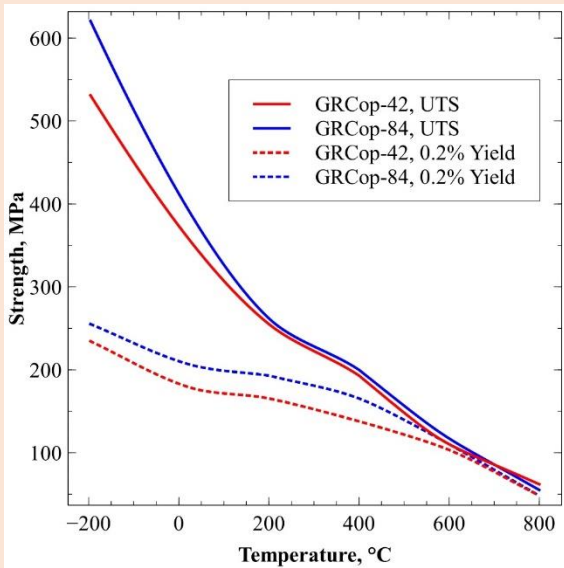
New alloy development using various additive manufacturing processes (PBF and DED) can yield performance improvements over traditional alloys



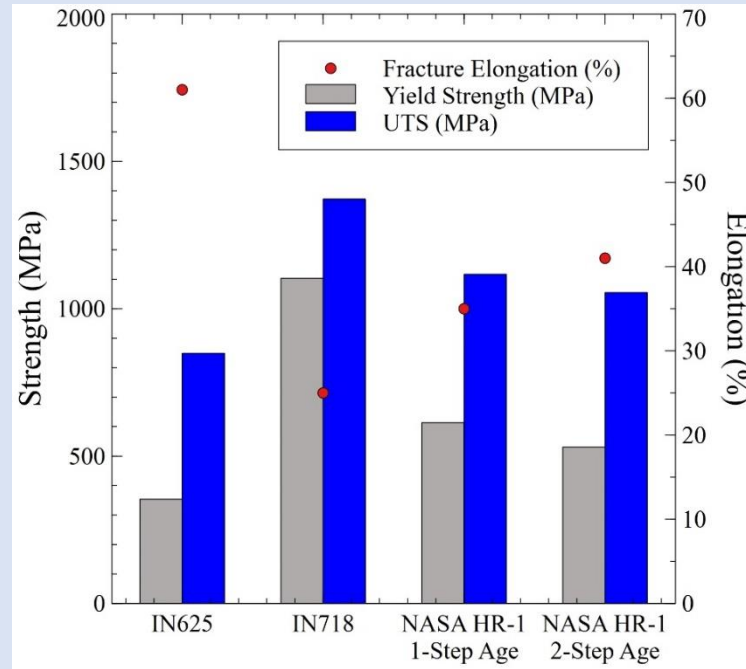
Enabling New Alloy Development using Additive Manufacturing



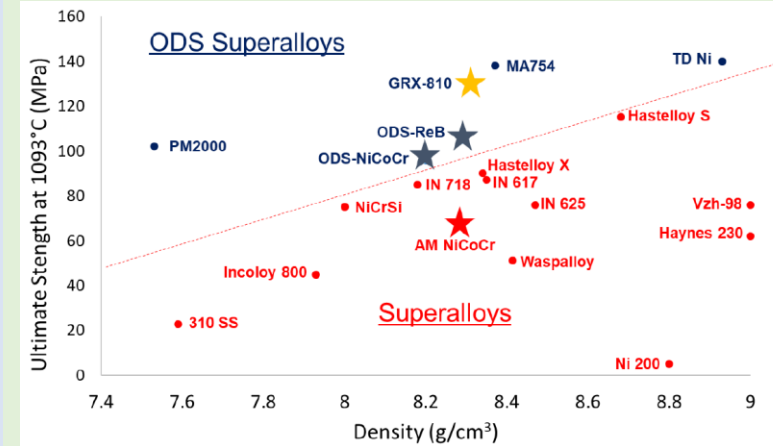
GRCop-42, High conductivity and strength for high heat flux applications



NASA HR-1, high strength superalloy for hydrogen environments



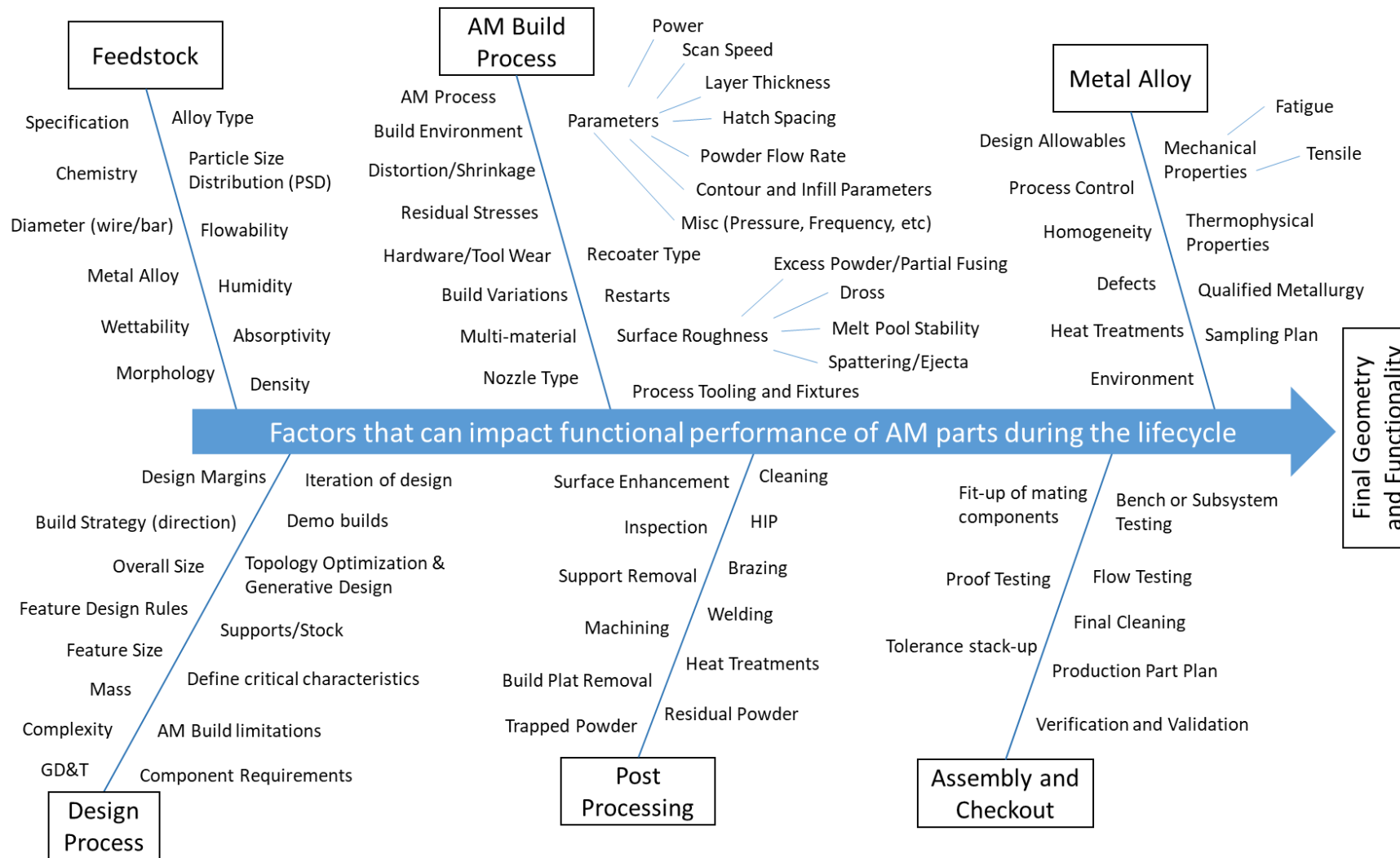
GRX-810, high strength, low creep rupture and oxidation at extreme temperatures



Ref: Tim Smith, Christopher Kantzos / NASA GRC 30



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

Bimetallic AM for combustion chambers



LP-DED Jacket



Cold spray Jacket

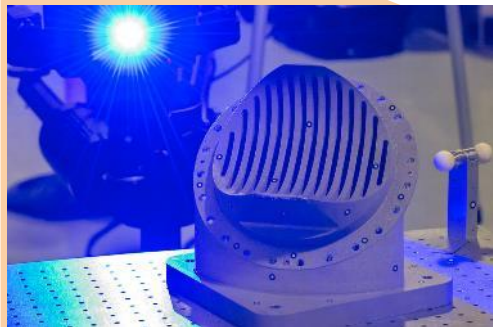


Direct deposit LP-DED nozzle
(Axial Bimetallic)



EBW-DED Jacket

Industrial Maturity and TRL of AM Processes

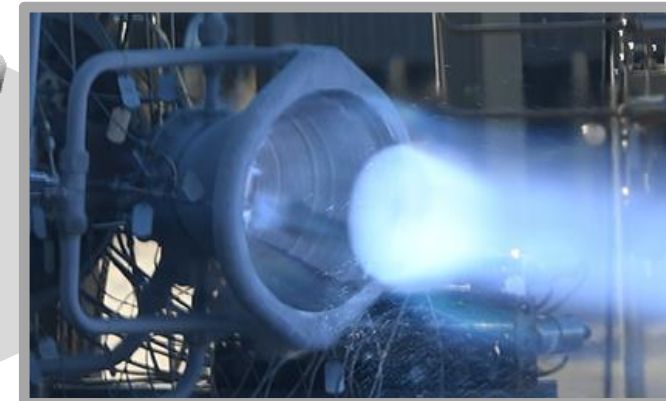


L-PBF



Cold spray

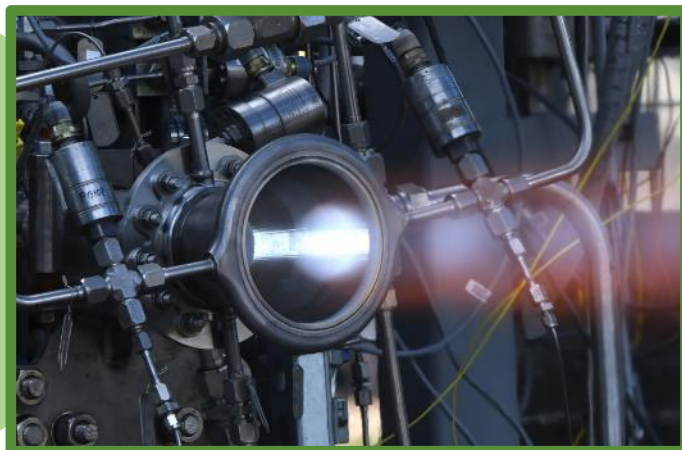
LP-DED



L-PBF

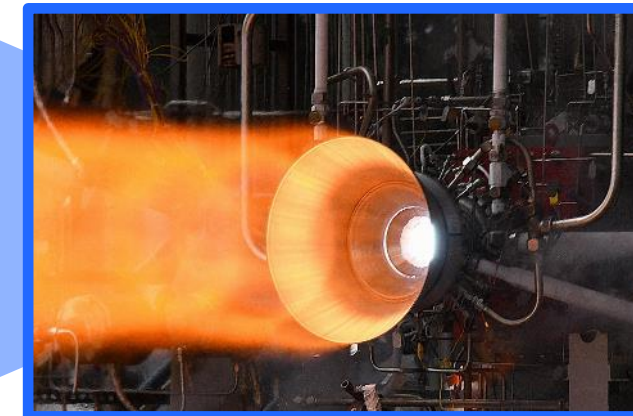


LW-DED



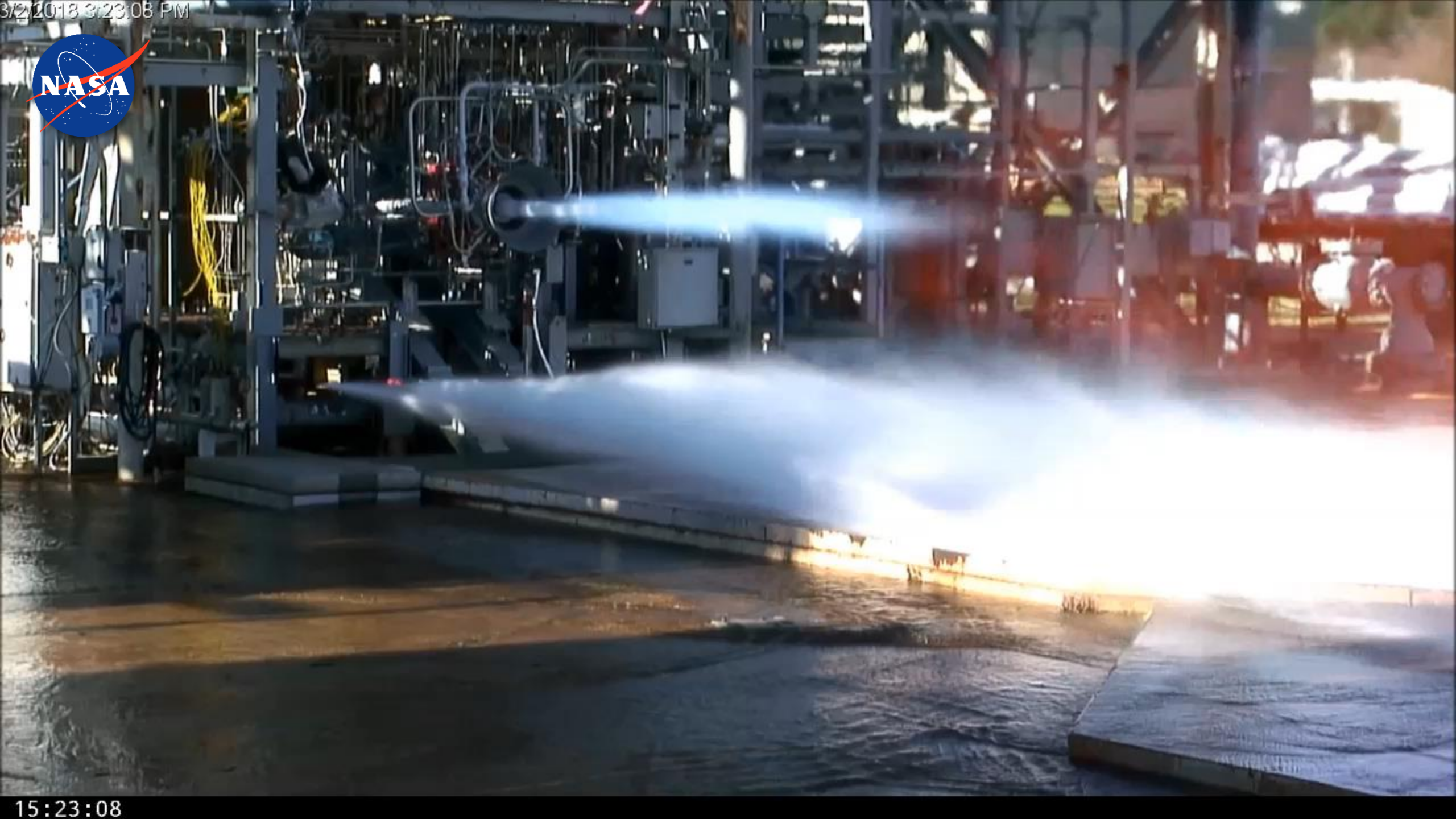
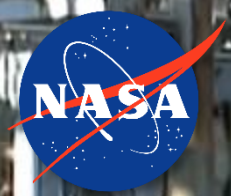
L-PBF

EBW-DED

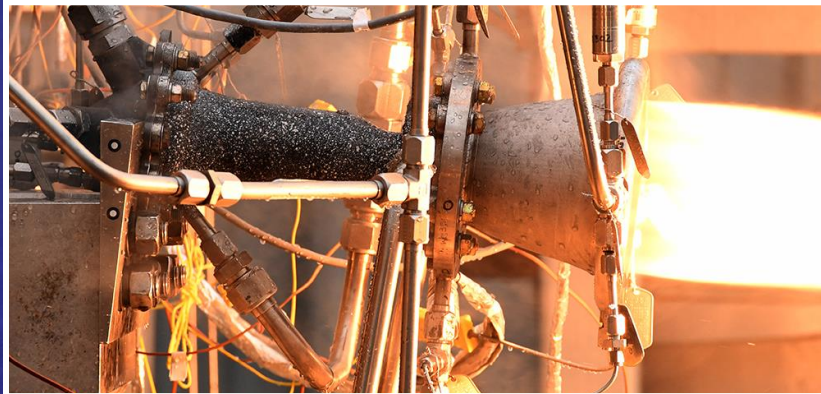


AW-DED

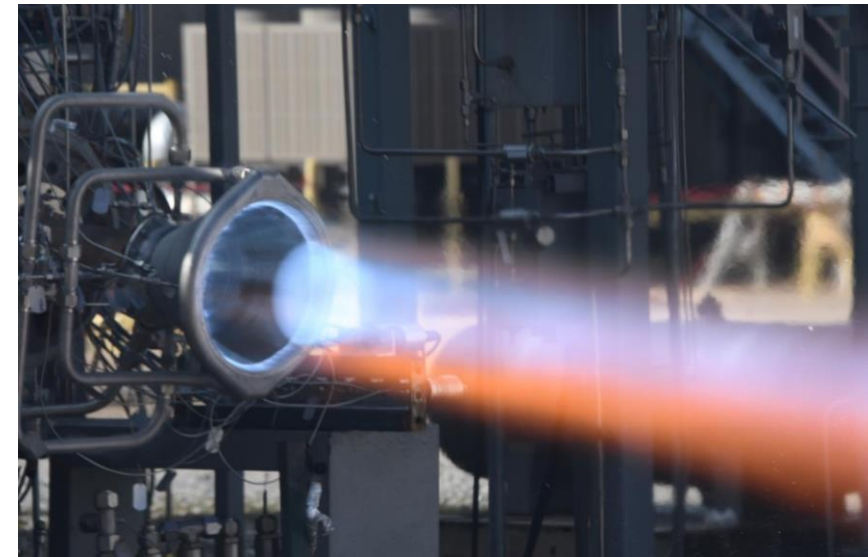




- High TRL and maturity of mechanical and thermophysical properties, component application, and supply chain.
- Over 43,000 seconds of time and 1,050 starts on >30 GRCop alloy chambers.
- Single L-PBF chamber unit achieved 296 starts and >10,600 seconds.
- Over 100,000 sec of accumulated hot-fire time on chambers, nozzles, injectors



LOX/RP-1



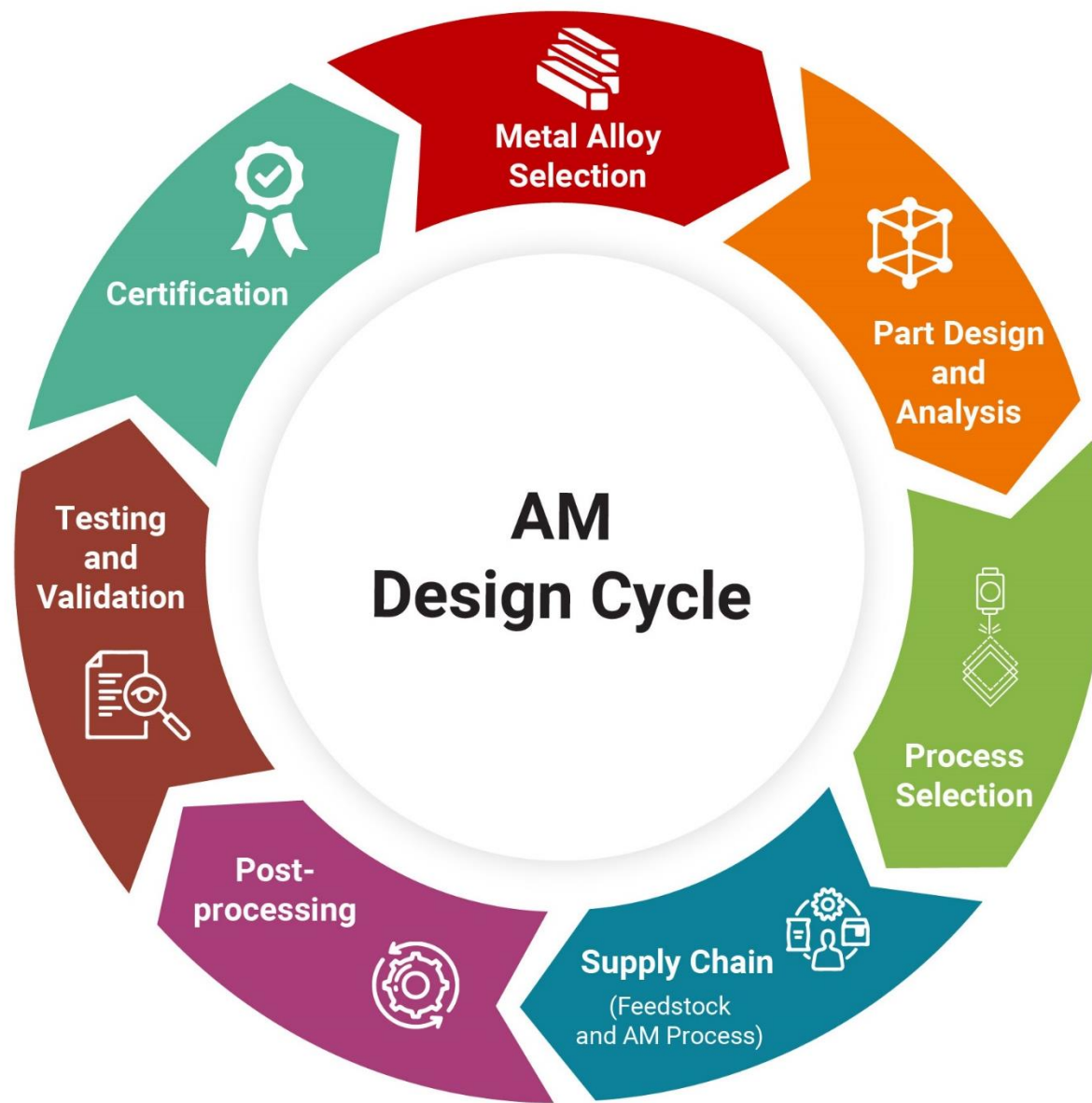
LOX/CH4



Design for Additive Manufacturing (DfAM)



AM Design Cycle



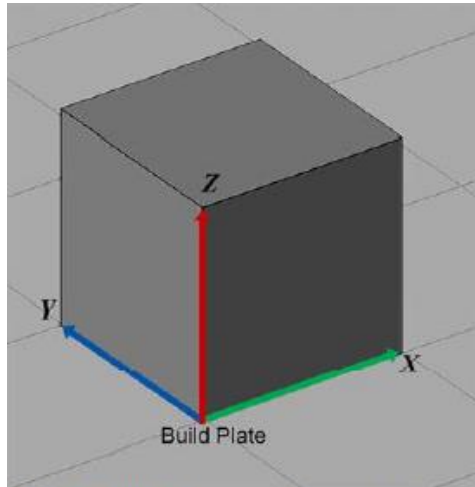


Fig. 7.1 AM reference coordinate system.

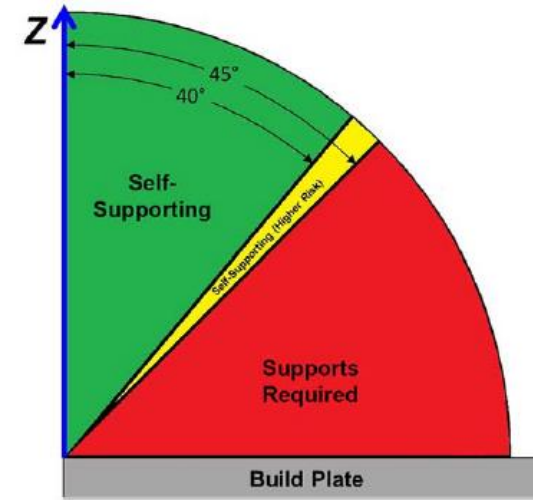


Fig. 7.14 Example of overhang surfaces in reference to the build plate and build direction (Z).

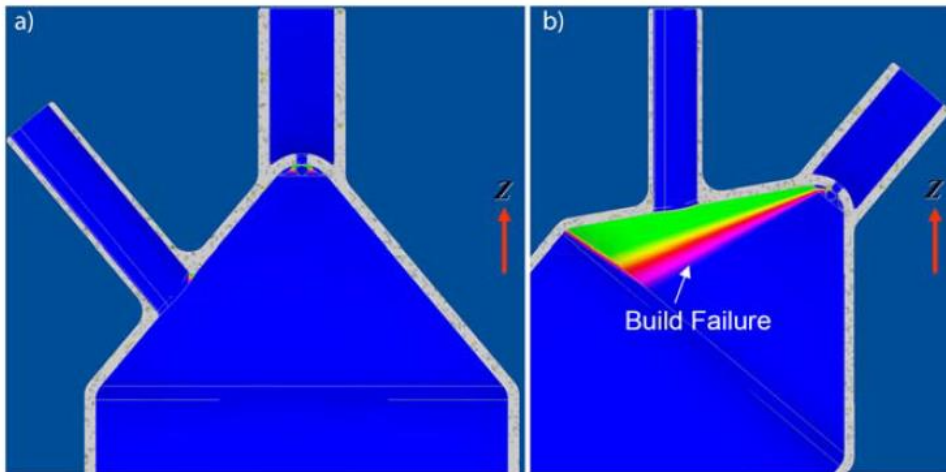


Fig. 7.16 Unsupported overhang surfaces vs. build direction. a) No unsupported surfaces. b) Unsupported surfaces.



Angle is measured in relation to the build direction, Z

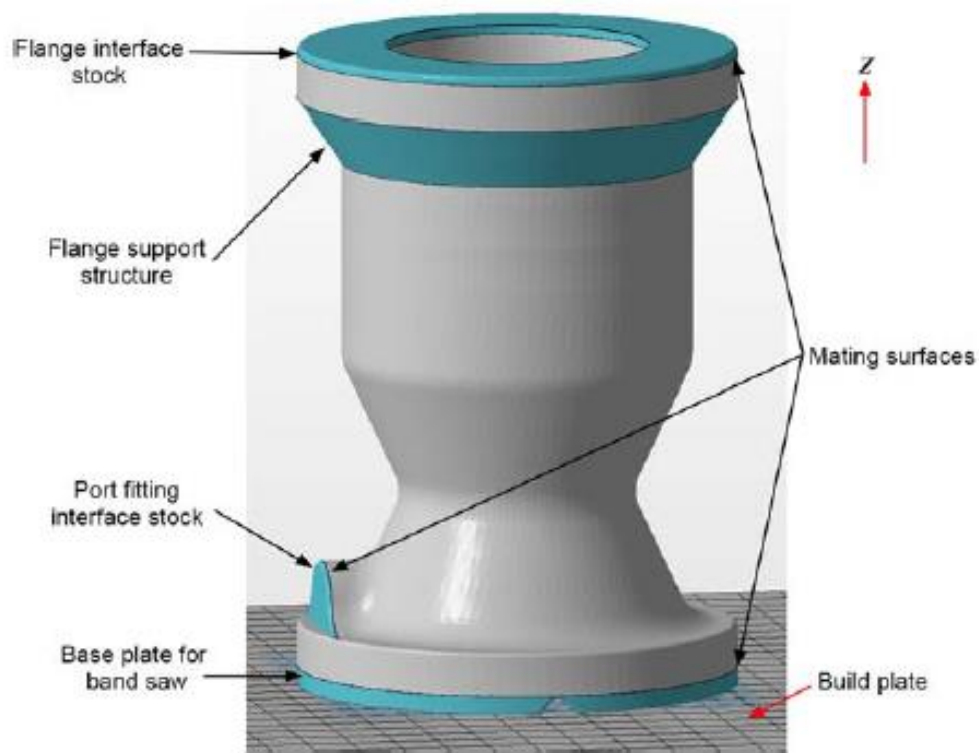


Fig. 7.11 Chamber design for L-PBF AM with sacrificial stock material added (turquoise regions).

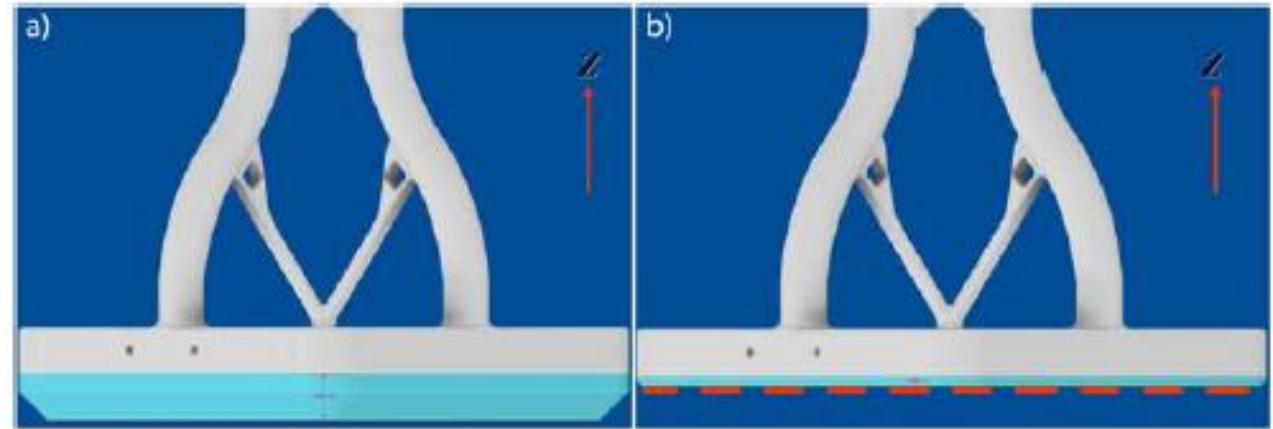


Fig. 7.13 Base-plate thickness vs. removal method for a) vertical band saw [5 mm (0.196 in.)] and b) wire-EDM [1 mm (0.039 in.)].

DfAM – Holes & Drain Ports

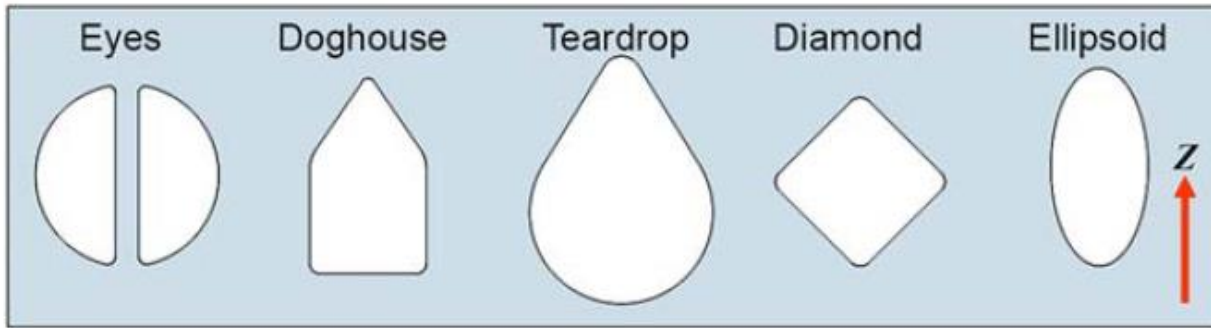


Fig. 7.18 Build failure observed at the tops of Ti6Al4V L-PBF holes oriented perpendicular to the build direction.



Fig. 7.20 Hole shape vs size, diamond slot, and surface roughness vs angle in L-PBF-built AISi10Mg.

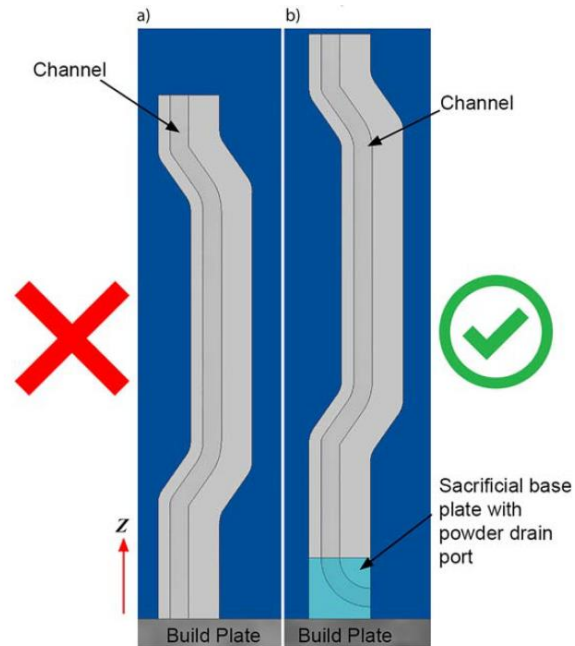


Fig. 7.26 a) Channel terminating at the build plate and b) base plate with powder drain port.

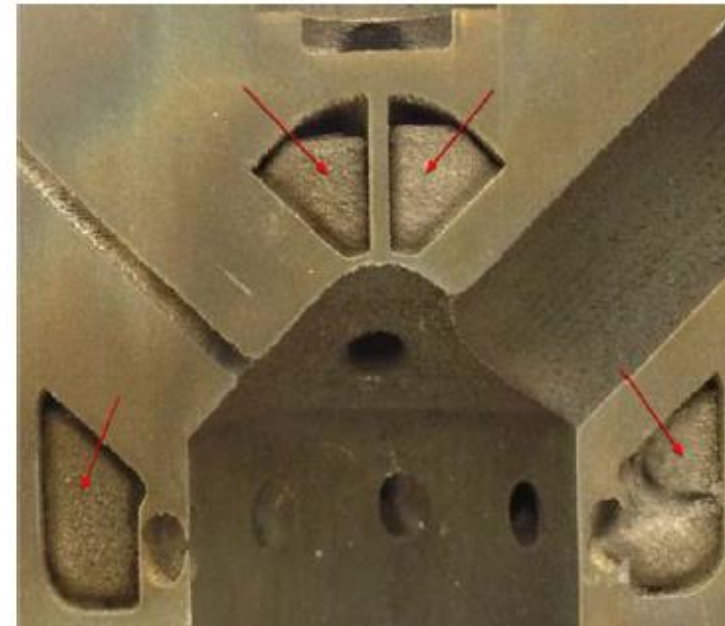


Fig. 5.5 Cross-sectional cut of a part with trapped powder that sintered during stress-relief heat treatment. (Source: NASA.)

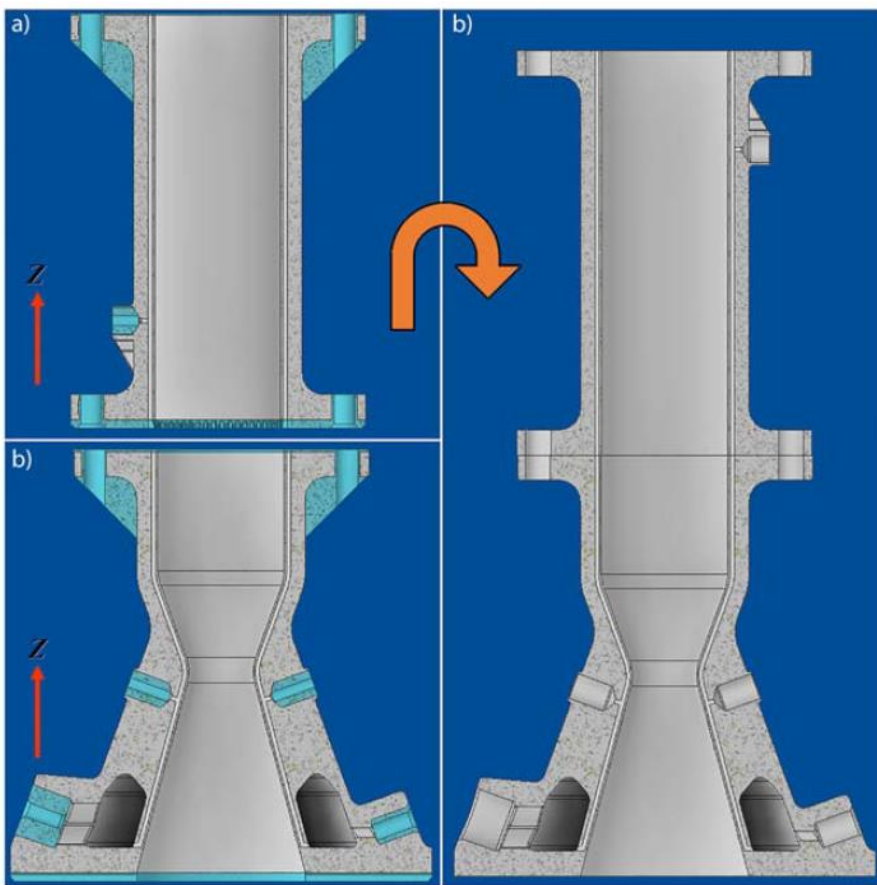


Fig. 7.29 a-b) Each L-PBF part orientation for optimized build. c) Assembly of parts.

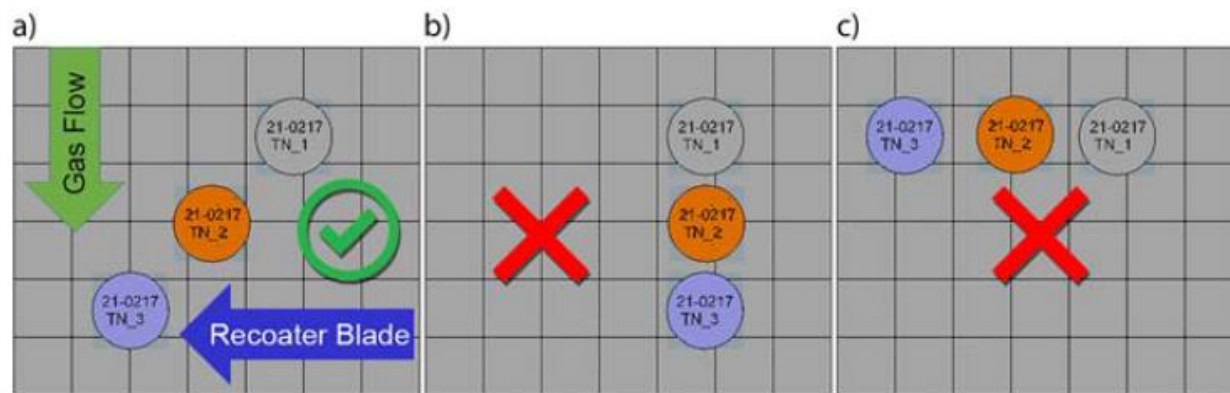


Fig. 7.31 Specimen placement relative to recoater and gas directions.

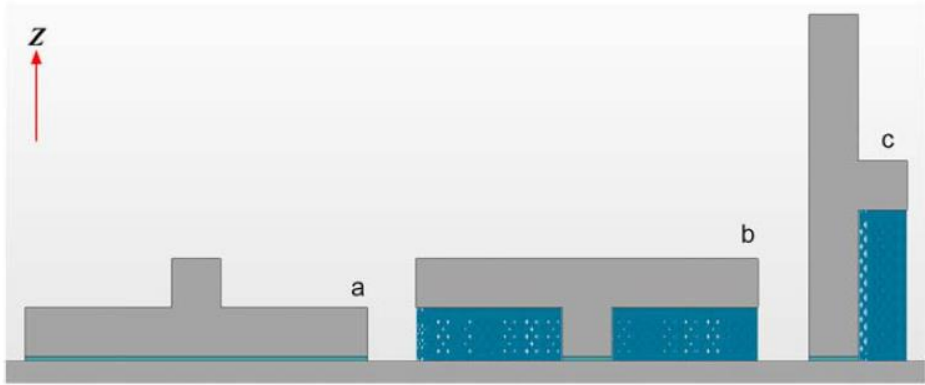


Fig. 7.22 Placement and volume of support structures (blue regions) are highly dependent on part orientation.

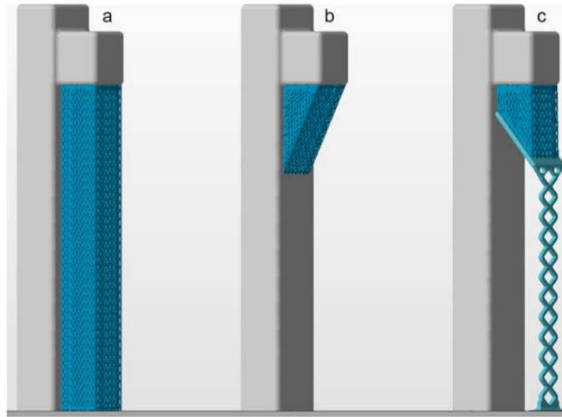


Fig. 7.23 Perforated block supports: a) full length, b) 30° angle, and c) projected onto a user-designed support scaffold.

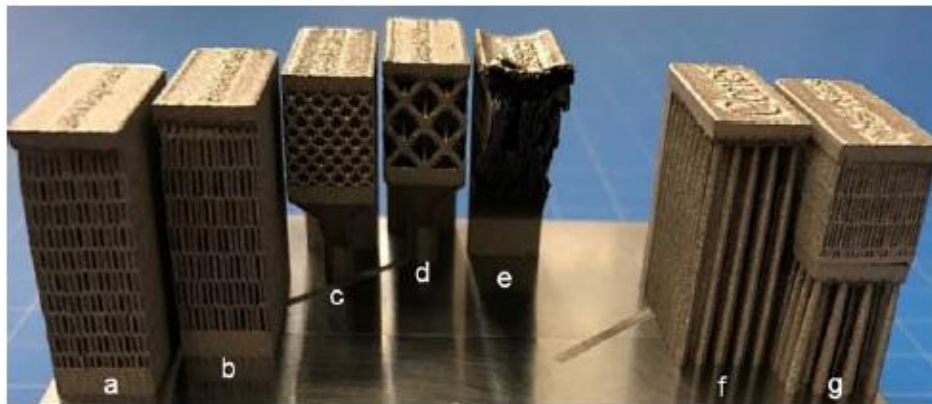


Fig. 5.12 L-PBF support examples. (Source: NASA.)



Fig. 5.13 Manual support removal using hand tools. (Source: NASA.)

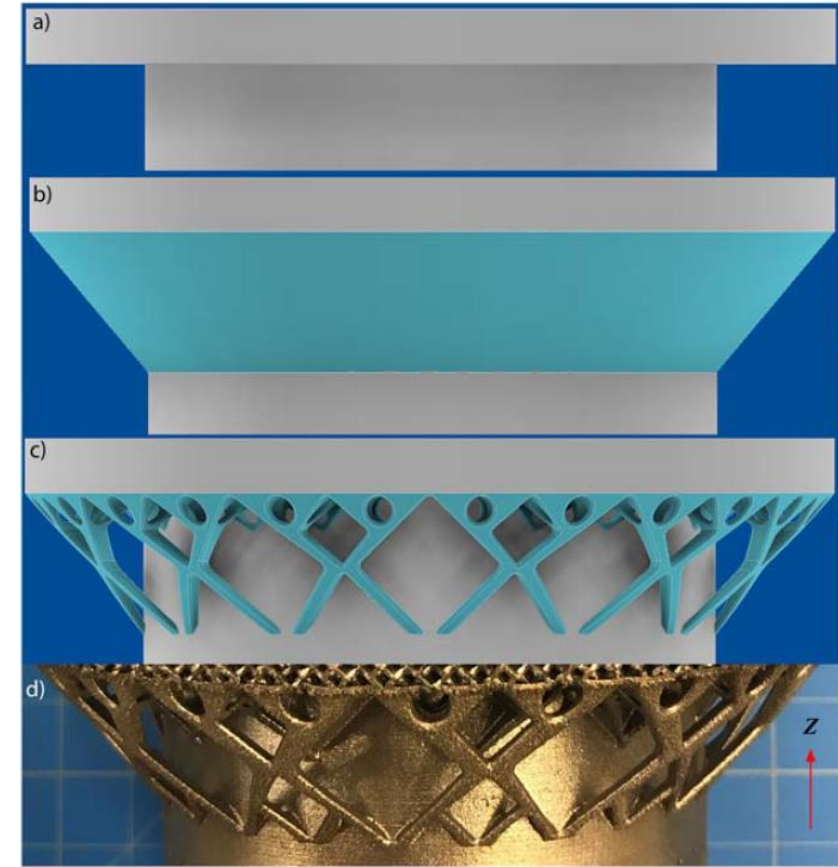


Fig. 7.25 Comparison of a) unsupported overhang flange, b) 40° sacrificial support, c) crown support, and d) Inconel 718 crown support made by L-PBF.

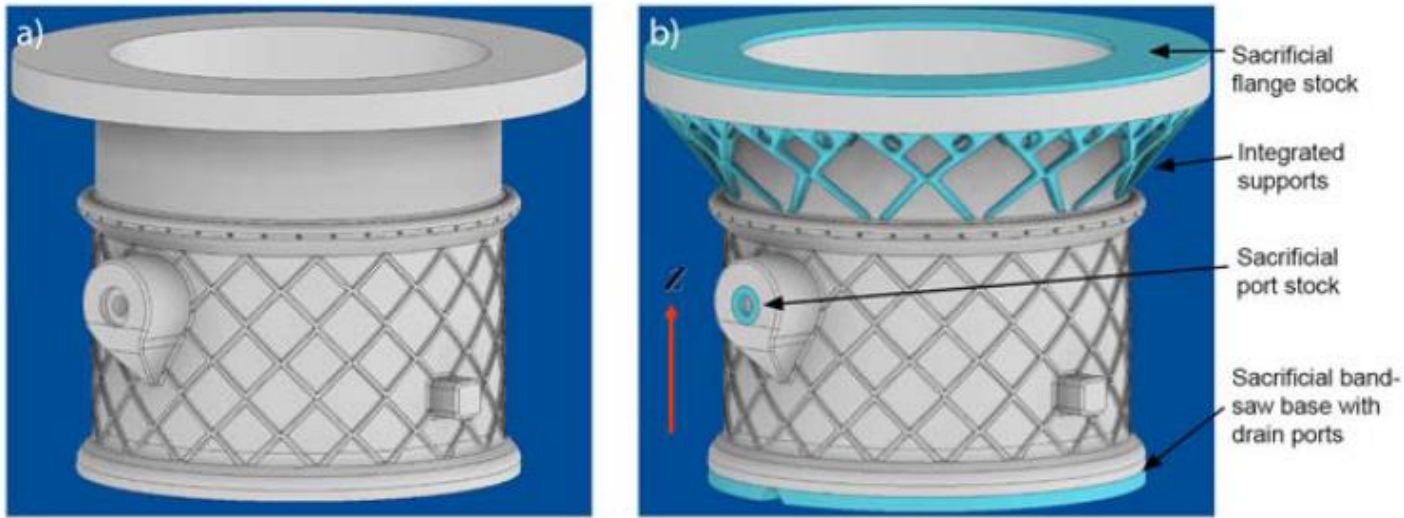


Fig. 7.28 Part a) in final machined condition and b) integrated supports, stock added to interfaces, and drain ports.

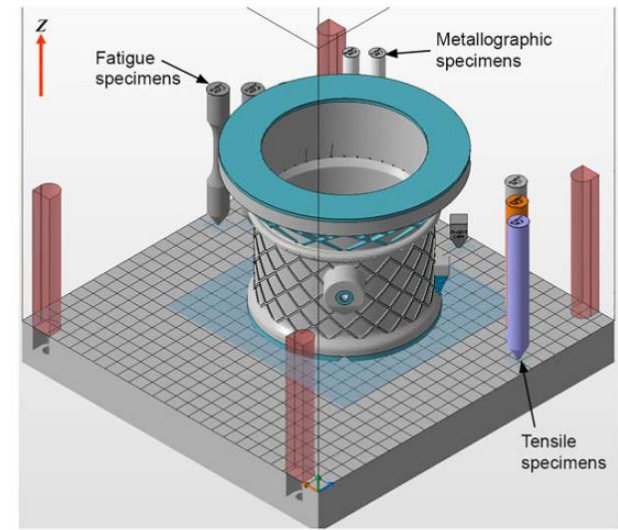


Fig. 7.30 Build layout of a part, support structures, and serialized witness specimens.

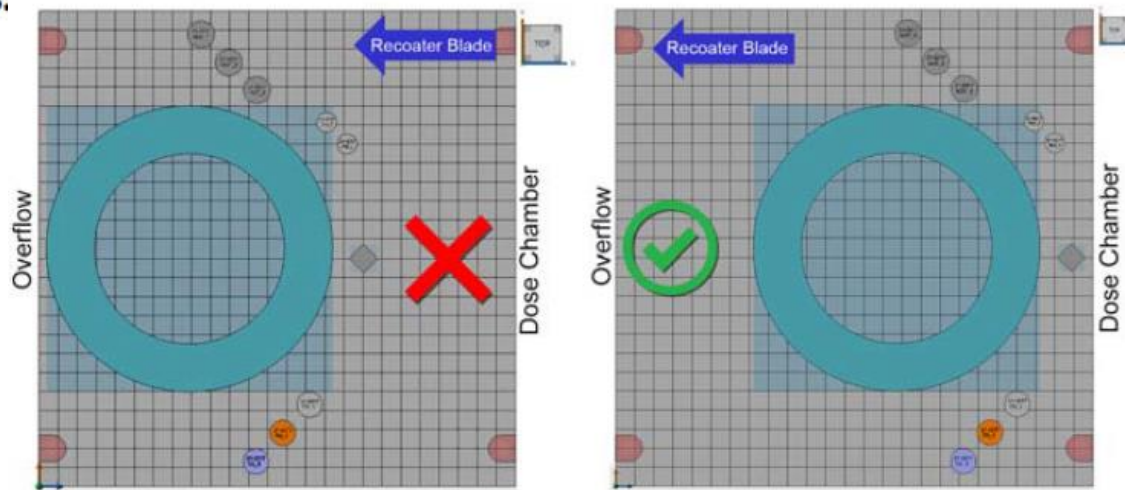


Fig. 7.32 Component placement relative to the dose chamber and recoater blade path.

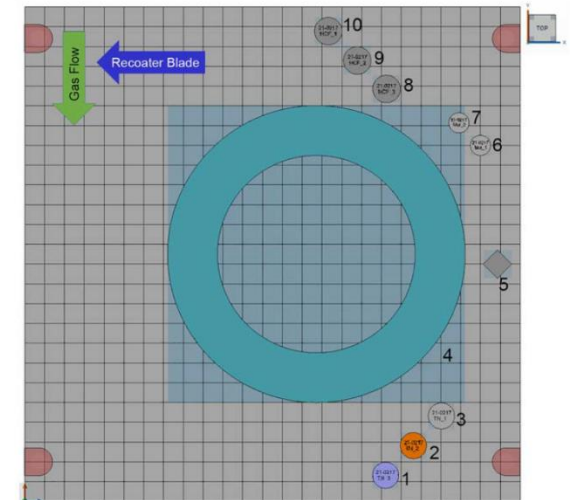
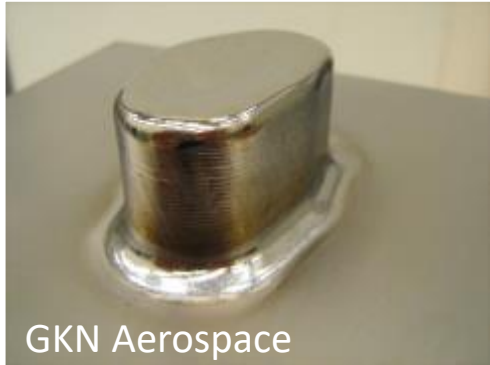


Fig. 7.33 Build layout top view with part positions and scan order optimized for a machine platform with perpendicular gas flow and recoater blade.

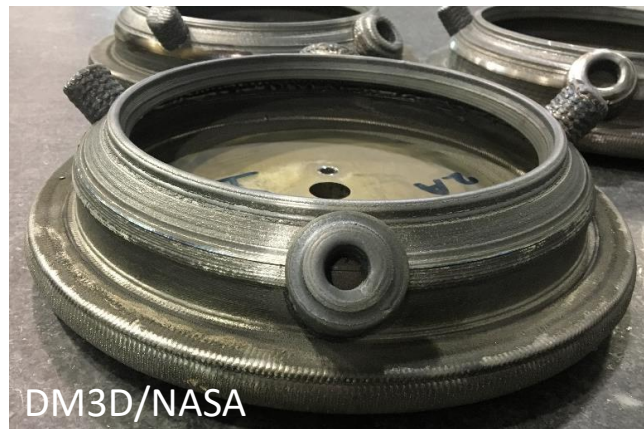
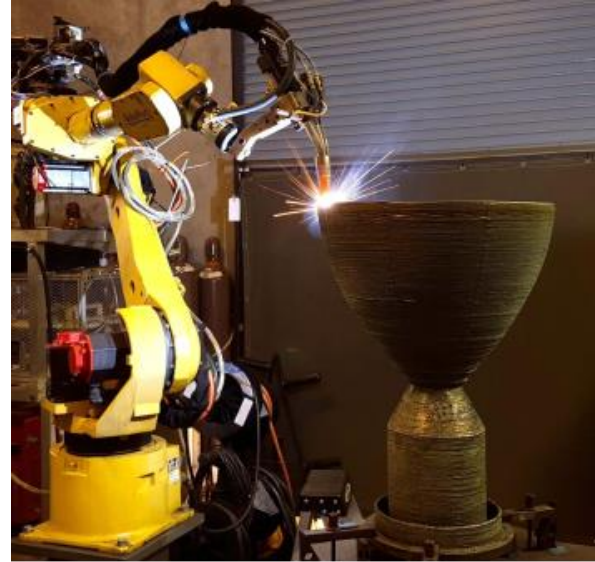
Huge Variety of Geometries



GKN Aerospace



DM3D/NASA



DM3D/NASA



RPMI



RPMI/NASA

Substrate

- Size, Material, Temper
- Integral or Sacrificial?

Material

- Chemistry and form
- Material feedstock effect on surface finish

Deposition Strategy and Parameters

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

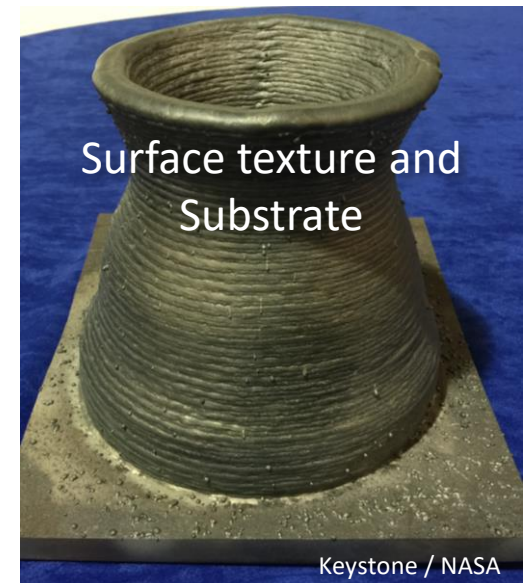
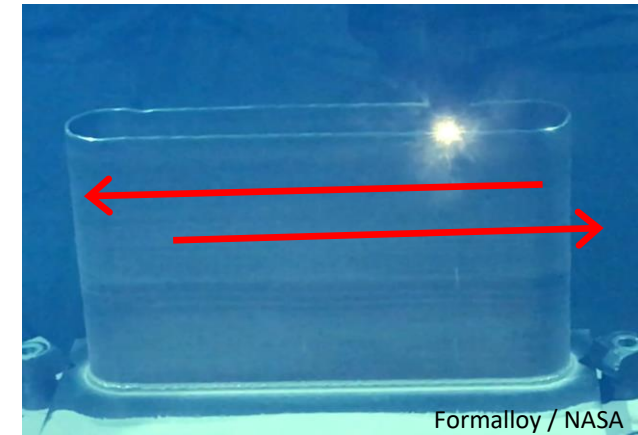
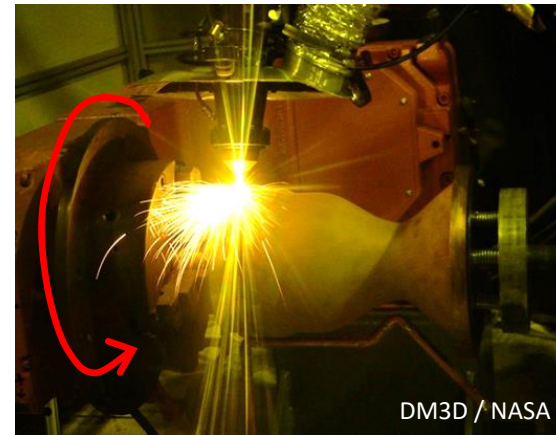
Machining

- Fixturing and datum locations

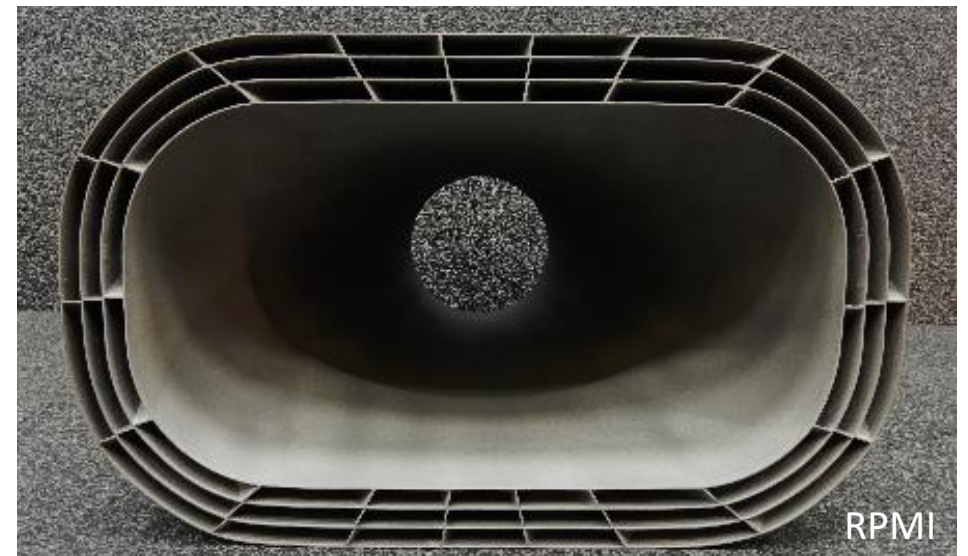
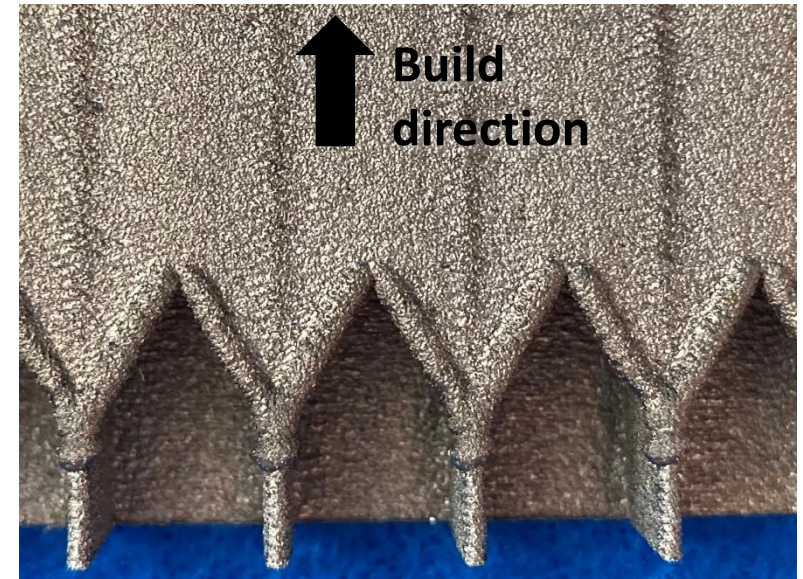
Inspection

- Surface interface with NDE and/or geometry compatibility

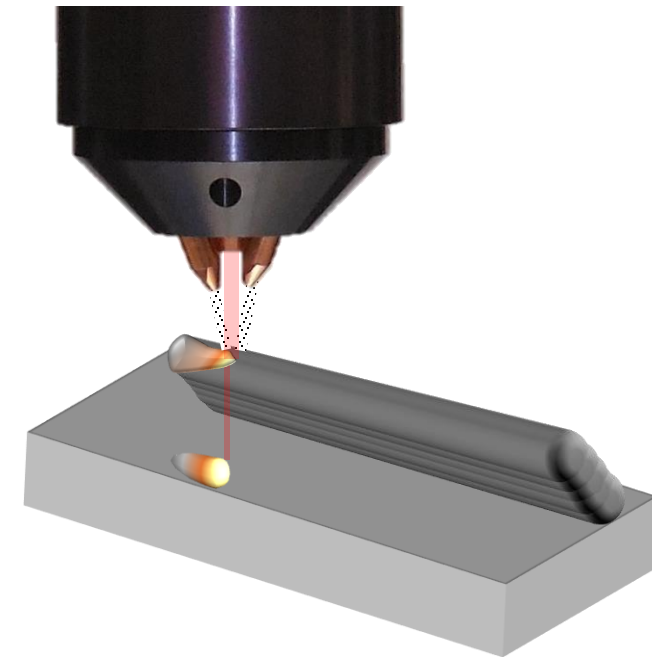
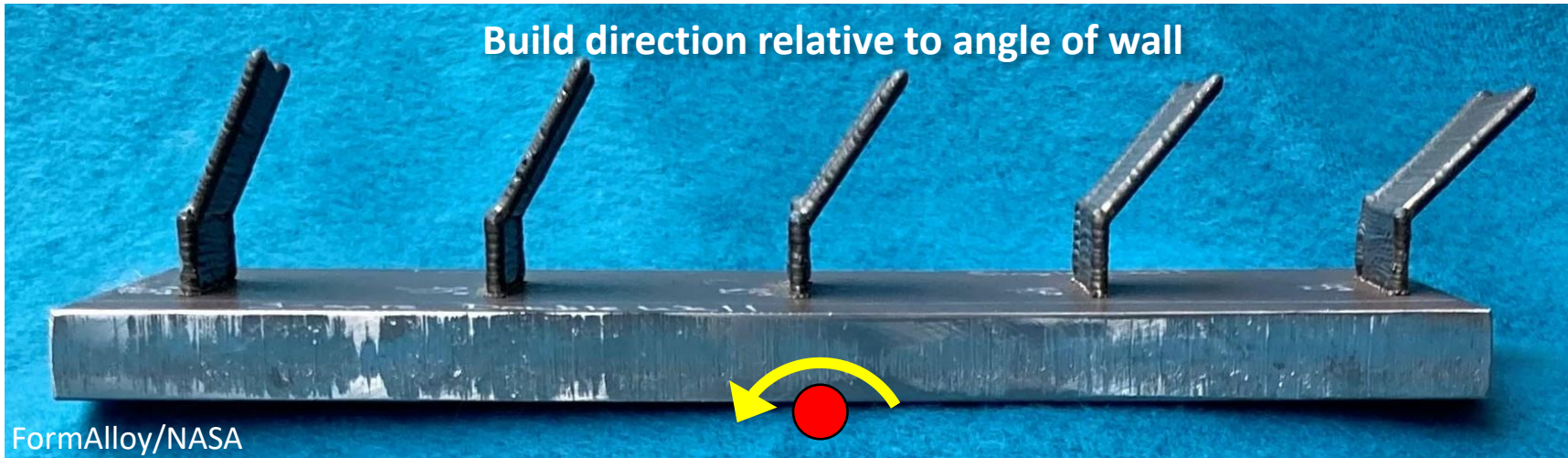
Example: Deposition Strategies



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



Build Angles depend on strategy



*Image courtesy of RPMI

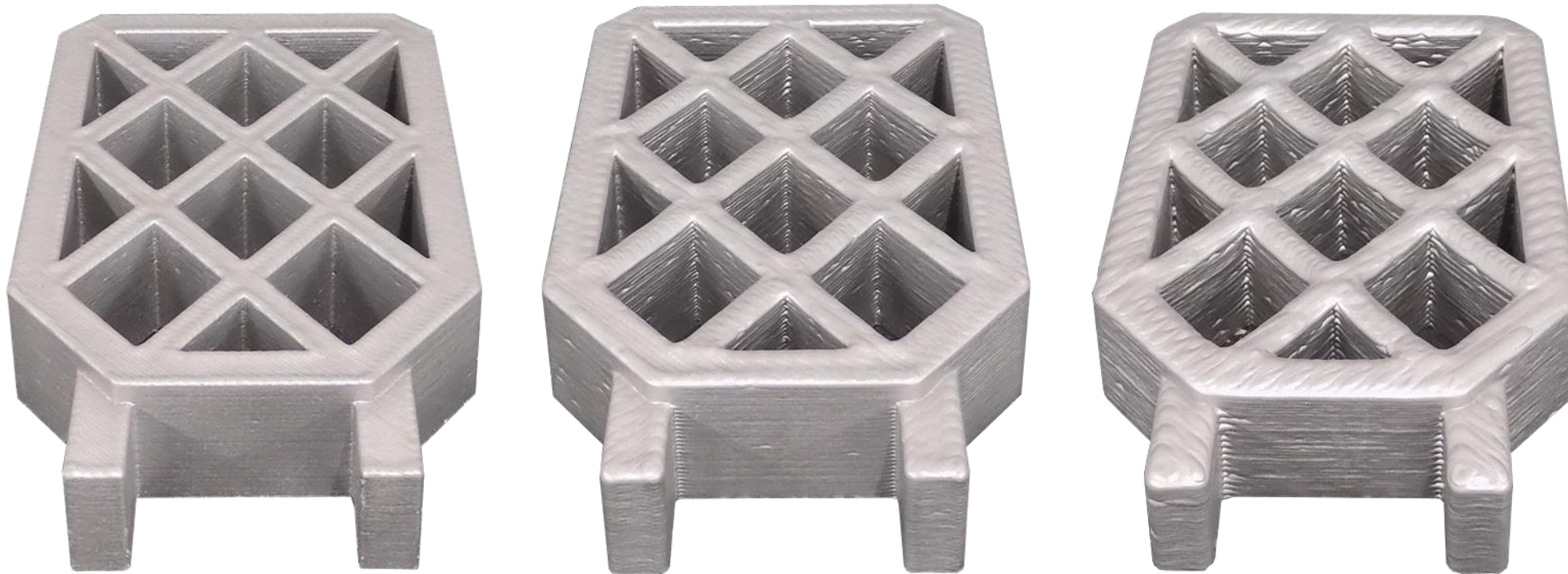
Ability to use multiple axes for complex features fabricated locally



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

Deposition Rate and Geometry

Laser Power: 1070 W	Laser Power: 2000 W	Laser Power: 2620 W
Dep. Rate: 1 in ³ /hr (23 cc/hr)	Dep. Rate: 3 in ³ /hr (49 cc/hr)	Dep. Rate: 5 in ³ /hr (82 cc/hr)
Deposition Time: 24 hours	Deposition Time: 11 hours	Deposition Time: 6 hours



Courtesy: RPM Innovations



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.



Post-Processing



General Process Flow (Post-Processing)

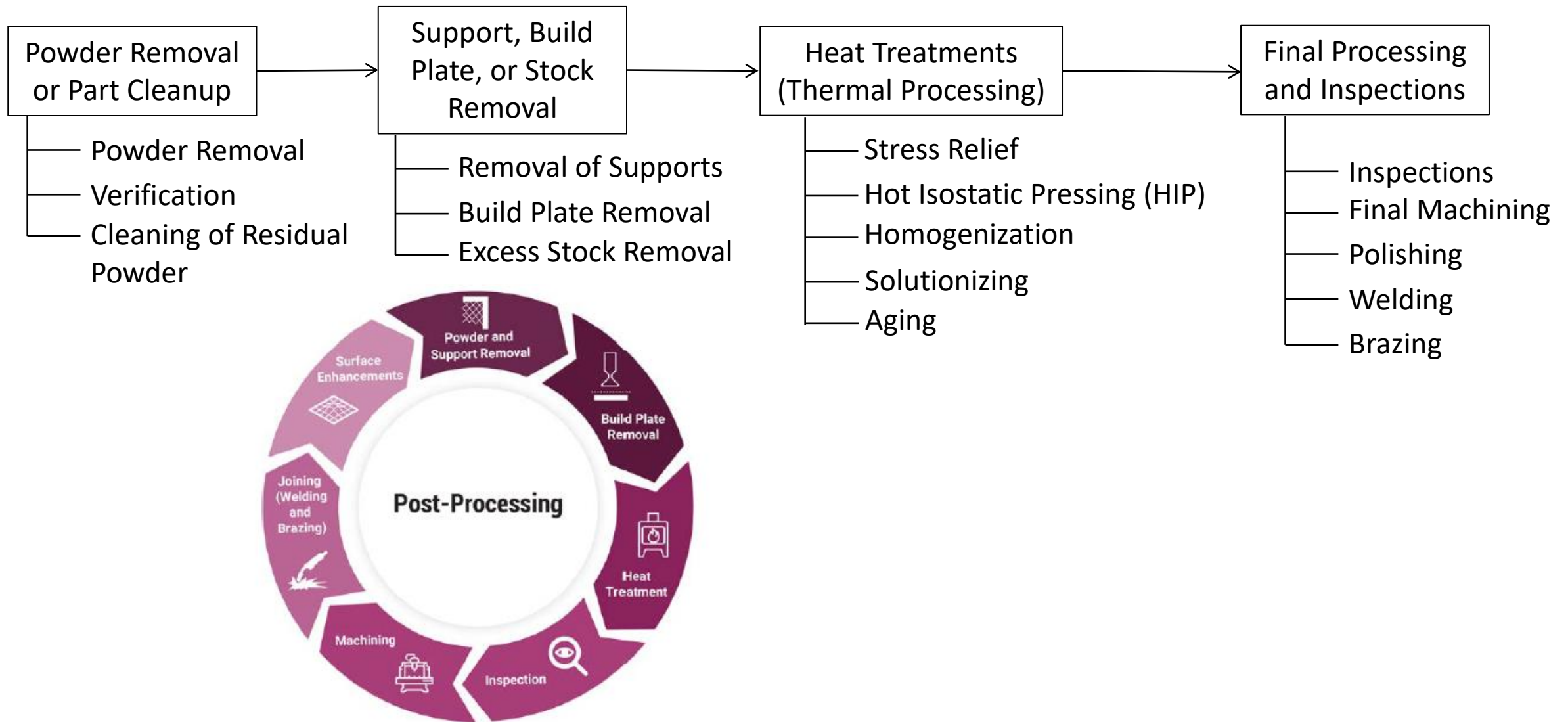


Fig. 5.1 General post-processing steps. The iterative aspect should be considered during the design phase.

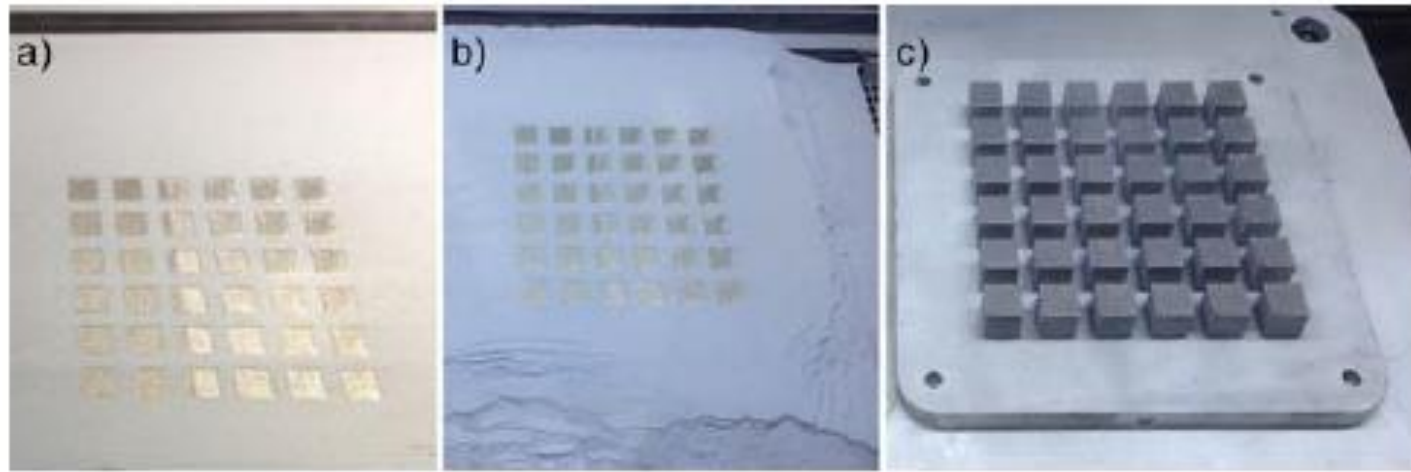


Fig. 5.3 Unpacking example: a) Build completion. b) Build plate raised. c) Powder removed.

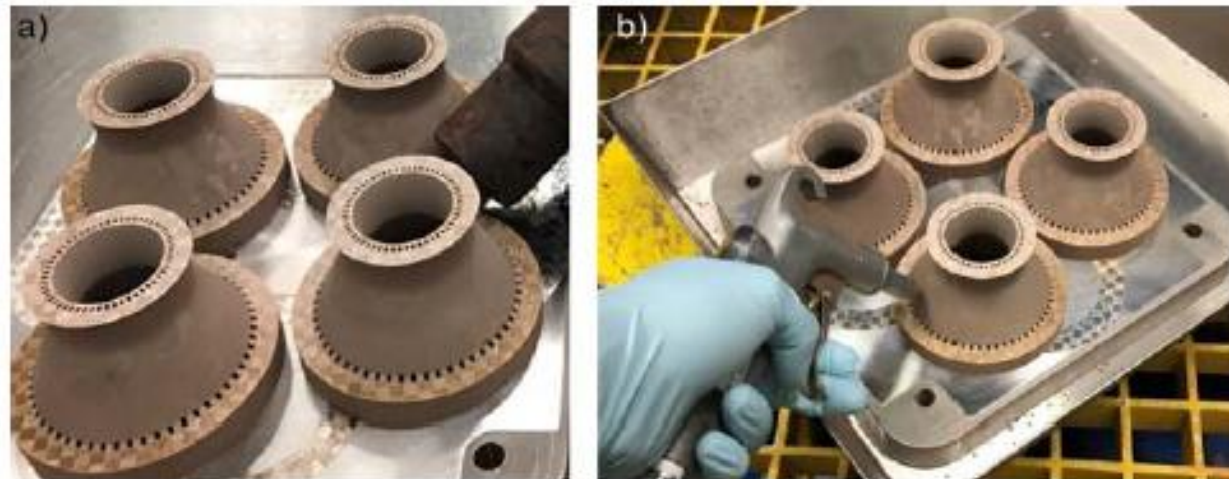


Fig. 5.8 Powder removal with a) a powder vacuum and b) compressed air. (Source: NASA.)

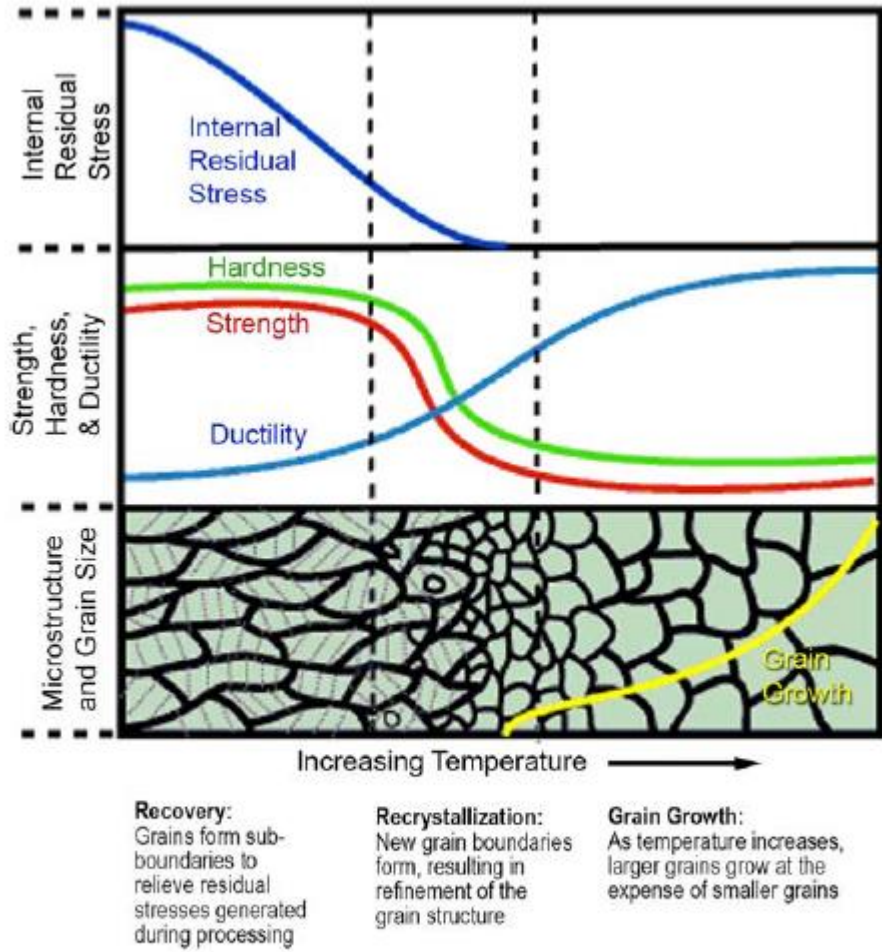


Fig. 4.20 Effects on metal alloy properties of the temperature-dependent recovery, recrystallization, and grain growth regions. (From GATE Metallurgical Engineering [58]; reprinted with permission of GATE Metallurgical Engineering.)

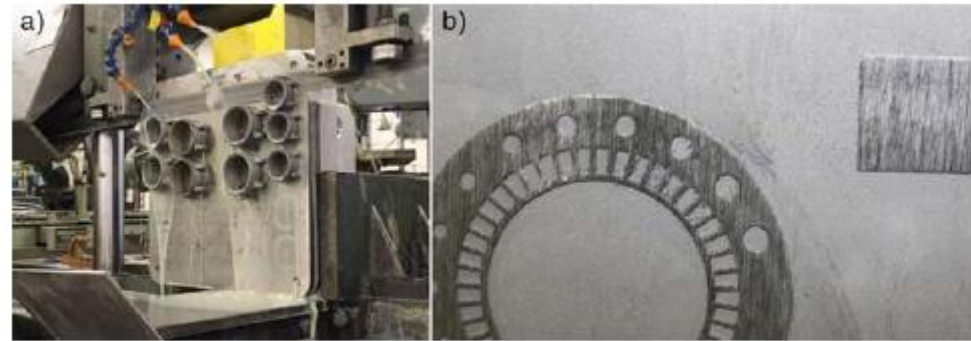


Fig. 5.22 a) Band saw cutting parts from build plate. b) Build plate surface after parts removed.



Fig. 5.23 L-PBF aluminum part fixtured wire-EDM cut chamber before the removal of specimens. (Source: Quadrus Advanced Manufacturing.)

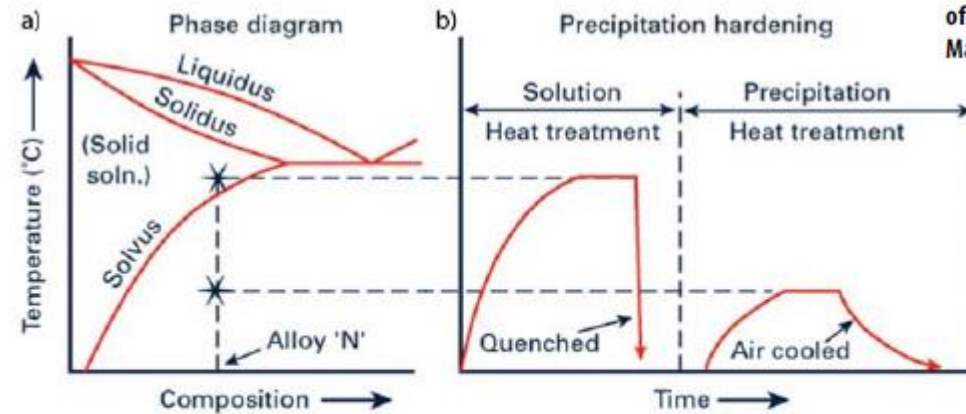


Fig. 4.22 a) General phase diagram and b) corresponding heat-treatment schedule for precipitation hardening. (From Ogunsanya et al. [67]; reprinted under the Creative Commons Attribution-Noncommercial 3.0 Unported License [CC BY-NC 3.0] license, <https://creativecommons.org/licenses/by-nc/3.0/>.)

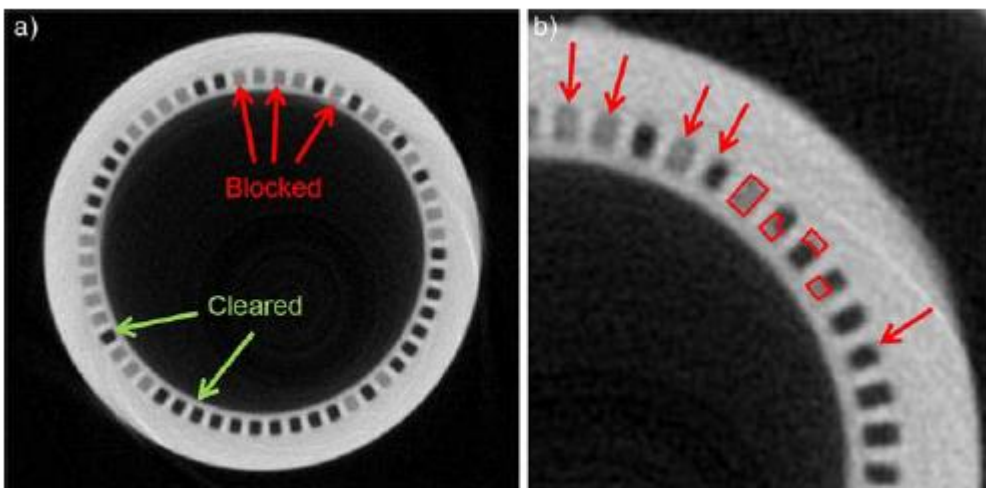


Fig. 5.11 X-ray images of a GRCop-84 chamber with trapped powder in channels. (Source: NASA.)

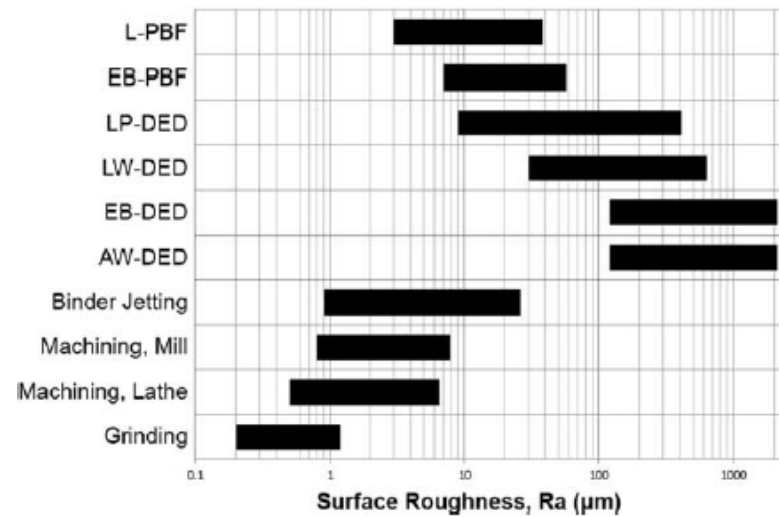


Fig. 5.50 General surface roughness values for selected metal AM processes.



Fig. 5.20 Different chemical support removal methods for original unaltered supports from the L-PBF process. (Source: NASA.)



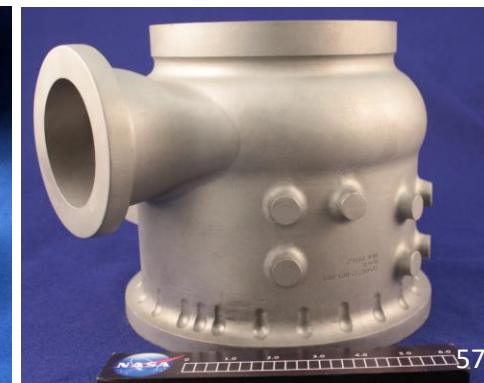
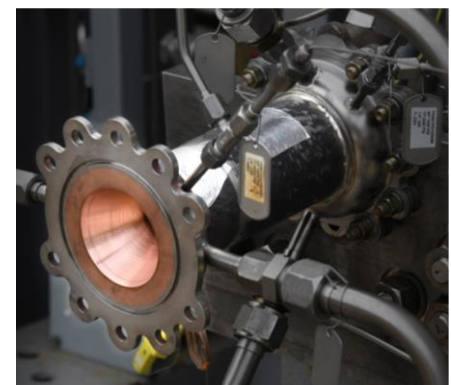
Post-Processing Summary



	Powder Removal and Verification	Support Removal*	Stress Relief**	Build Plate Removal	Heat Treatment Required?	Post-Curing	Final Machining ***
Laser Powder Bed Fusion (L-PBF)	Y	Y	Y	Y	Y	N	O
Electron Beam Powder Bed Fusion (EB-PBF)	Y	Y	N	Y	Y	N	O
Blown Powder Directed Energy Deposition (BP-DED)	Y	Y	Y	Y	Y	N	Y
Arc-Deposition DED	N	N	Y	Y	Y	N	Y
Laser Hot-wire DED	N	N	Y	Y	Y	N	Y
Electron Beam DED	N	N	Y	Y	Y	N	Y
Laser Wire DED	N	N	Y	Y	Y	N	Y
Ultrasonic	N	N	N	N	O	N	Y
Friction Stir	N	N	N	N	O	N	Y
Coldspray	N	N	N	Y	O	N	Y
Binder Jet	Y	O	N	N	Y	Y	O

Y = Requires operation
 N = Does not require
 O = May Require

- 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.





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

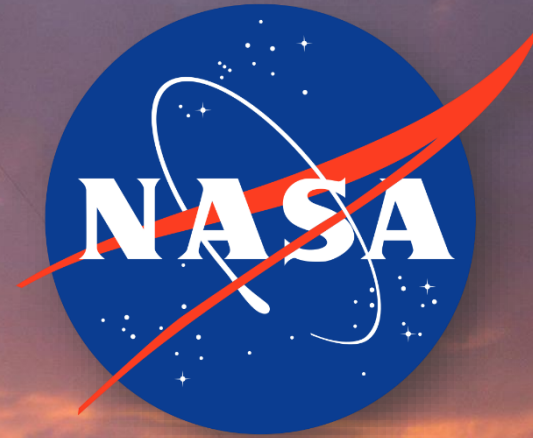
<https://arc.aiaa.org/doi/book/10.2514/4.106279>

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.



Contact:

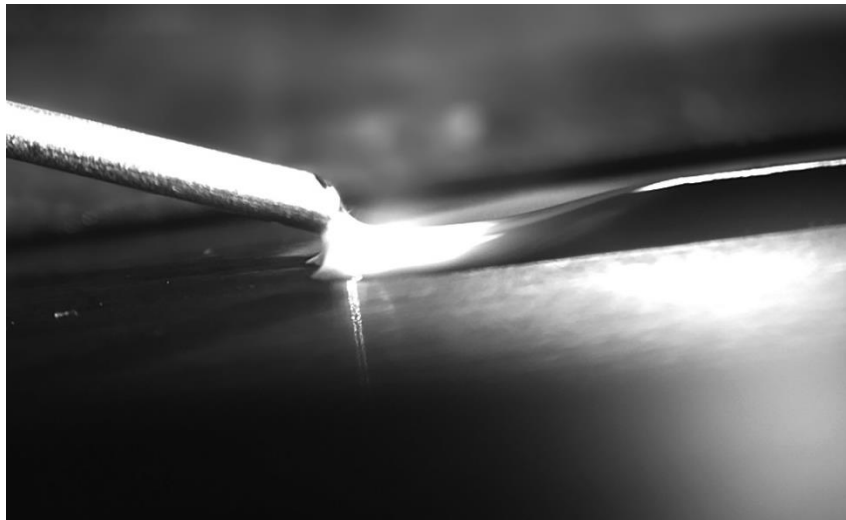
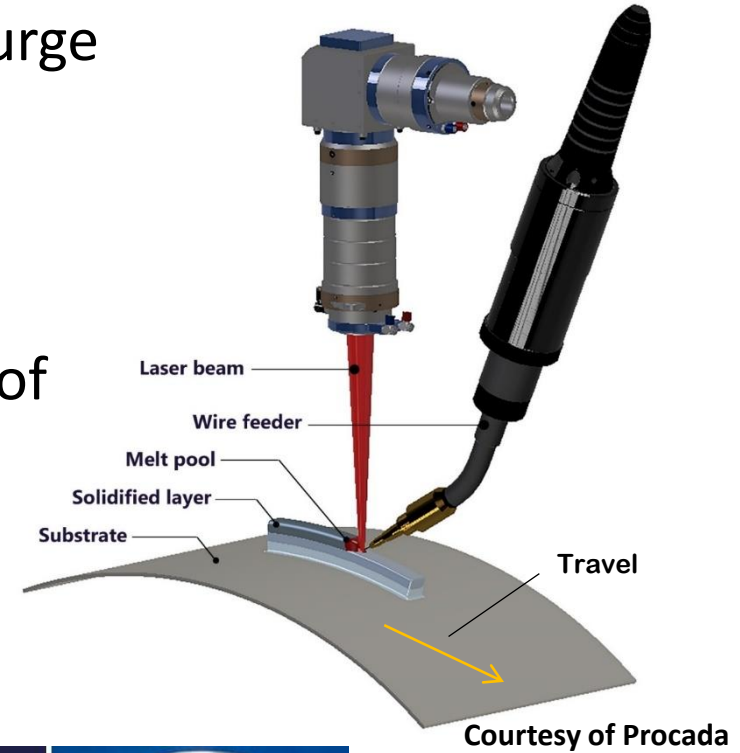
Paul Gradl

NASA MSFC

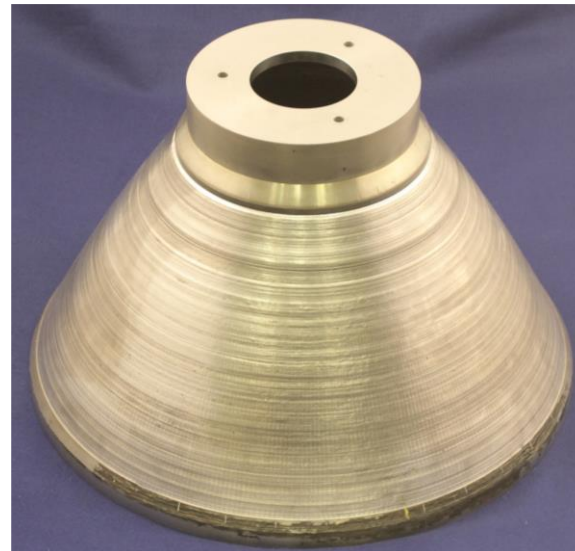
Paul.R.Gradl@nasa.gov

Laser Wire DED (LW-DED)

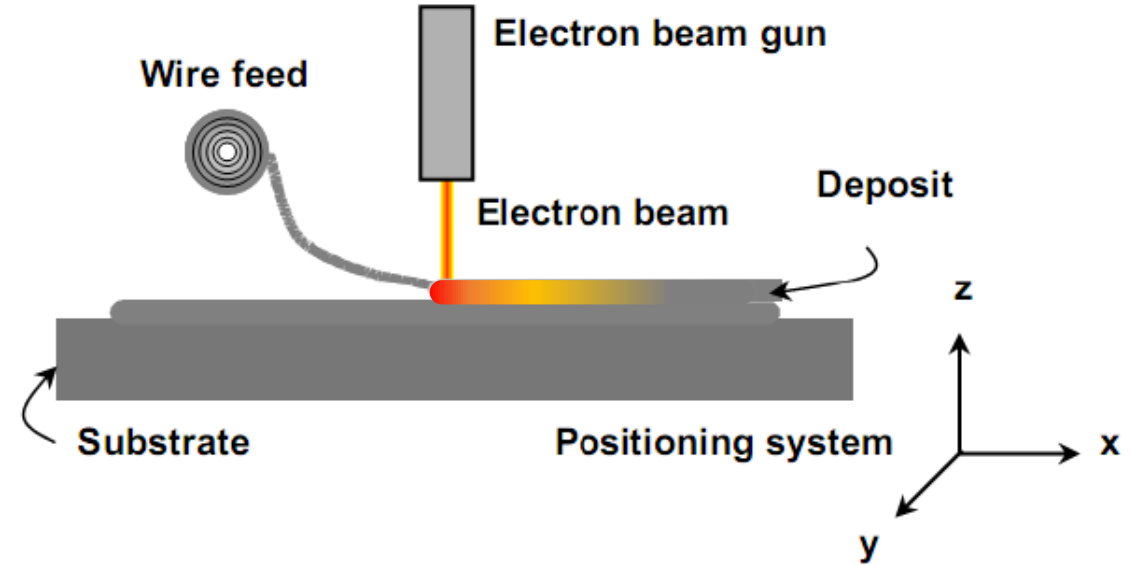
- Uses a laser energy source with a off-axis wire feed and local purge
- 100% efficiency in material usage
- High deposition rates, but balances low heat input
- Can be used on complex surfaces
- Key parameters: Laser Power, Wire feedrate, Travel rate, Angle of Head, Shielding gas flowrate



Courtesy of Procada



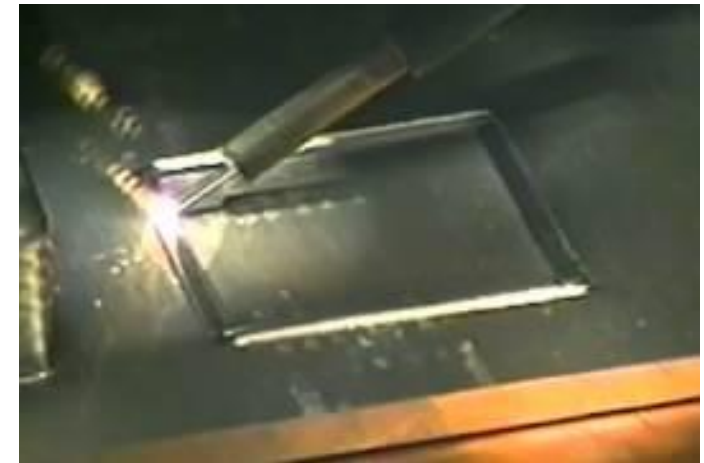
- Uses electron beam energy source with a wire feed inside vacuum chamber
- 100% efficiency in material usage
- High deposition rates
- Key parameters: Beam current and acceleration voltage, Wire Feedrate, Travel Rate, Angle of Turntable



Monolithic EB-DED Freeform

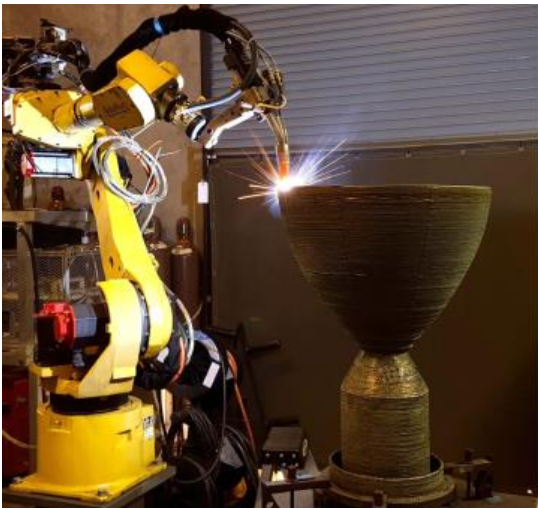
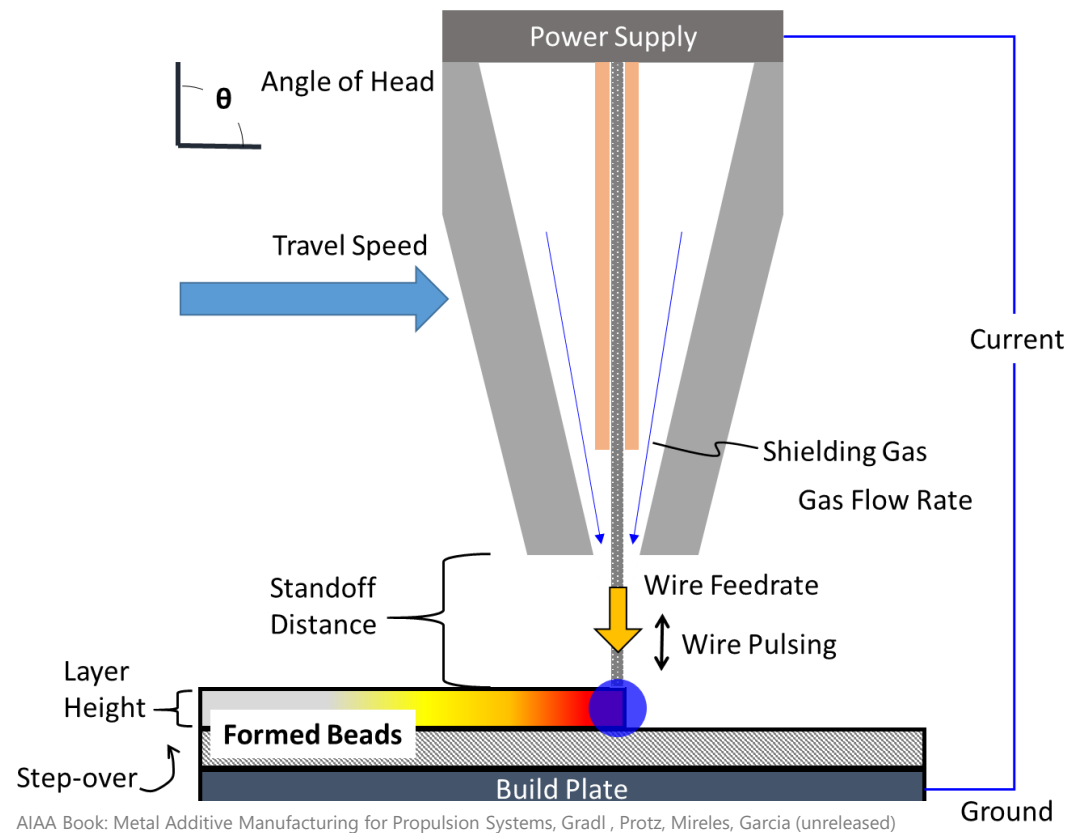


EB-DED Inco 625 Jacket on L-PBF GRCop-84 Liner



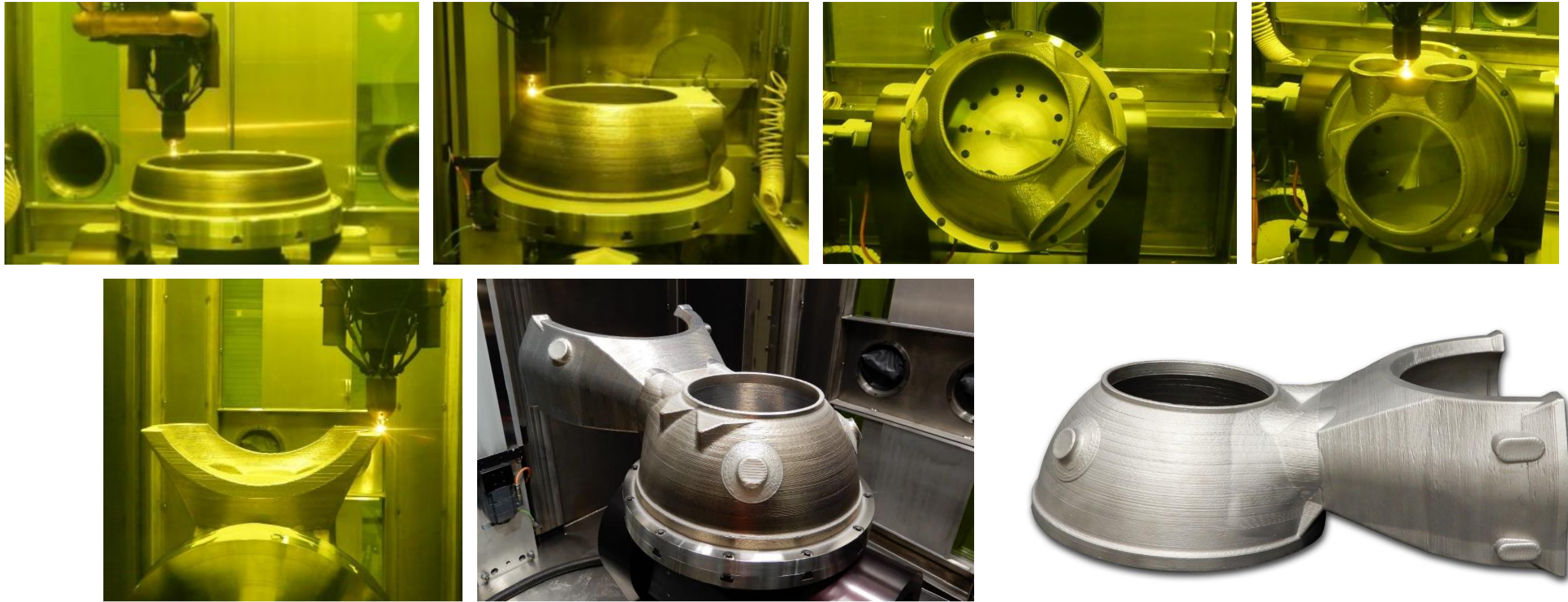
Arc Wire DED (AW-DED)

- Electric energy source providing arc with co-axial wire feed and local purge
- Very high efficiency of material usage
- Low cost process
- Key parameters: Voltage, Current, Wire Pulse Rate, Wire Feedrate, Travel Rate, Angle of Head and Turntable, Shielding Gas flowrate



Courtesy: GEFERTEC

Ability to use multiple axes for complex features fabricated locally



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

Comparison of L-PBF and DED

Different methods for different components!

Laser Powder Bed Fusion (L-PBF)



Directed Energy Deposition (DED)



Feature Resolution / Complexity	High resolution of features Wall thicknesses and holes <0.010"	Medium resolution of features Walls >0.040" and limited holes
Deposition Rate	Low build rates <0.3 lb/hr	High Build rates lbs per hour (some systems >20lb/hr)
Multi-alloys / Gradient Materials	Monolithic materials in single build	Option for multi-alloys or gradients within single build
Materials Available	High number of materials available and being developed	High number of materials available and being developed
Production Rates	Higher volume with several parts in a single build	Generally limited to single builds; longer programming/setup time
Scale / Size of components	Limited to existing build volumes <15.6" dia (400mm) or 16"x24"x19"	Scale is limited to gantry or robot size
Added Features / Repair	No (limited) ability to add material to existing part	Can add material or features to an existing part



Acknowledgements



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

- John Fikes
- Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) Project
- Long Life Additive Manufacturing Assembly (LLAMA) Project
- Space Launch System (SLS) Program
- Mike Ogles
- Nima Shamsaei
- Drew Hope
- Matt Melis
- Lynn Machamer
- RPM Innovations (RPMI)
- Tyler Blumenthal
- DM3D
- GE Research
- Bhaskar Dutta
- REM Surface Engineering
- Powder Alloy Corp
- AP&C
- Keystone Synergistic
- Formalloy
- Auburn University (NCAME)
- Fraunhofer CLA
- Tal Wammen
- Tom Teasley
- Scott Chartier
- Test Stand 115 crew
- Kevin Baker
- Matt Medders
- Adam Willis
- Marissa Garcia
- Nunley Strong
- Gregg Jones
- Marissa Garcia
- Dwight Goodman
- Will Brandsmeier
- Jonathan Nelson
- Bob Witbrodt
- Shawn Skinner
- Megan Le Corre
- Will Evans
- John Ivester
- Will Tilson
- Zach Jones
- Dave Ellis
- Jim Lydon
- Brian West
- Gabe Demeneghi
- Dave Ellis
- Judy Schneider / UAH
- David Myers
- Ron Beshears
- James Walker
- Steve Wofford
- Jessica Wood
- Robert Hickman
- Johnny Heflin
- Mike Shadoan
Keegan Jackson
- Many others in Industry, commercial space and academia



Acknowledgements



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

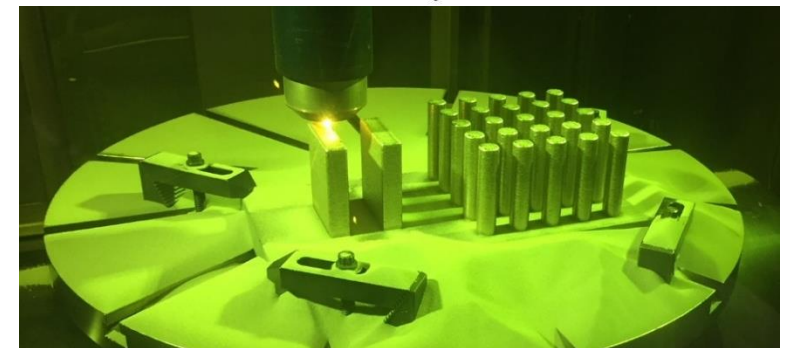
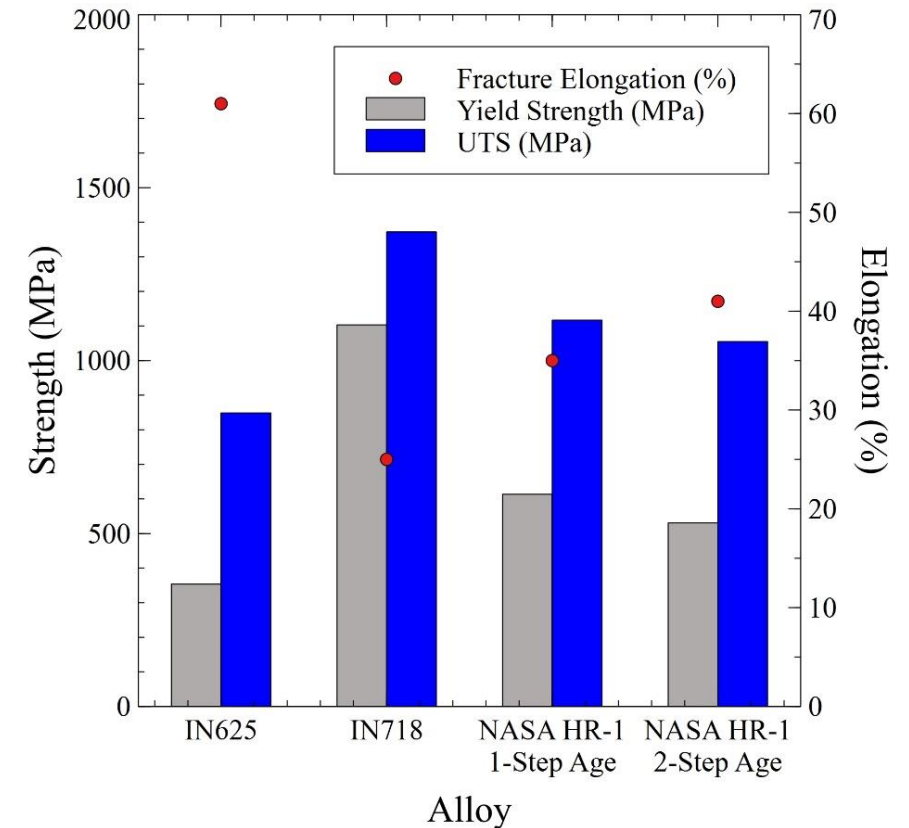
- John Fikes
- Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) Project
- Long Life Additive Manufacturing Assembly (LLAMA) Project
- Space Launch System (SLS) Program
- Mike Ogles
- Nima Shamsaei
- Drew Hope
- Matt Melis
- Lynn Machamer
- RPM Innovations (RPMI)
- Tyler Blumenthal
- DM3D
- GE Research
- Bhaskar Dutta
- REM Surface Engineering
- Powder Alloy Corp
- AP&C
- Keystone Synergistic
- Formalloy
- Auburn University (NCAME)
- Fraunhofer CLA
- Tal Wammen
- Tom Teasley
- Scott Chartier
- Test Stand 115 crew
- Kevin Baker
- Matt Medders
- Adam Willis
- Marissa Garcia
- Nunley Strong
- Gregg Jones
- Marissa Garcia
- Dwight Goodman
- Will Brandsmeier
- Jonathan Nelson
- Bob Witbrodt
- Shawn Skinner
- Megan Le Corre
- Will Evans
- John Ivester
- Will Tilson
- Zach Jones
- Dave Ellis
- Jim Lydon
- Brian West
- Gabe Demeneghi
- Dave Ellis
- Judy Schneider / UAH
- David Myers
- Ron Beshears
- James Walker
- Steve Wofford
- Jessica Wood
- Robert Hickman
- Johnny Heflin
- Mike Shadoan
Keegan Jackson
- Many others in Industry, commercial space and academia



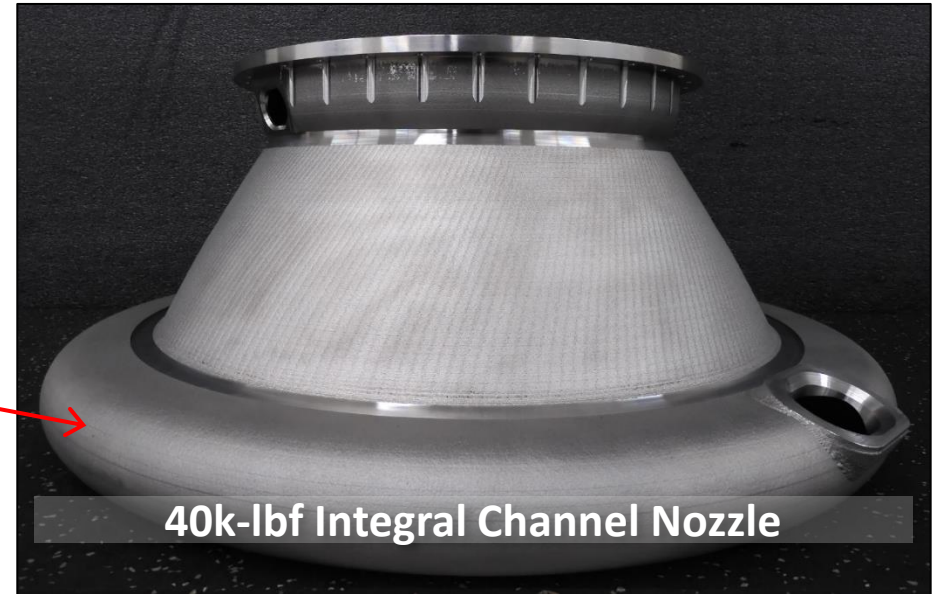
New Alloy Development using AM – NASA HR-1



- **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.



NASA HR-1 Components Fabricated using LP-DED



- Oxidation and blanching resistance during thermal and oxidation-reduction cycling.
- Maximum use temperature $\sim 800^{\circ}\text{C}$, 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).

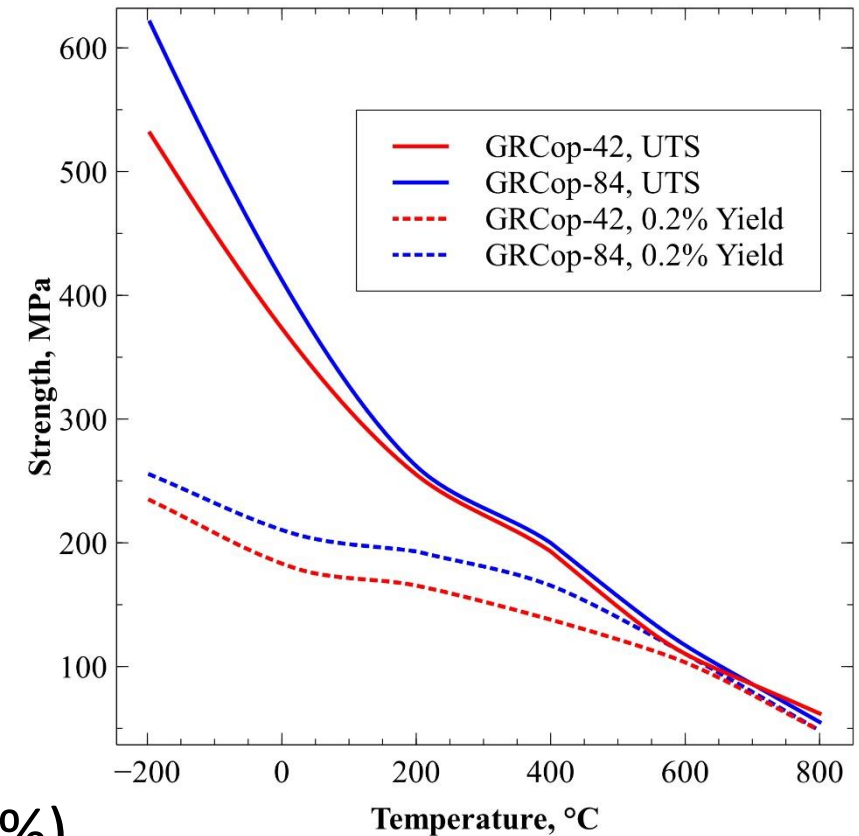




Comparison of GRCop-84 and GRCop-42



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	<i>Target <50 ppm</i>	<i>Target <50 ppm</i>
O	<i>Target <250 ppm</i>	<i>Target <250 ppm</i>
Al	<i>Target <100 ppm</i>	<i>Target <100 ppm</i>
Si	<i>Target <100 ppm</i>	<i>Target <100 ppm</i>
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.



References



- Gradl, P. “Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles.” AIAA-2016-4771, Paper presented at 52nd AIAA/SAE/ASEE Joint Propulsion Conference, July 27, 2016. Salt Lake City, UT.
- Gradl, P. R., & Protz, C. S. (2020). Technology advancements for channel wall nozzle manufacturing in liquid rocket engines. *Acta Astronautica*, 174, 148-158. <https://doi.org/10.1016/j.actaastro.2020.04.067>
- Gradl, P.R., Greene, S.E., Brandsmeier, W., Johnston, I. Hot-fire Testing and Large-scale Deposition Manufacturing Development Supporting Liquid Rocket Engine Channel Wall Nozzle Fabrication, Paper presented at 65th JANNAF Propulsion Meeting/10th Liquid Propulsion Subcommittee, May 21-24, 2018. Long Beach, CA.
- 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>
- Gradl, P., Greene, S., Protz, C., Bullard, B., Buzzell, J., Garcia, C., Wood, J., Osborne, R., Hulka, J. Cooper, K. Additive Manufacturing of Liquid Rocket Engine Combustion Devices: A Summary of Process Developments and Hot-Fire Testing Results. 54th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4625). July 9-12, 2018. Cincinnati, OH.
- Gradl, P., Protz, C., Cooper, K., Garcia, C., Ellis, D., Evans, L. GRCop-42 Development and Hot-fire Testing using Additive Manufacturing Powder Bed Fusion for Channel-cooled Combustion Chambers. 55th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. August 19-21, Indianapolis, IN. AIAA-2019-4228
- Gradl, P., Protz, C., Wammen, T. Additive Manufacturing Development and Hot-fire Testing of Liquid Rocket Channel Wall Nozzles using Blown Powder Directed Energy Deposition Inconel 625 and JBK-75 Alloys. 55th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. August 19-21, Indianapolis, IN. AIAA-2019-4362
- Gradl, P., Protz, C., Fikes, J., Clark, A., Evans, L., Miller, S., Ellis, D.L., Hudson, T. Lightweight Thrust Chamber Assemblies using Multi-Alloy Additive Manufacturing and Composite Overwrap. AIAA Propulsion and Energy Forum. August 24-26. Virtual. (2020). AIAA-2020-3787.
- ASTM International. (2016). *ASTM F3187 - 16 Standard Guide for Directed Energy Deposition of Metals*. ASTM.Org. <https://www.astm.org/Standards/F3187.htm>
- Anderson, R., Terrell, J., Schneider, J., Thompson, S. and Gradl, P., 2019. Characteristics of Bi-metallic Interfaces Formed During Direct Energy Deposition Additive Manufacturing Processing. *Metallurgical and Materials Transactions B*, pp.1-10.
- Onuike, B., Heer, B. and Bandyopadhyay, A., 2018. Additive manufacturing of Inconel 718—copper alloy bimetallic structure using laser engineered net shaping (LENS™). *Additive Manufacturing*, 21, pp.133-140.
- Bandyopadhyay, A. and Heer, B., 2018. Additive manufacturing of multi-material structures. *Materials Science and Engineering: R: Reports*, 129, pp.1-16
- Gradl, P., Protz, C., Wammen, T. “Additive Manufacturing Development and Hot-fire Testing of Liquid Rocket Channel Wall Nozzles using Blown Powder Directed Energy Deposition Inconel 625 and JBK-75 Alloys”. 55th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. August 19-22. Indianapolis, IN. (2019).
- Gradl, P., Mireles, O. and Andrews, N., 2019. Introduction to Additive Manufacturing for Propulsion Systems. M19-7605. AIAA Propulsion and Energy Forum and Exposition; August 19, 2019 - August 22, 2019; Indianapolis, IN; United States. [10.13140/RG.2.2.13113.93285](https://doi.org/10.13140/RG.2.2.13113.93285)
- Hauser, C. Additive Manufacturing Seminar: Blown Powder Activities. TWI Materials and Joining Technologies. Retrieved from: www.twi-global.com/_resources. (2015)
- Karczewski, K., Pęska, M., Ziętała, M. and Polański, M., 2017. Fe-Al thin walls manufactured by laser engineered net shaping. *Journal of Alloys and Compounds*, 696, pp.1105-1112.