Introduction to Additive Manufacturing for Propulsion and Energy Systems

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AIAA SciTech

Overview of Presentation

- Introduction
- Metal AM Process Selection
- Overview of AM Materials & Microstructure
- Metal AM Feedstock
- AM Post-Processing
- Design for the AM (DfAM) Lifecycle
- Example use cases

The Case for Additive Manufacturing in Propulsion

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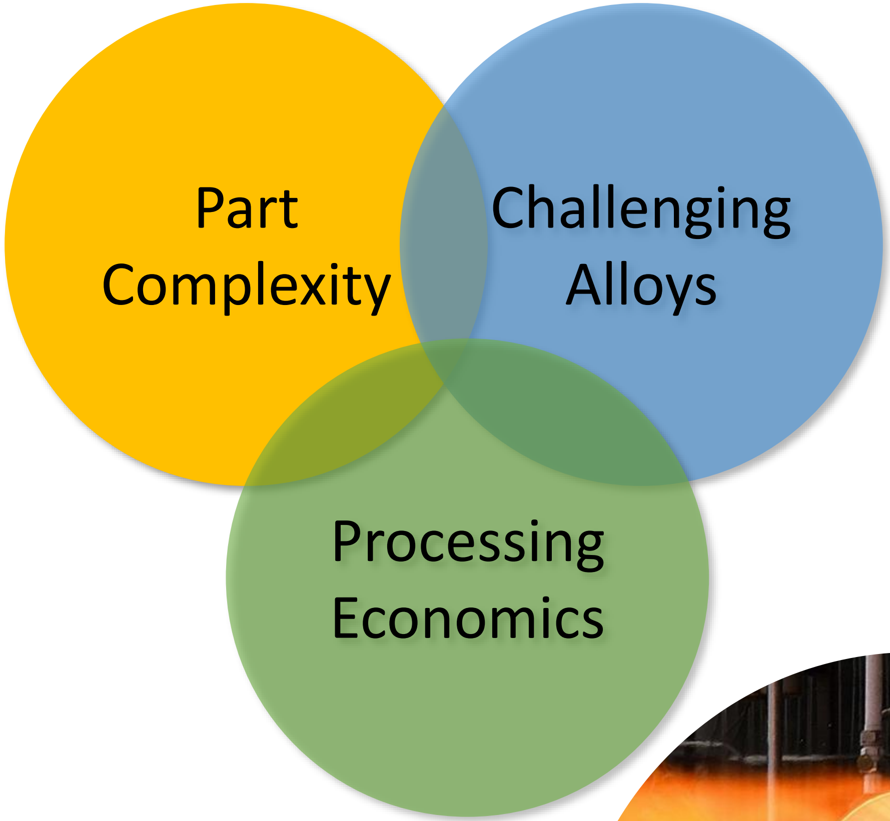
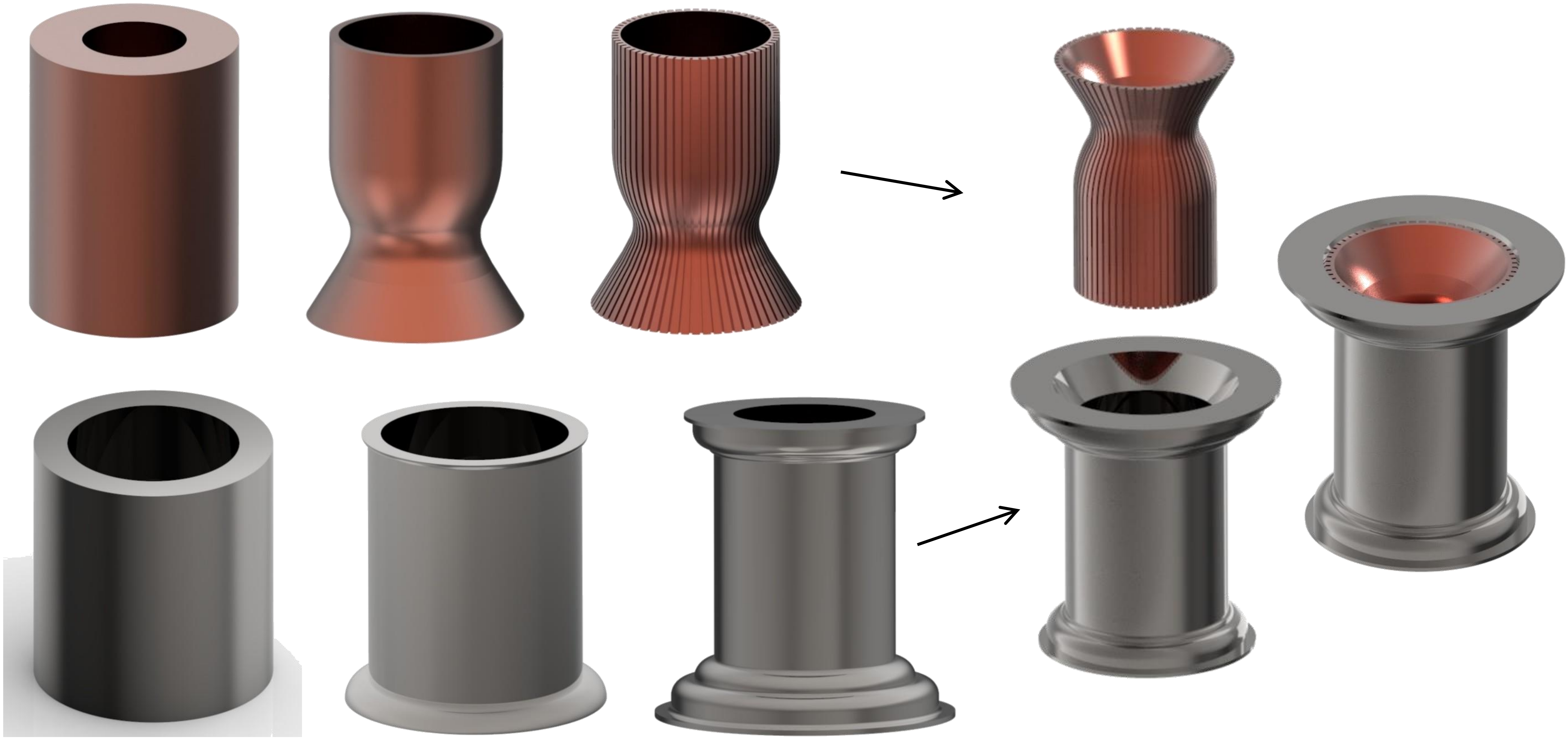
- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
    - Lead times reduced by 2-10x
    - Cost reduced by more than 50%

- 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



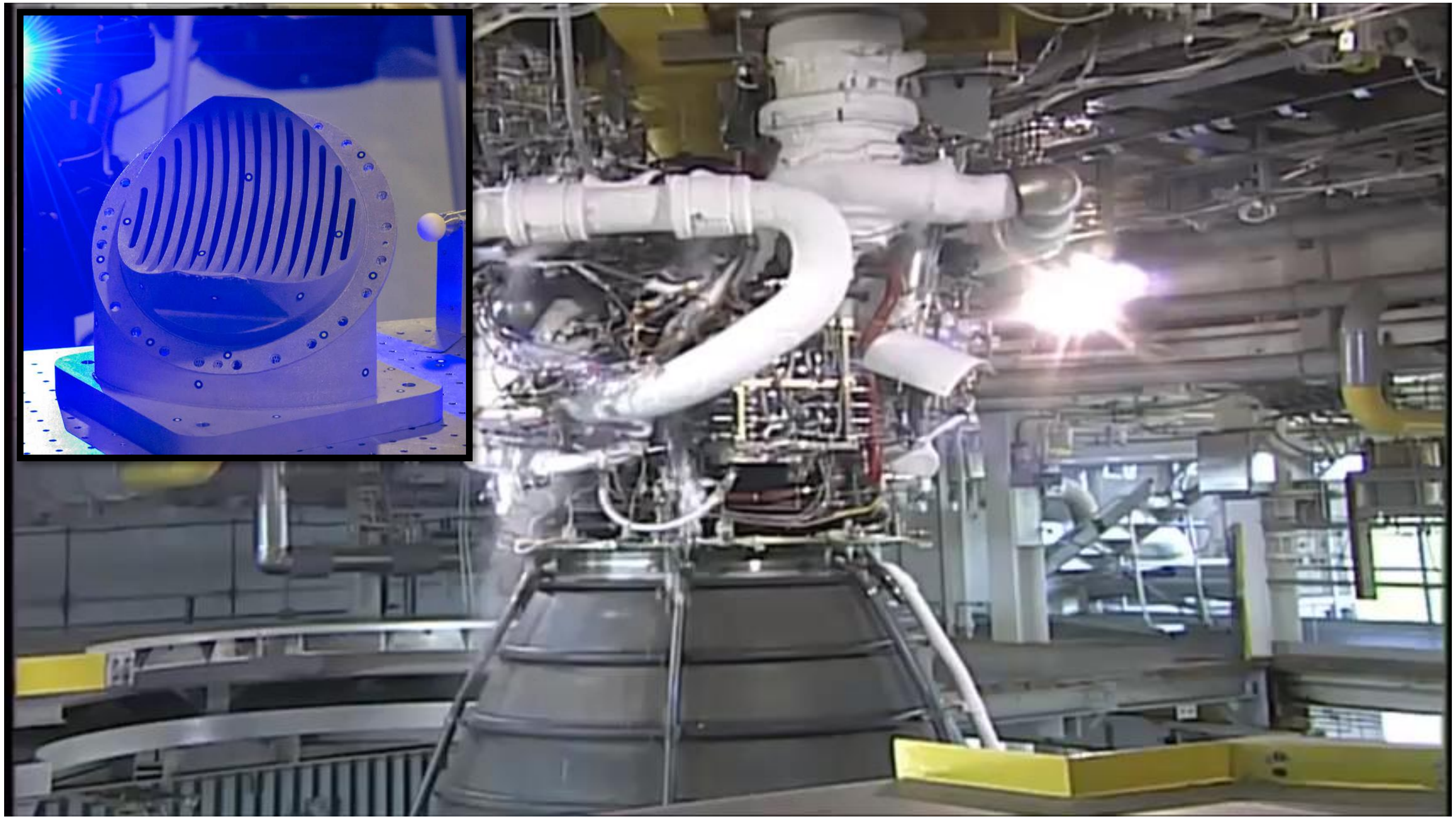
A rocket combustion chamber case study for AM

*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>

NASA

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

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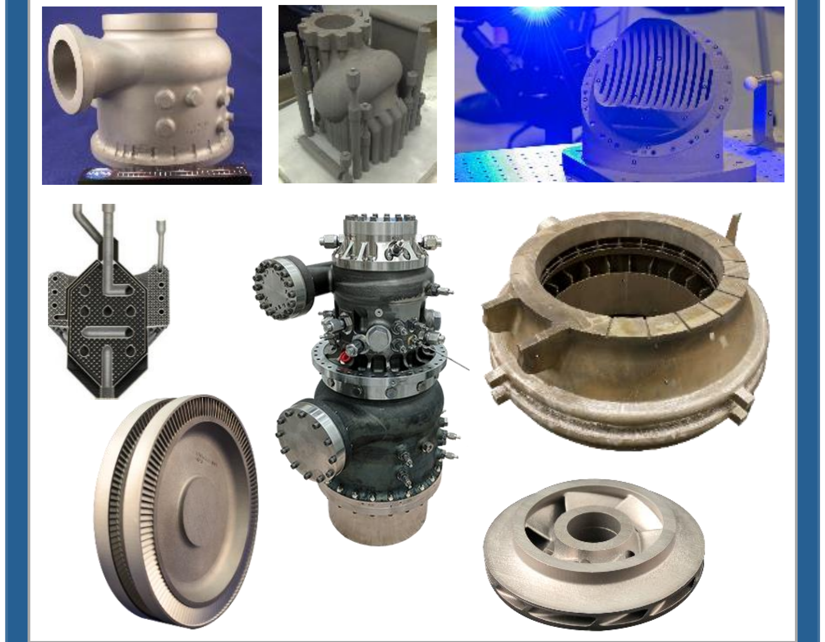
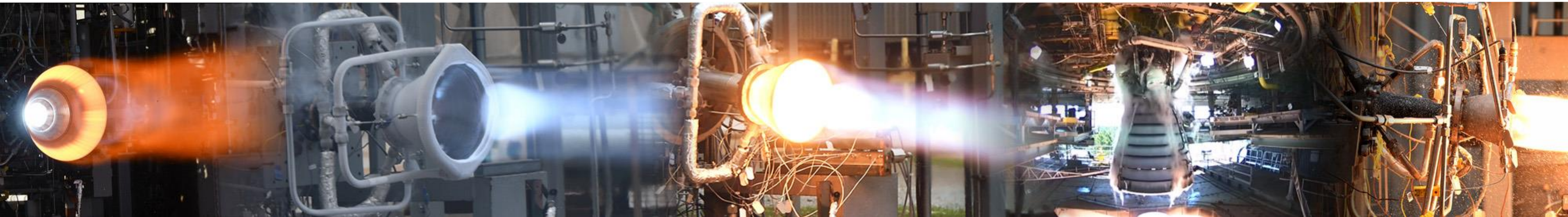
Laser Powder Bed Fusion (L-PBF) Copper Alloys combined with other AM processes to provide bimetallic

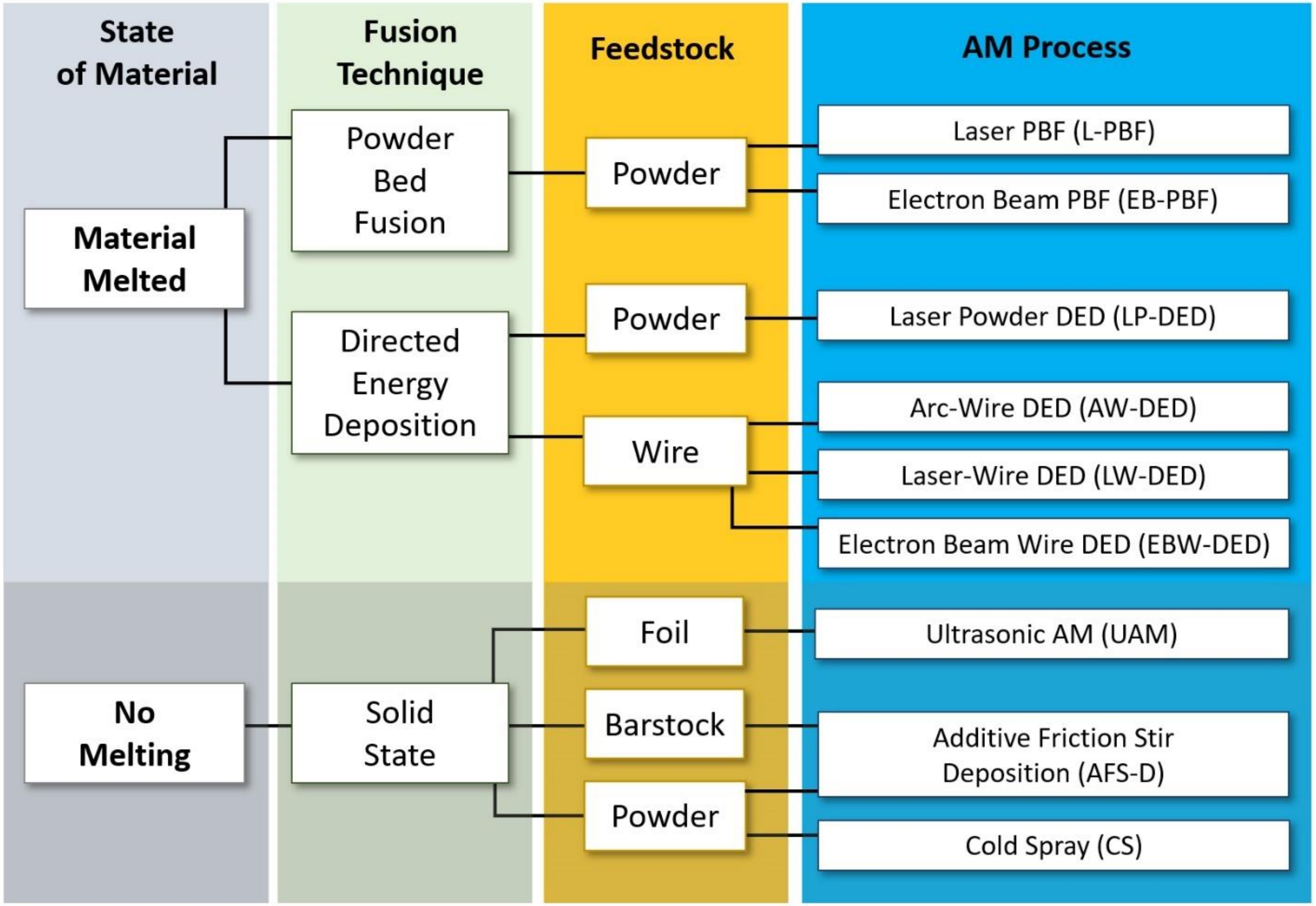
Directed Energy Deposition



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

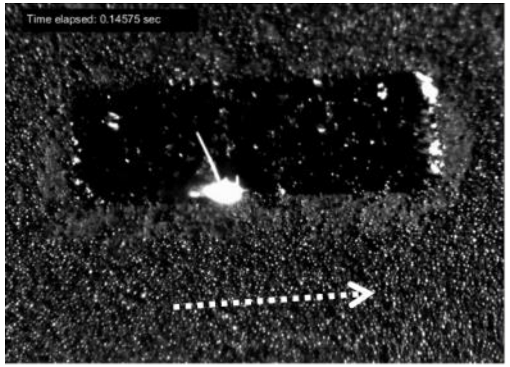


Various Metal AM Processes



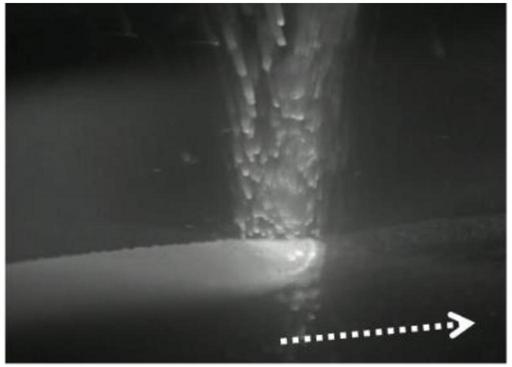
Many AM processes exists and must be traded (along with traditional techniques) to optimize

AM Processes for various applications

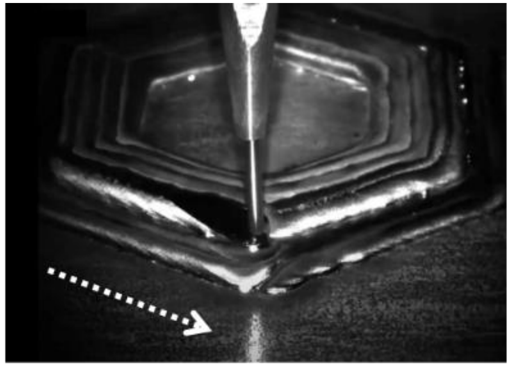


Laser Powder Bed Fusion

Electron Beam Powder Bed Fusion

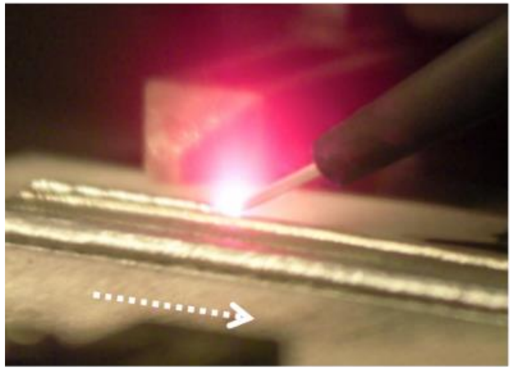


Laser Powder DED

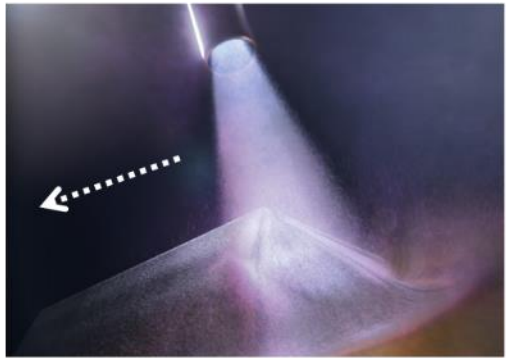


Laser Wire DED

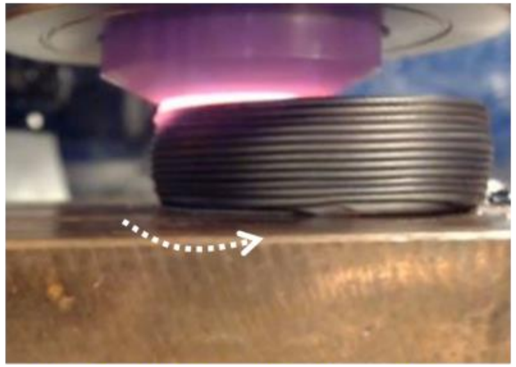
Arc Wire DED



Electron Beam Wire DED



Cold Spray



Additive Friction Stir Deposition

Ultrasonic Additive Manufacturing

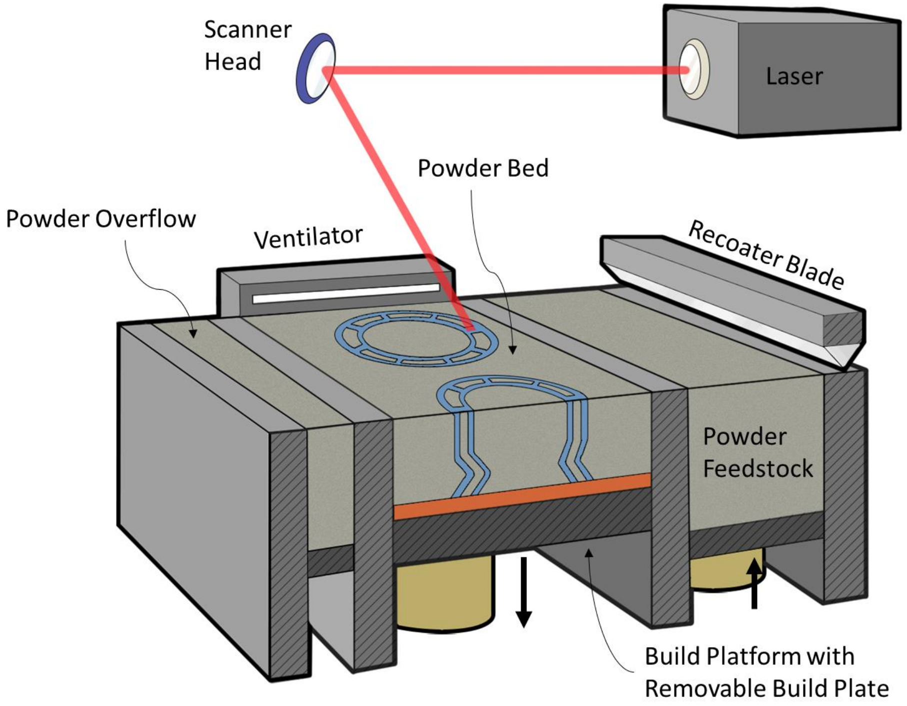
**Not inclusive of all metal AM processes*

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: Formalloy],* D) Laser Wire DED *[Credit: Ramlab and Cavitar],* E) Arc Wire DED *[Credit: Institut Maupertuis and Cavitar],* F) Electron Beam DED *[NASA],* G) Cold spray *[Credit: LLNL],* H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM *[Credit: Fabrisonic].*

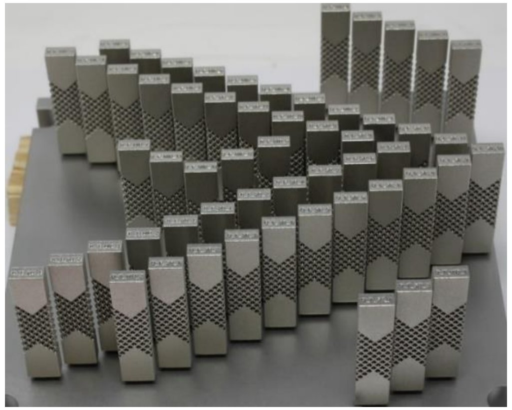
Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). “Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components”. (Journal Article In Release)

Laser Powder Bed Fusion (L-PBF)

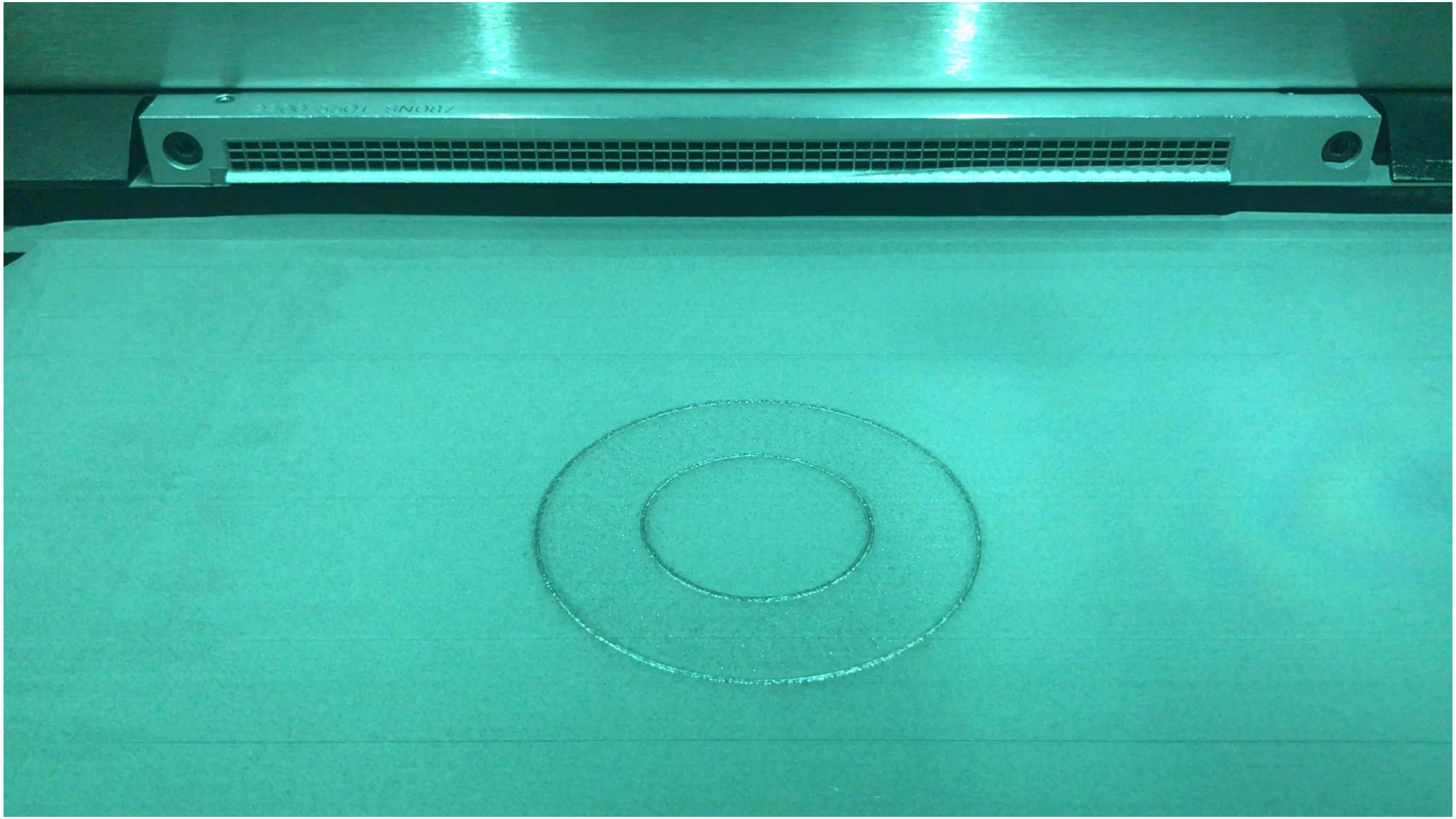
- **Laser Powder Bed Fusion (L-PBF)**
  - Basic Process: Layer-by-layer powder-bed approach where desired features are melted using a laser and solidify.
  - Advantages: High feature resolution, complex internal designs such as cooling channels.
  - Disadvantages: Scale limited and does not provide a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



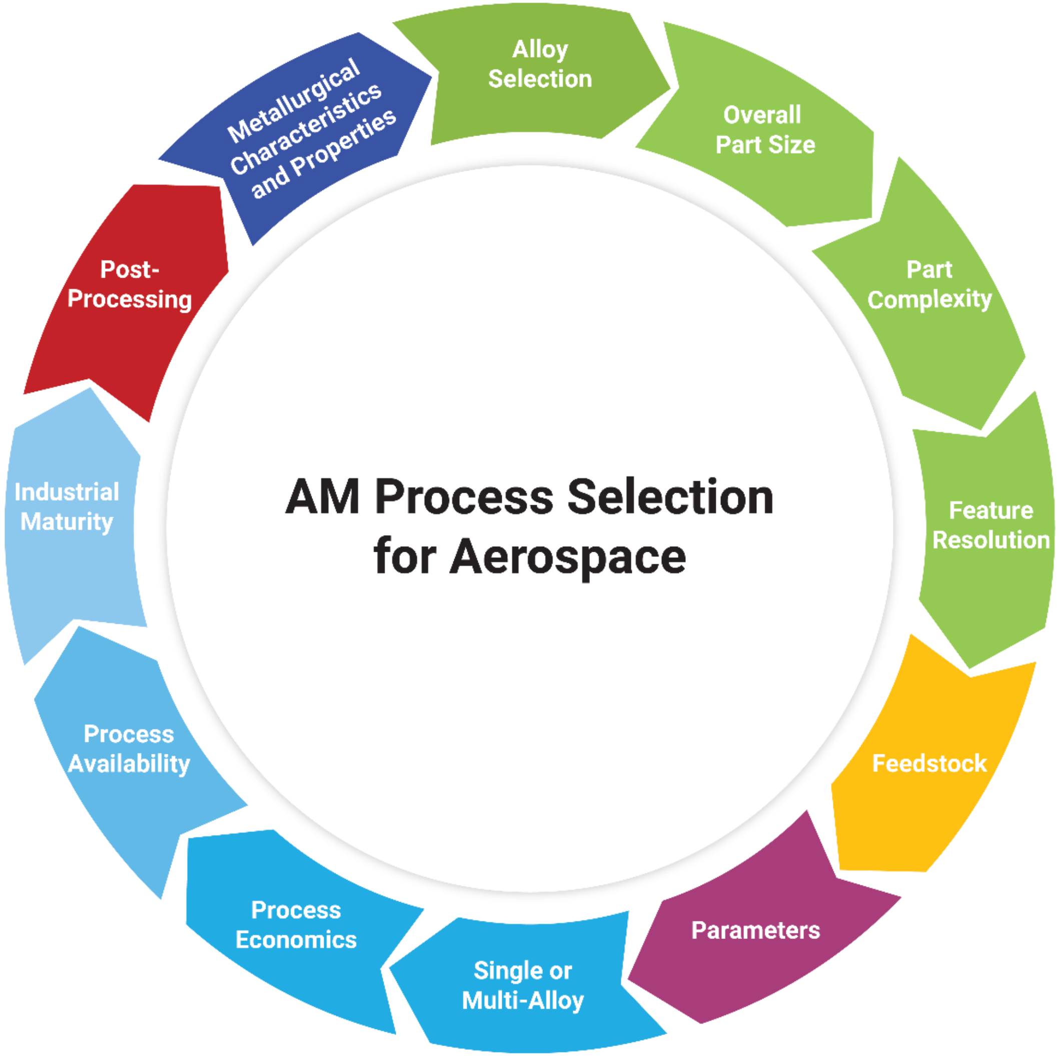
- **Electron Beam Melting**
  - Basic Process: Similar to L-PBF but uses an electron beam.
  - Advantages: Performed in-near vacuum, which is useful for reactive materials such as Ti6A4V.



Laser Powder Bed Fusion (L-PBF)



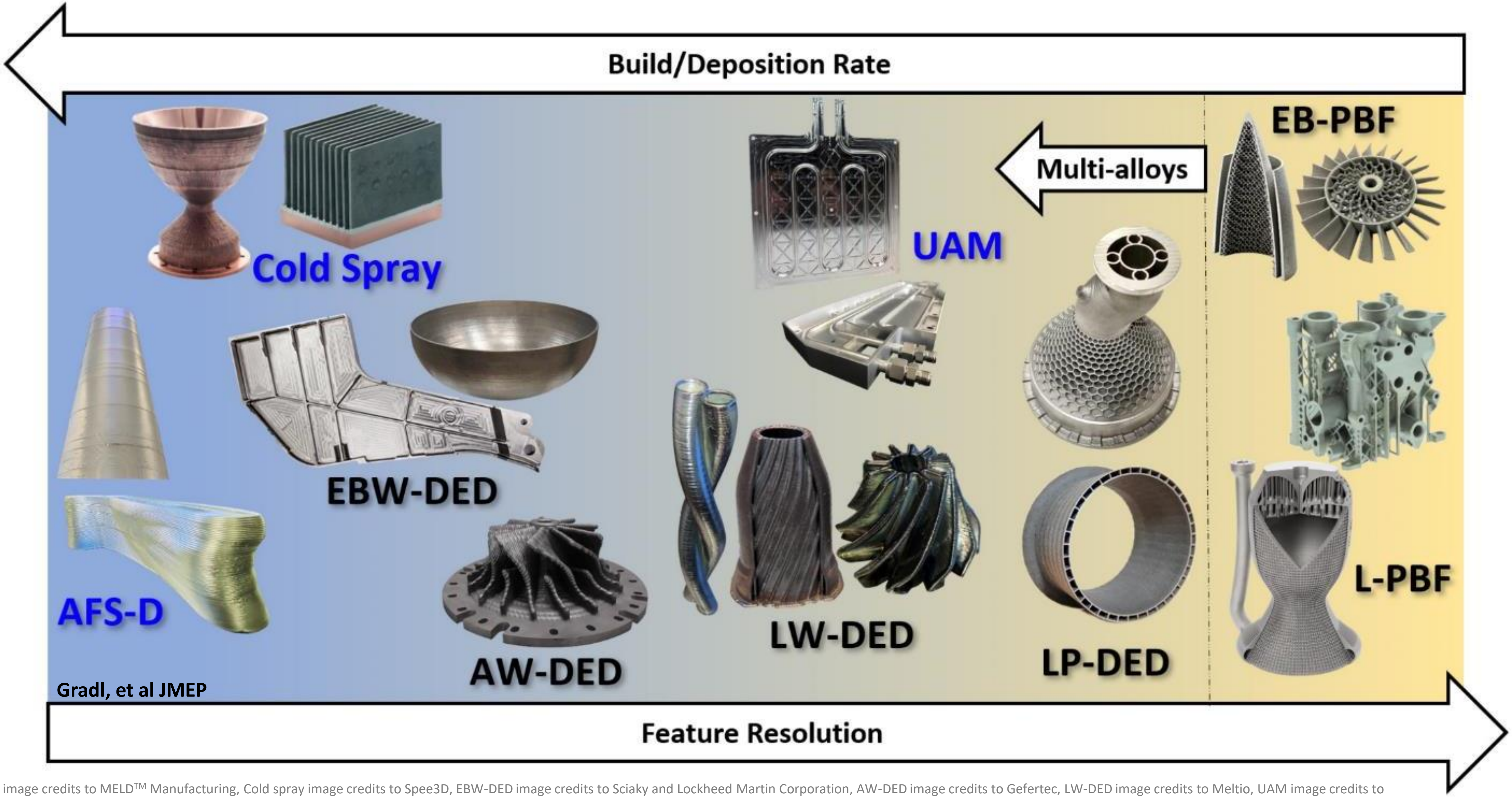
Methodical AM Process Selection



- 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?

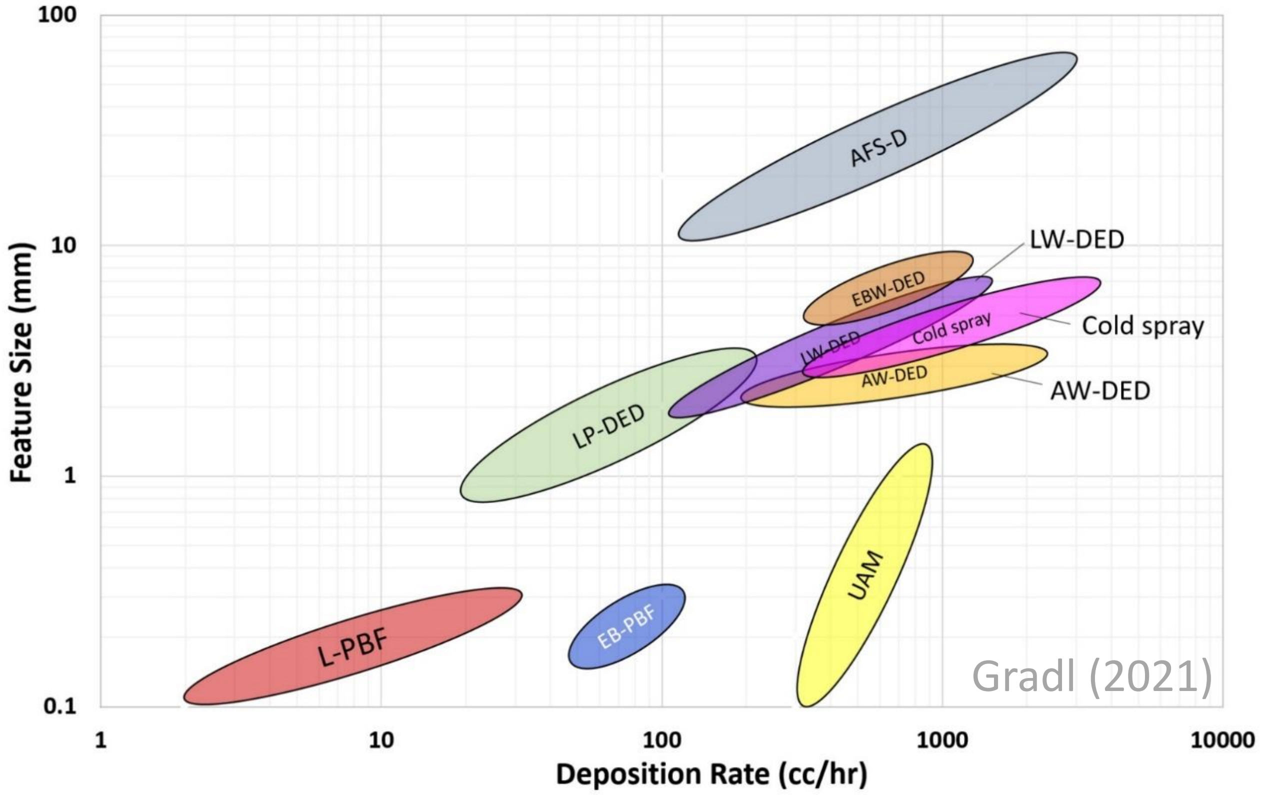
Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Release)

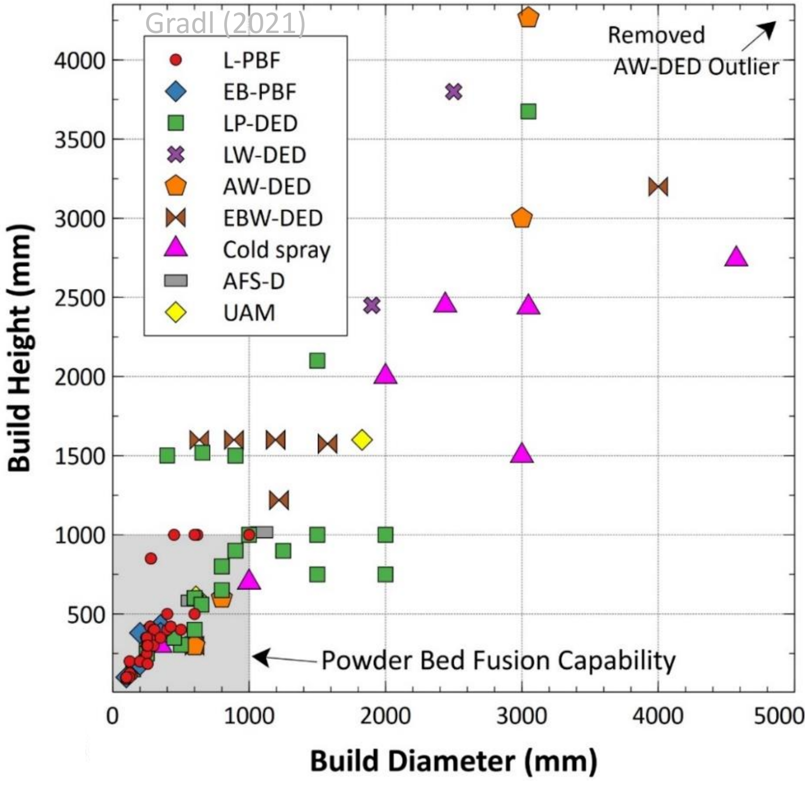
Criteria and Comparison Various Metal AM Processes



CREDITS: AFS-D image credits to MELD™ Manufacturing, Cold spray image credits to Spee3D, EBW-DED image credits to Sciaky and Lockheed Martin Corporation, AW-DED image credits to Gefertec, LW-DED image credits to Meltio, UAM image credits to Fabrisonic and NASA JPL, LP-DED image credits to DEPOZ project led by IRT Saint-Exupery and Formalloy, L-PBF image credits to Renishaw plc and CellCore GmbH/Sol Solutions Group AG, EB-PBF image credits to Wayland and GE Additive/Arcam.

Various criteria for selecting AM techniques





Complexity of Features

Scale of Hardware

Material Physics

Cost

Material Efficiency

Speed of Process

Material Properties

Internal Geometry

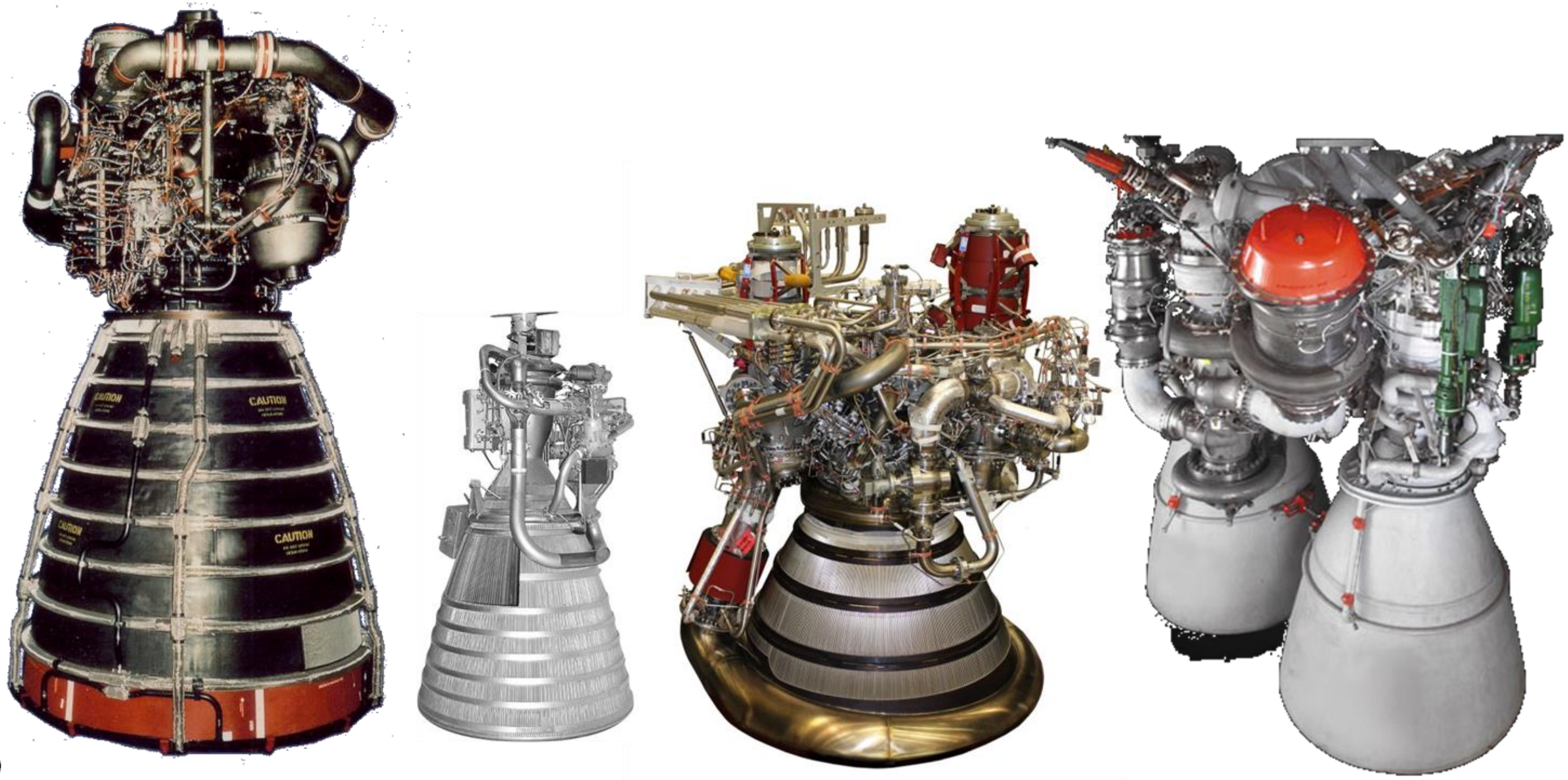
Availability

Post Processing

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

Large Scale Additive Manufacturing for Nozzles

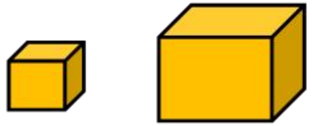
SSME/RS-25 | **RL-10A-4** | **J-2X, Regen Only** | **RD-180**



90″ | 46″ | 70″ | 56″

Nozzle Exit Dia.

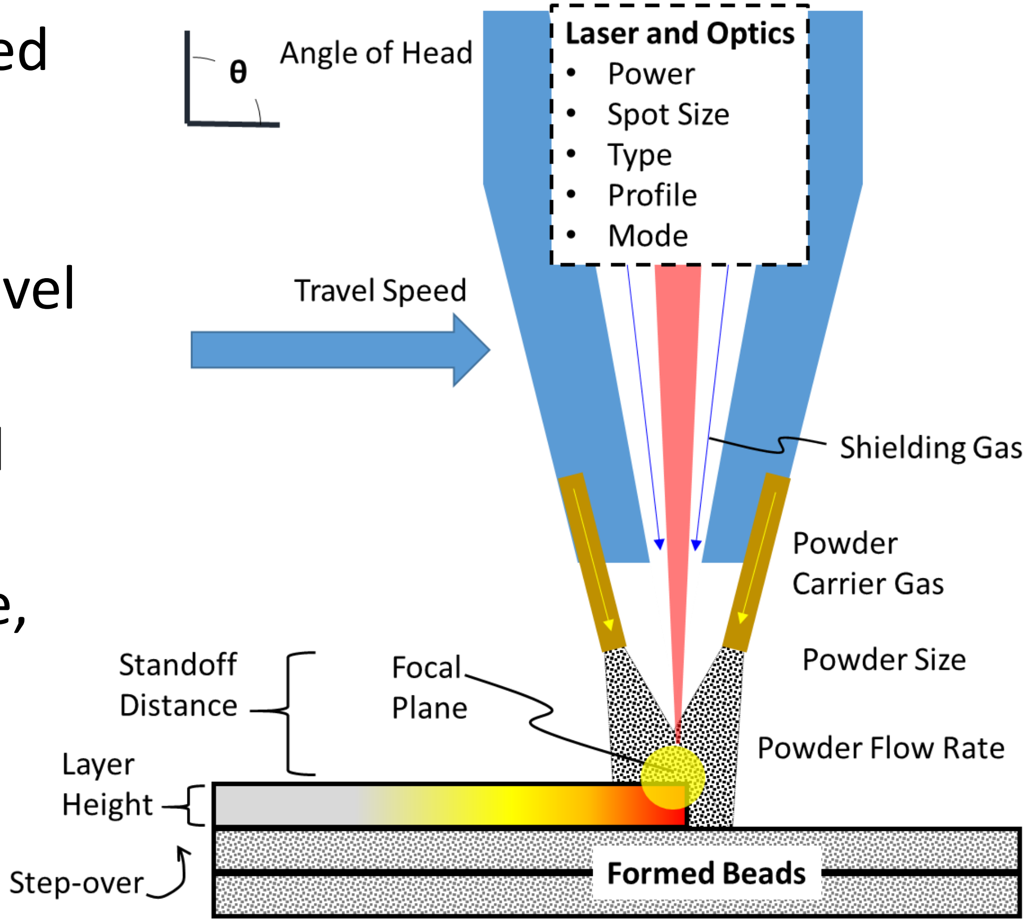
L-PBF Build Boxes



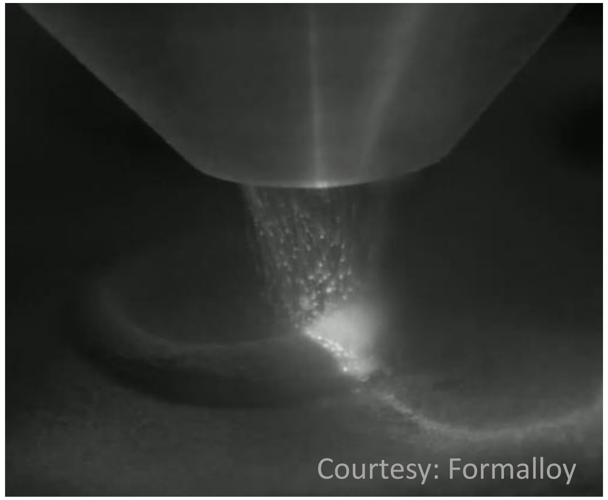
10x10x10 15.5x24x19
(inches)

LP-DED Process Overview

- 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

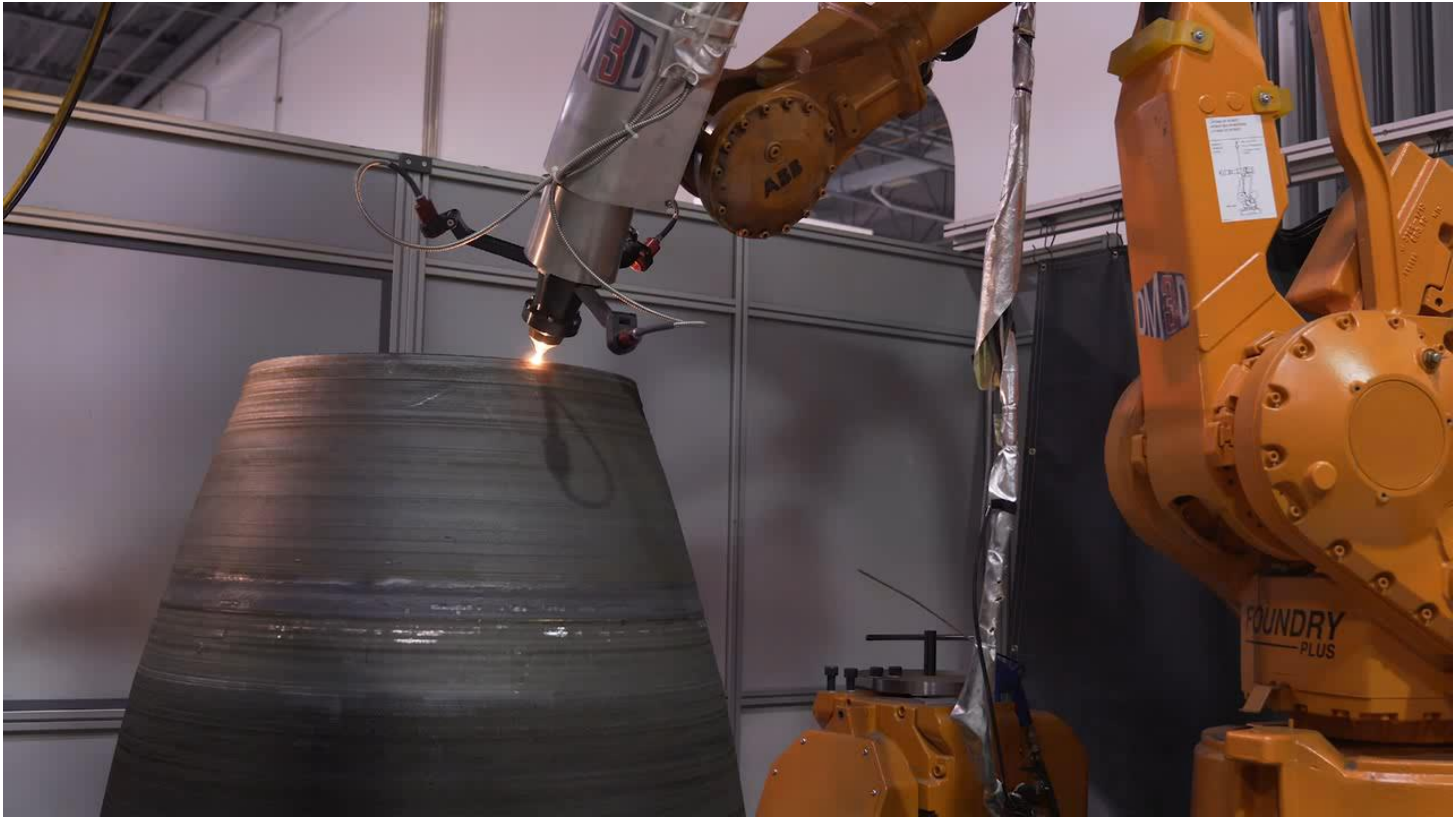


AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl , Protz, Mireles, Garcia (unreleased)

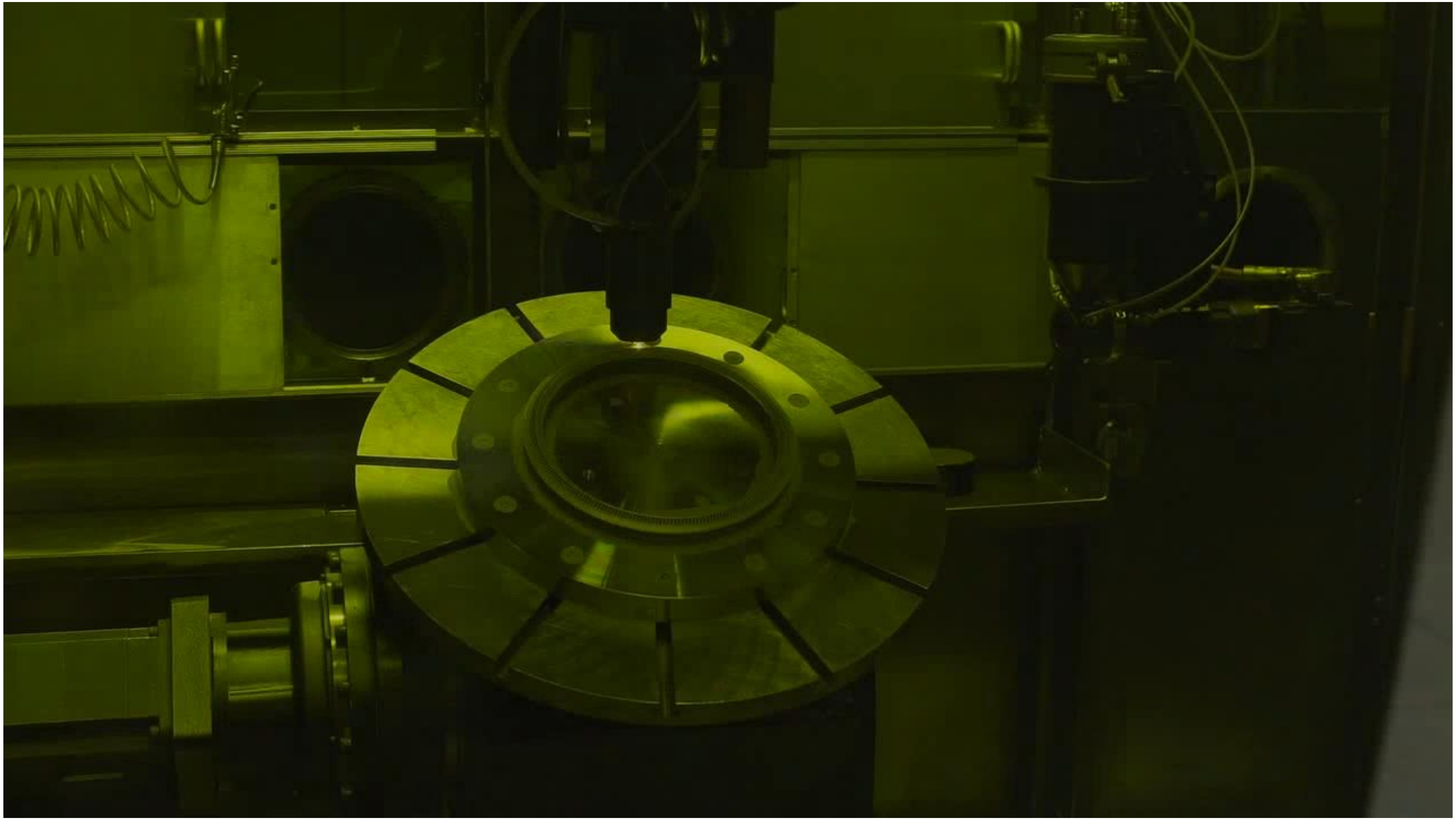


- Gradl, P. R., & Protz, C. S. (2020). Technology advancements for channel wall nozzle manufacturing in liquid rocket engines. *Acta Astronautica*. https://doi.org/10.1016/j.actaastro.2020.04.067
- AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl et al (unreleased)

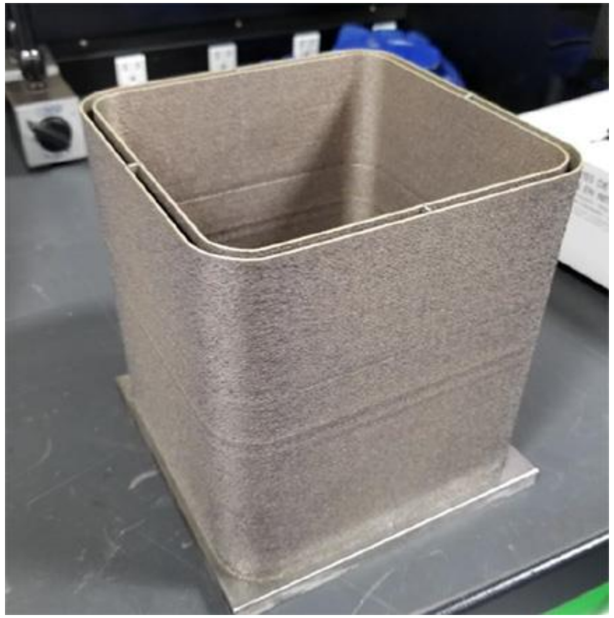
Laser Powder Directed Energy Deposition (DED)

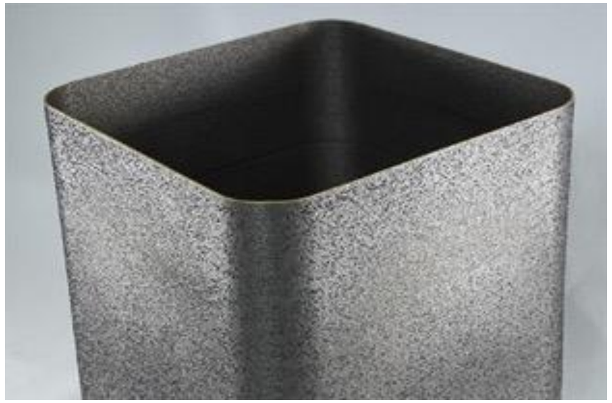


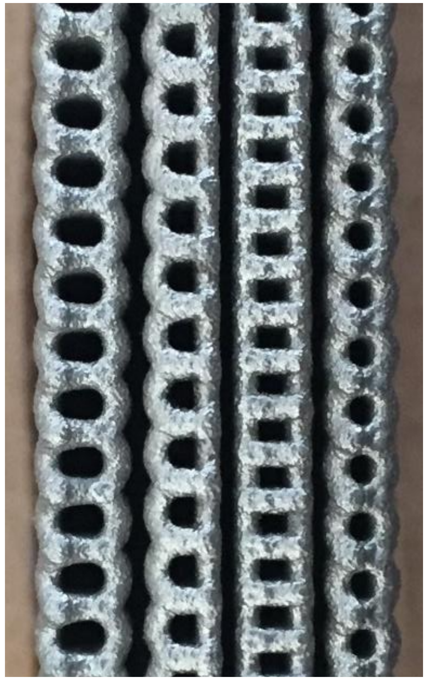
Example of LP-DED with small features



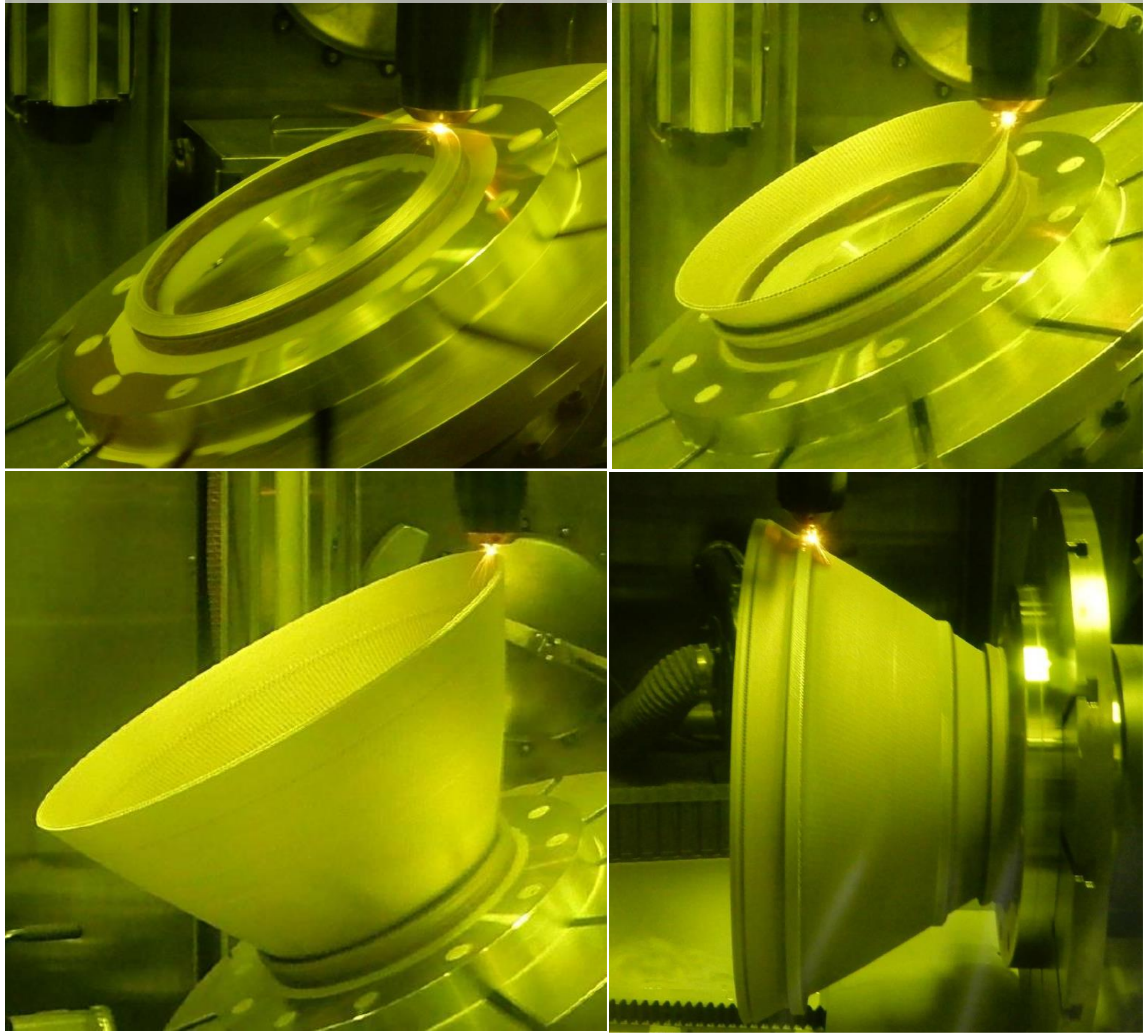
Large-scale Thin Wall Deposition of Nozzles







Process Development for DED of nozzles



LP-DED Large Scale Nozzle Development

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

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

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

EXPLORE MOON to MARS

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

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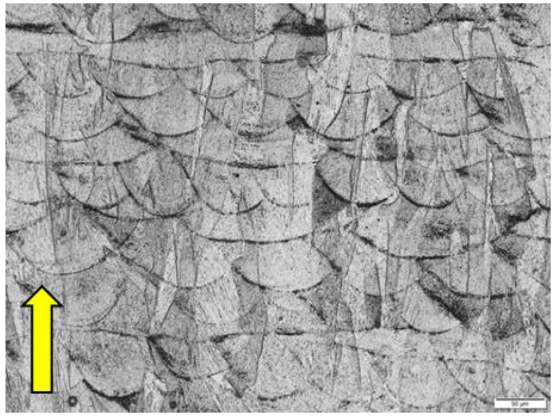
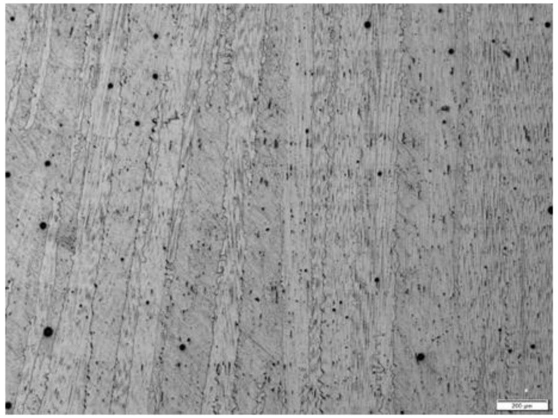
Microstructure of Various AM Processes
Alloy 625 – As-Built

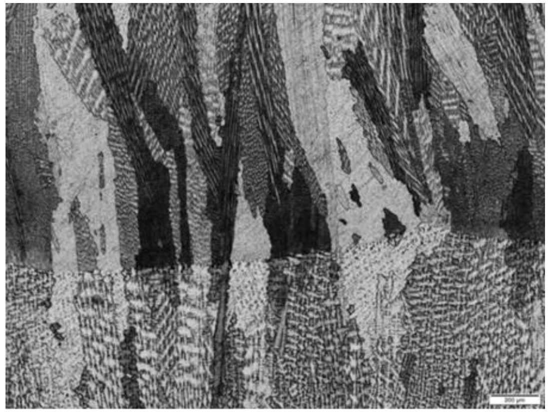


Laser Powder Bed Fusion

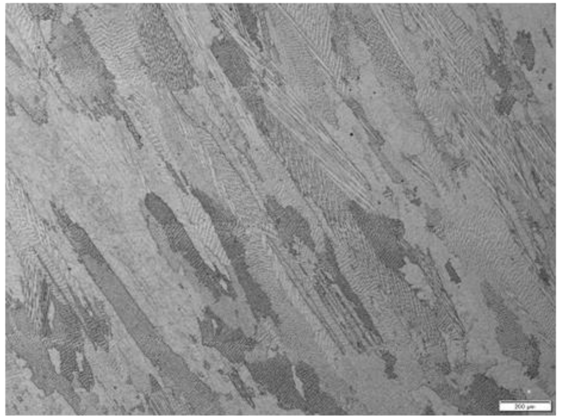


Electron Beam Powder Bed Fusion

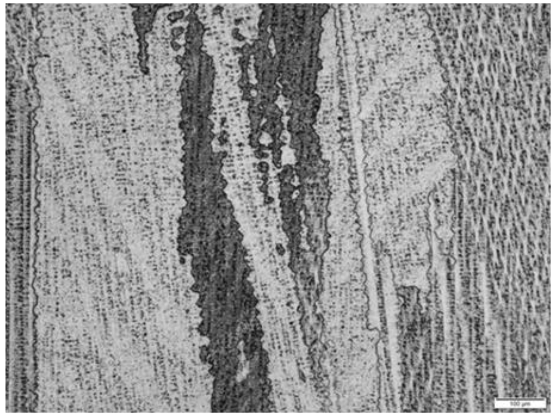
Laser Powder DED (1070 W)



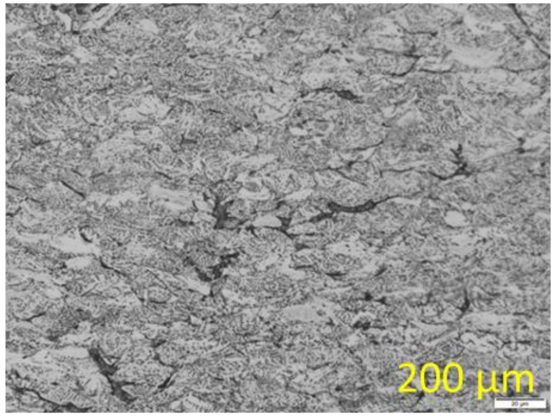
Electron Beam Wire DED



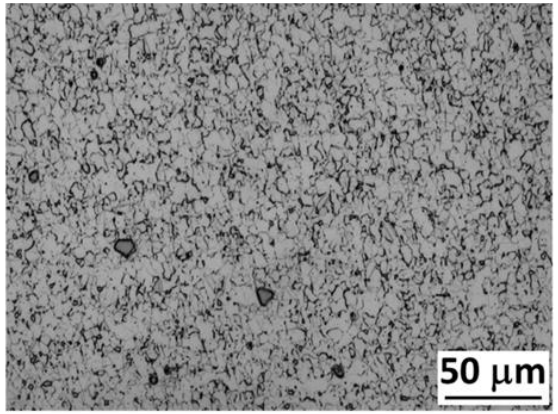
Laser Wire DED



Arc Wire DED



Cold Spray



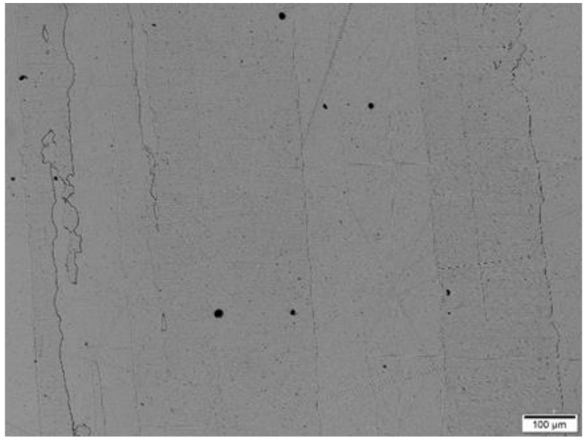
Additive Friction Stir Deposition

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

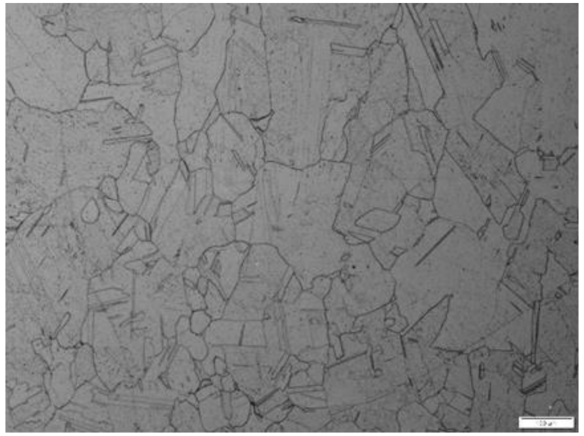
- Gamon, A., Arrieta, E., Gradl, P.R., Katsarelis, C., Murr, L.E., Wicker, R.B., Medina, F., 2021. Microstructure and hardness comparison of as-built Inconel 625 alloy following various additive manufacturing processes. Results in Materials 12. https://doi.org/10.1016/j.rinma.2021.100239
- Gradl, P.,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

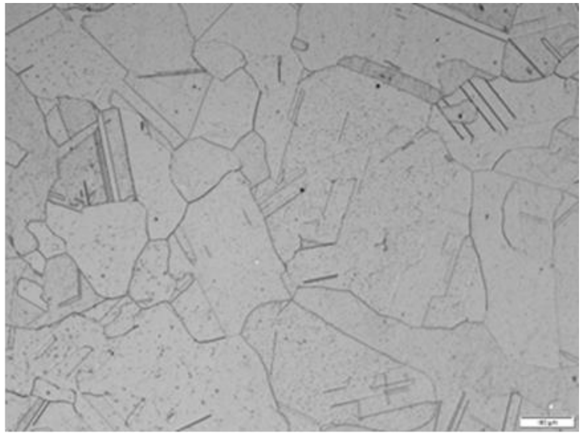
Laser Powder Bed Fusion



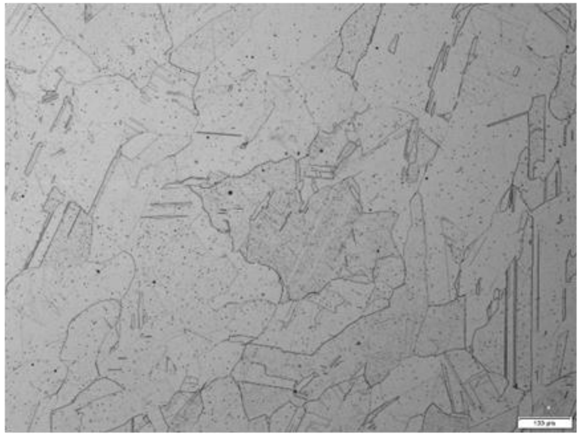
Electron Beam PBF



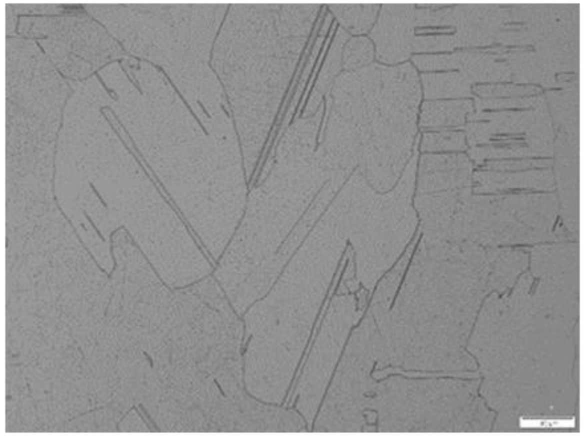
Laser Powder DED (1070 W)



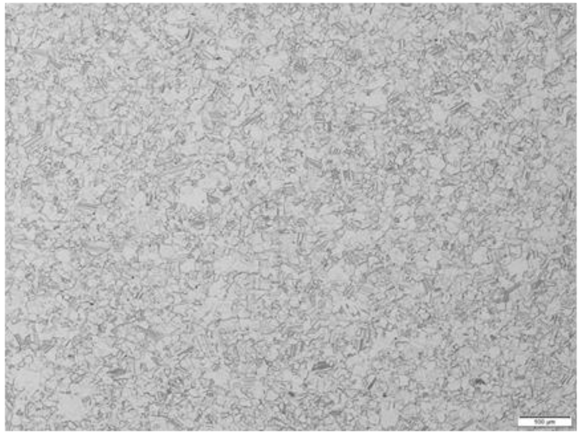
Electron Beam Wire DED



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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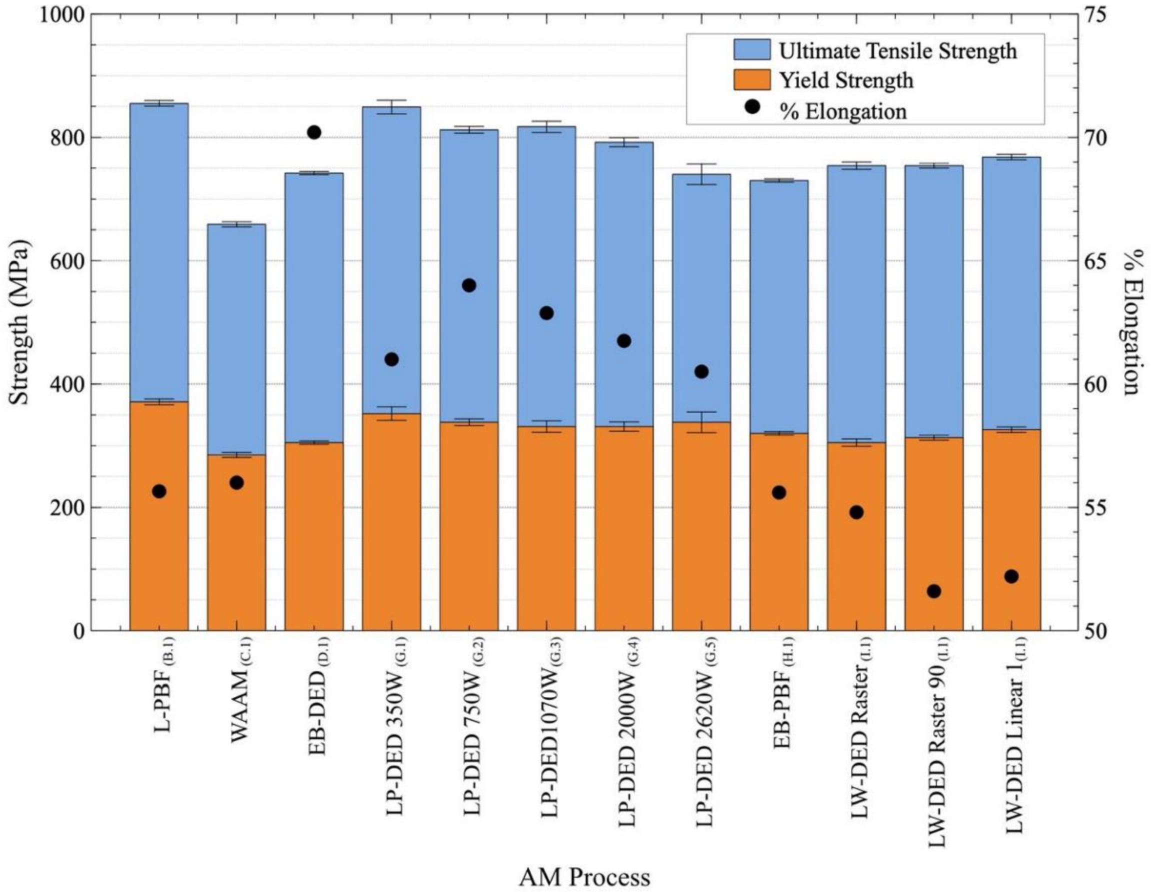
Material Properties for Various AM Processes

- 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**

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

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

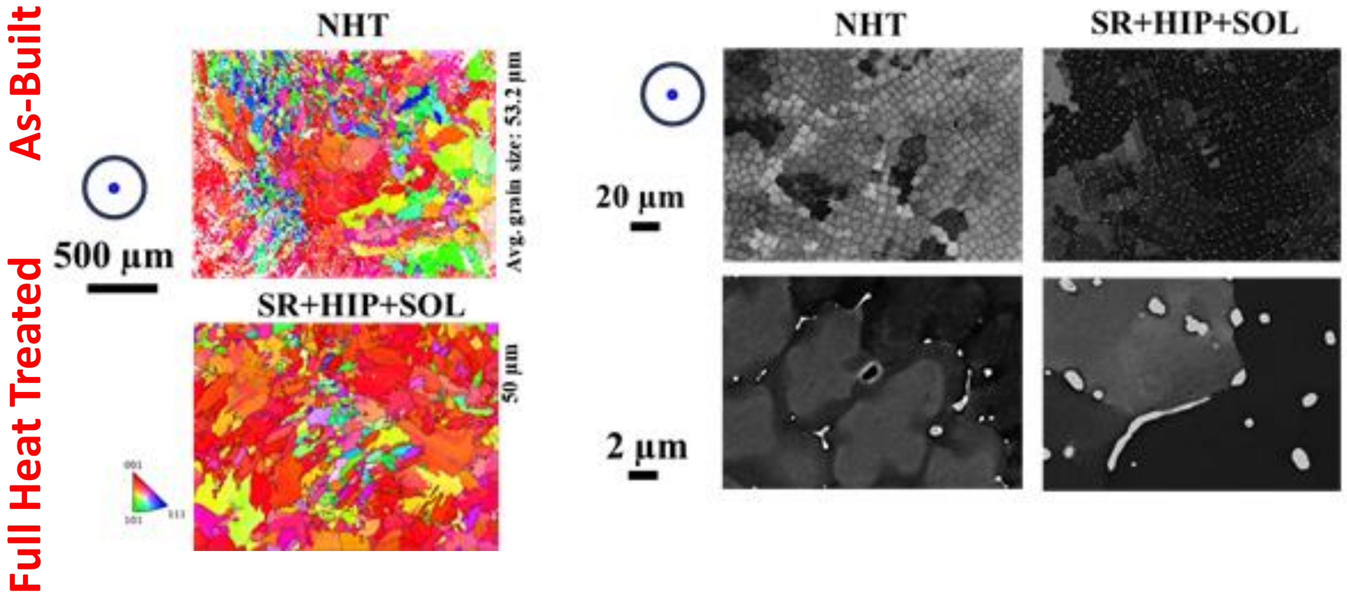
Material	Process
Monel K500	LP-DED
Monel K500	L-PBF
GRCop-42	L-PBF
GRCop-42	LP-DED
GRCop-84	L-PBF
C-18150	L-PBF
Ti6Al-4V	L-PBF
Ti6Al-4V	LP-DED
Ti6Al-4V	LW-DED
Ti6Al-4V	EBW-DED
Ti6242	L-PBF
Ti6242	LP-DED
GRX-810	L-PBF
GRX-810	LP-DED
Haynes 214-ODS	L-PBF
C-103	LP-DED

55+ Alloys in characterization

Data example of Haynes 230 LP-DED

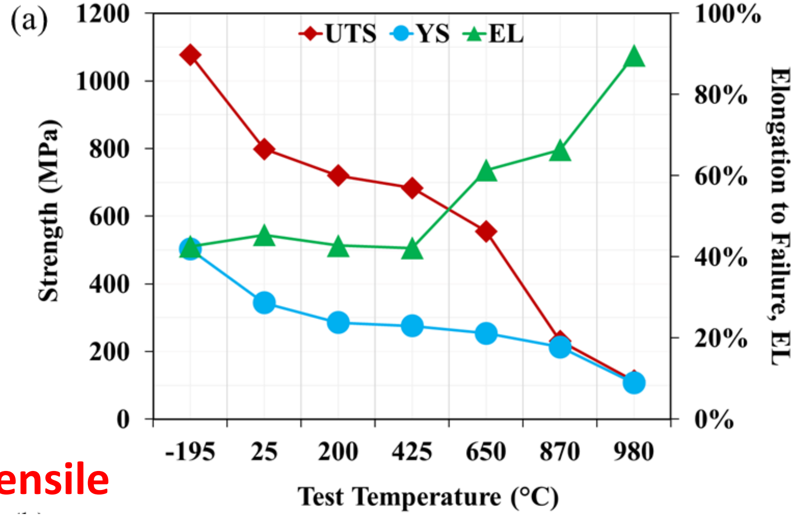
Power (W)	Layer height (µm)	Travel speed (mm/min)	Powder feed rate (g/min)
1070	381	1016	19.10

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

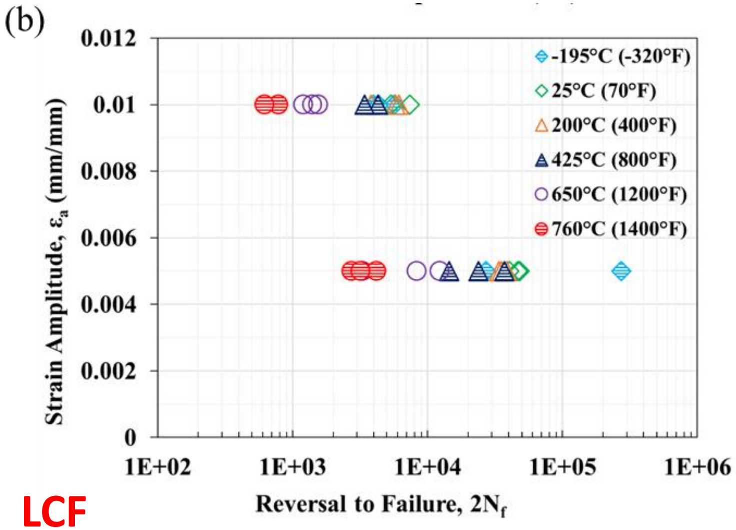


[2] HIP per ASTM F3301

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



Tensile



LCF

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**


GRCop-42 L-PBF

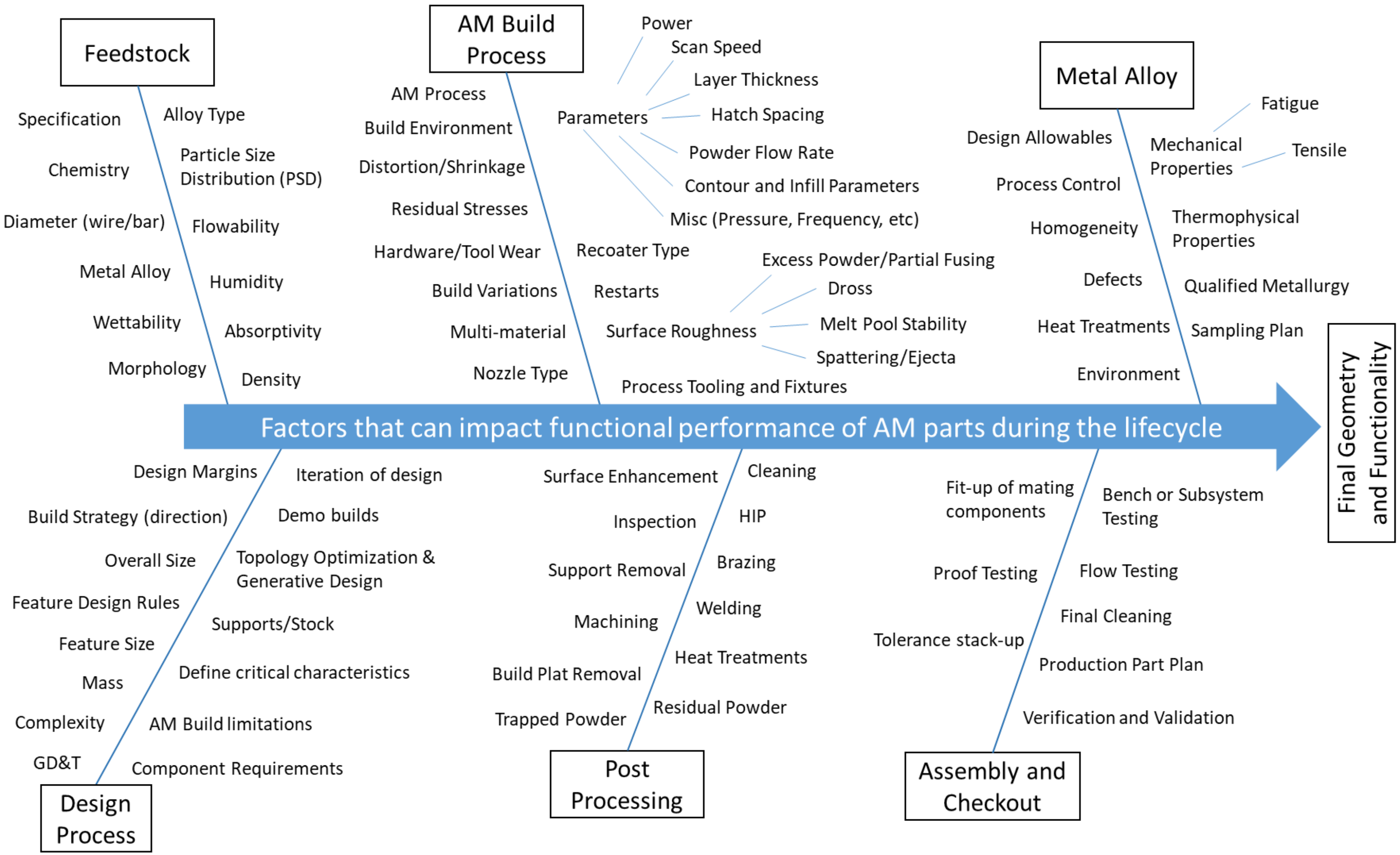

NASA HR-1 LP-DED


GRX-810 L-PBF


C103 L-PBF

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

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

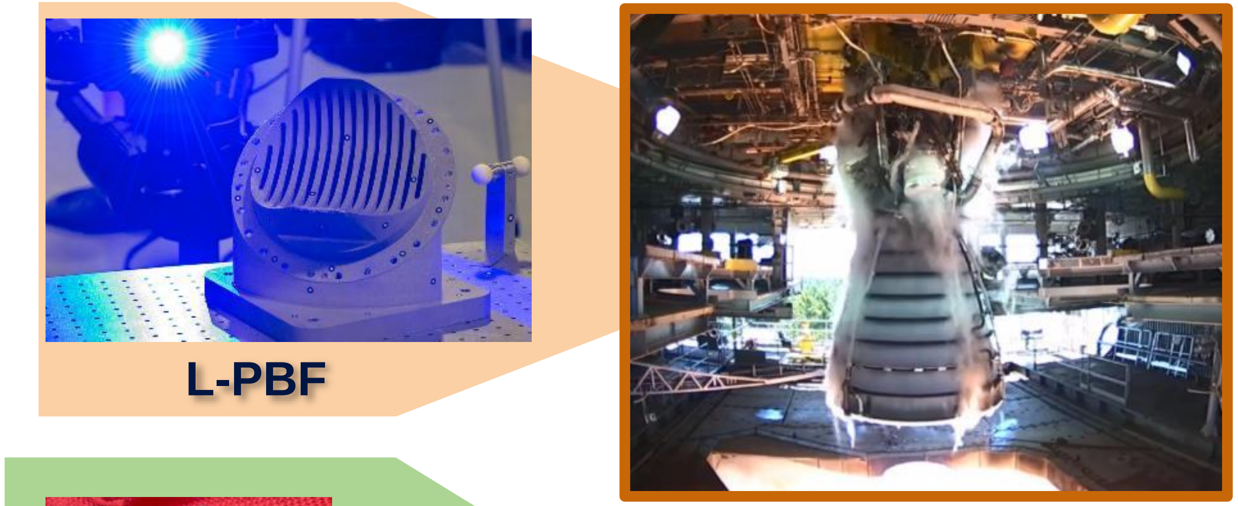
LP-DED Jacket

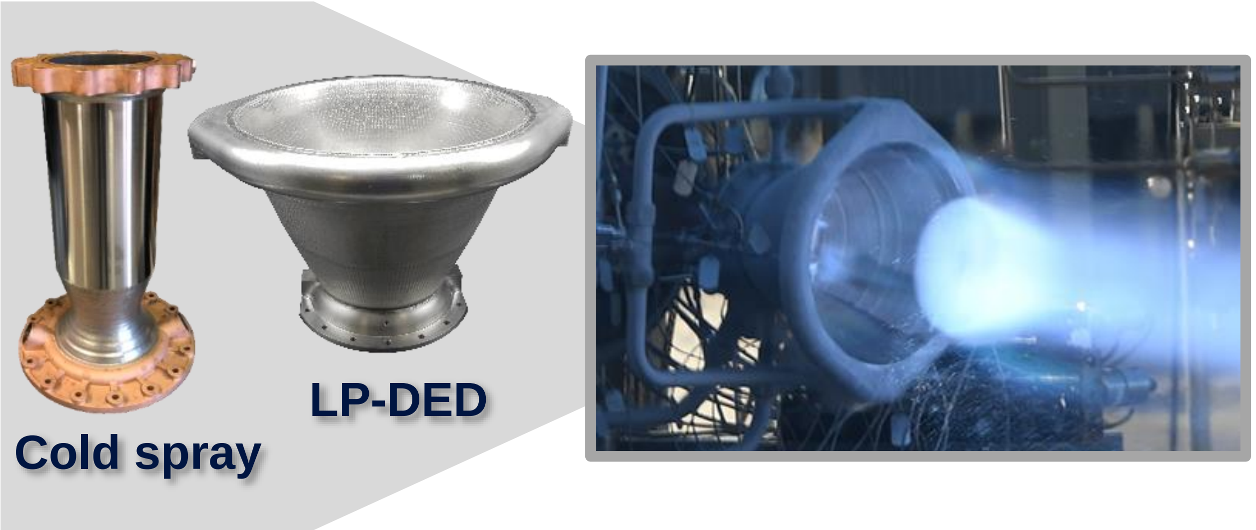
Cold spray Jacket

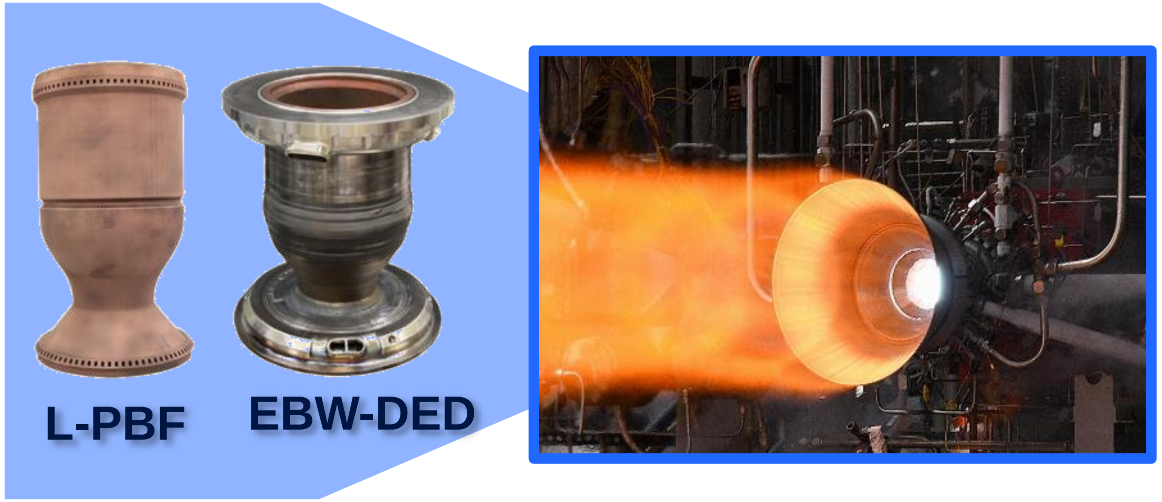
Direct deposit LP-DED nozzle
(Axial Bimetallic)

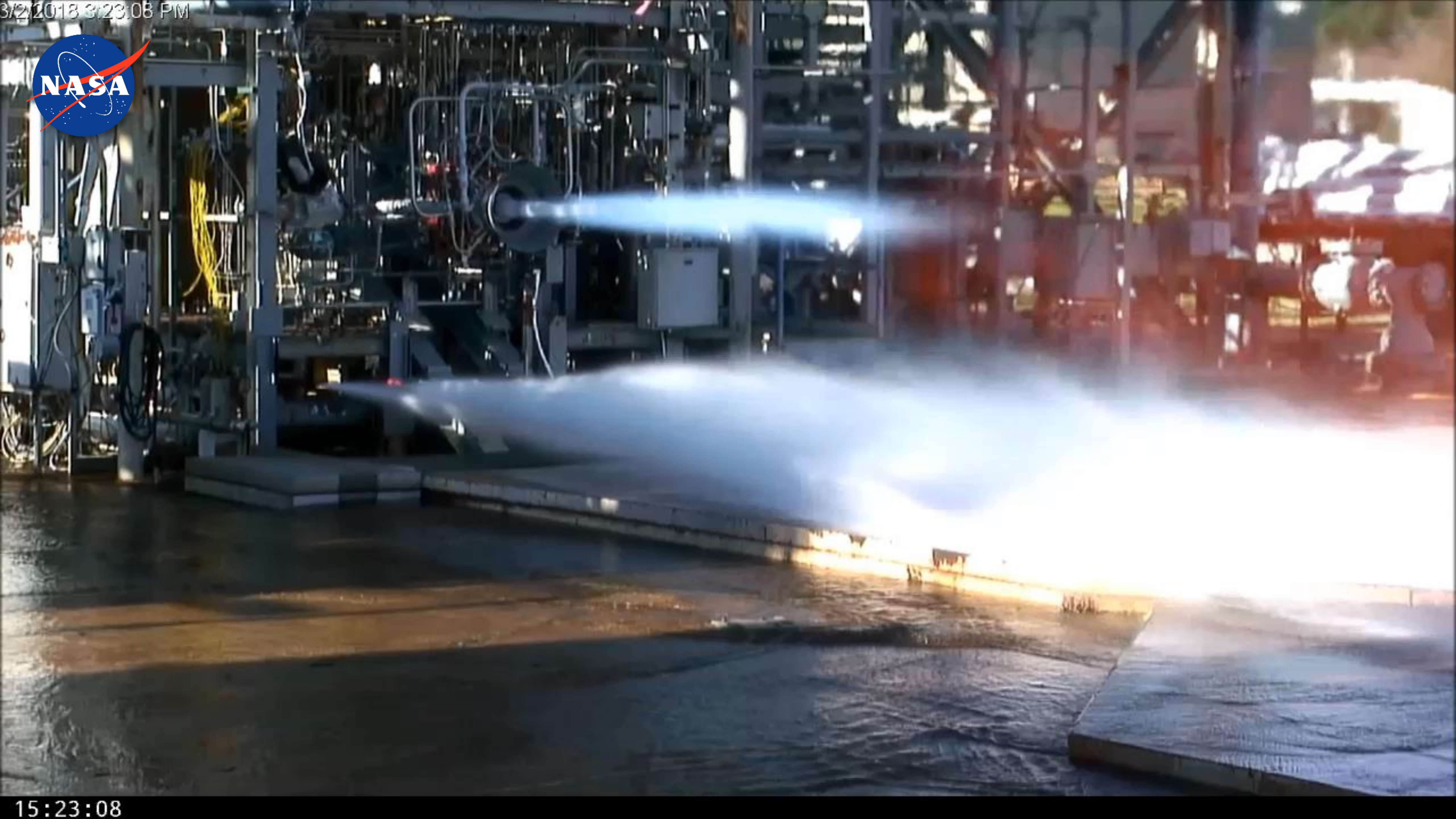
EBW-DED Jacket

Industrial Maturity and TRL of AM Processes





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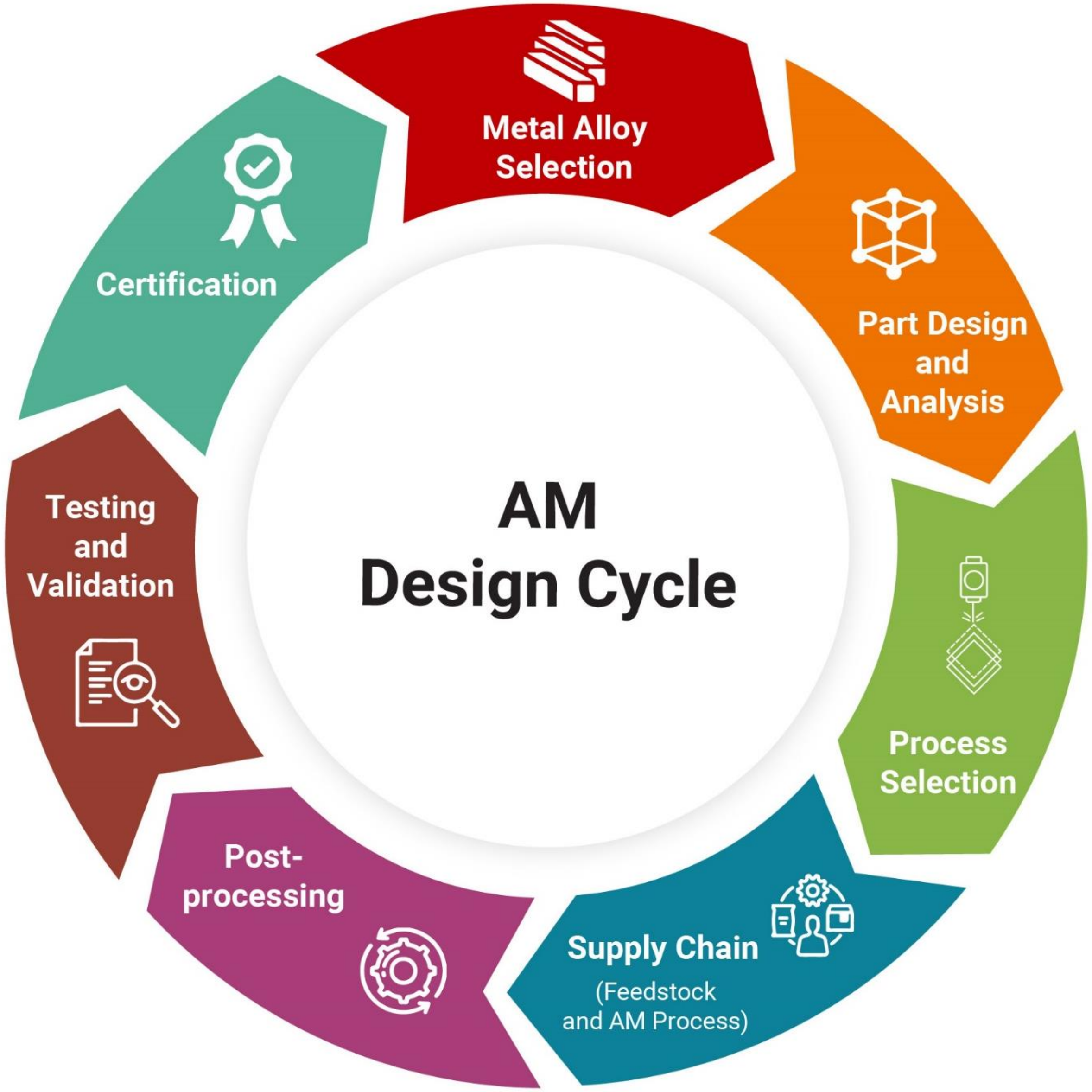
Design for Additive Manufacturing (DfAM)

AM Design Cycle



DfAM – Coordinates & Overhang Surfaces

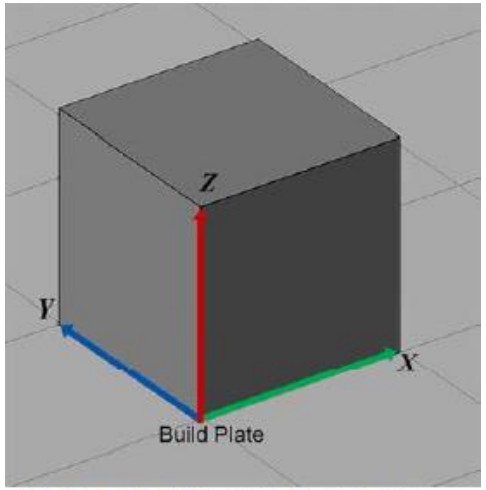


Fig. 7.1 AM reference coordinate system.

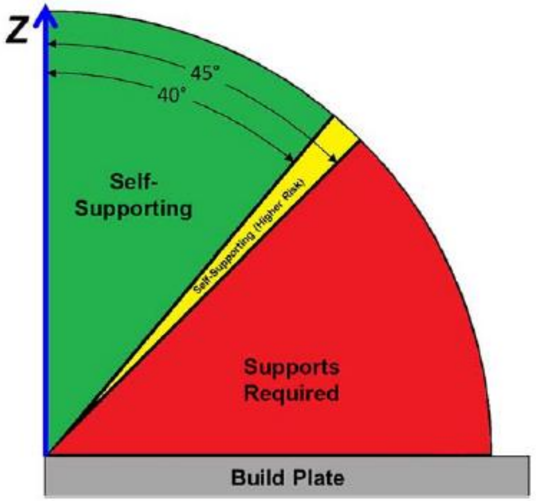


Fig. 7.14 Example of overhang surfaces in reference to the build plate and build direction (*Z*).

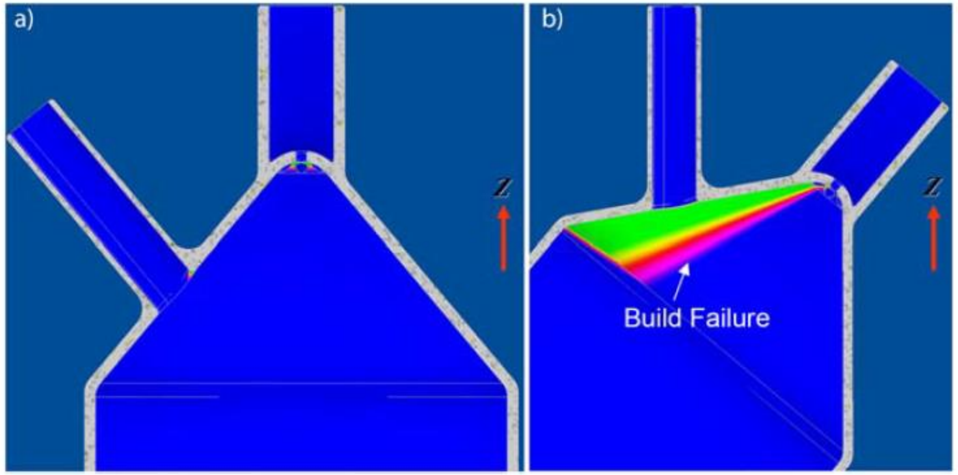
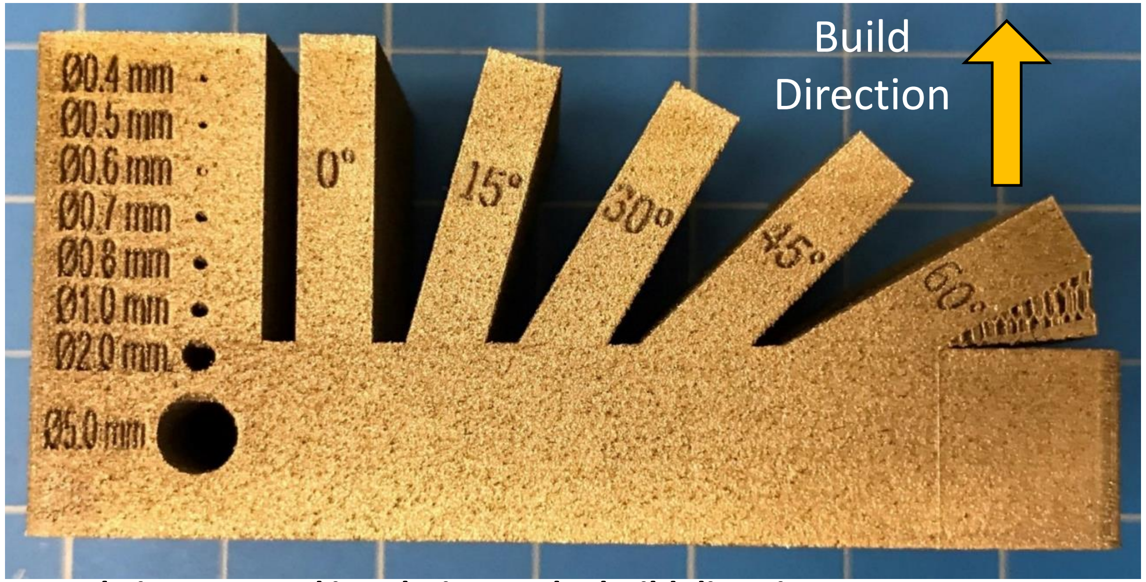


Fig. 7.16 Unsupported overhang surfaces vs. build direction. a) No unsupported surfaces. b) Unsupported surfaces.



Angle is measured in relation to the build direction, *Z*

DfAM – Sacrificial Volumes

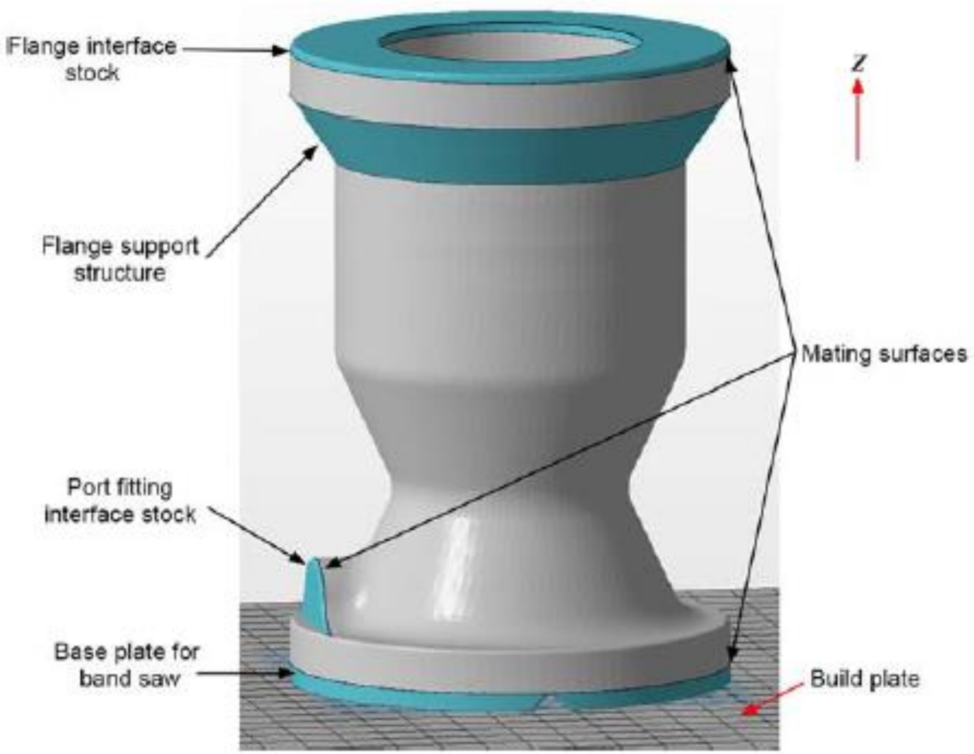


Fig. 7.11 Chamber design for L-PBF AM with sacrificial stock material added (turquoise regions).

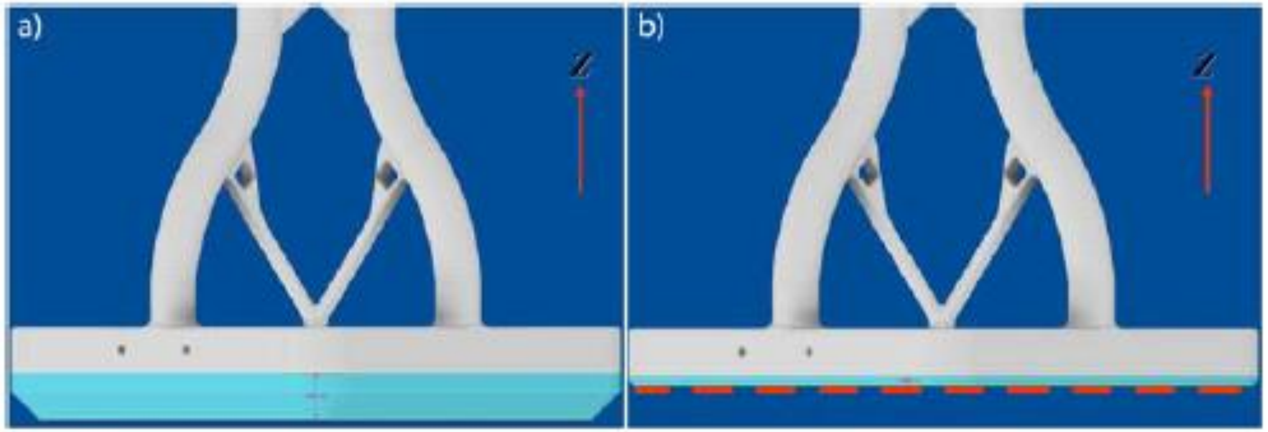


Fig. 7.13 Base-plate thickness vs. removal method for a) vertical band saw [5 mm (0.196 in.)] and b) wire-EDM [1 mm (0.039 in.)].

DfAM – Holes & Drain Ports

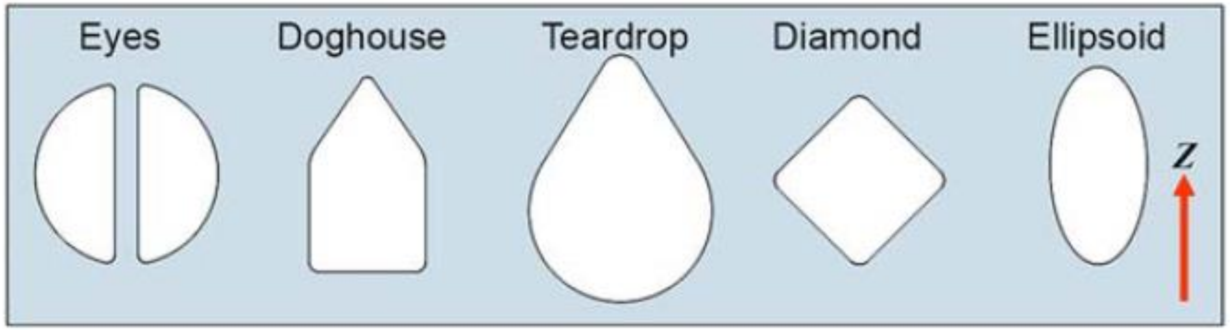


Fig. 7.18 Build failure observed at the tops of Ti6Al4V L-PBF holes oriented perpendicular to the build direction.

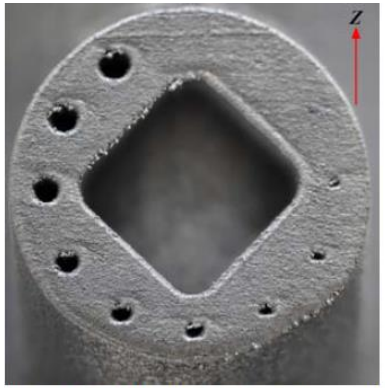


Fig. 7.20 Hole shape vs size, diamond slot, and surface roughness vs angle in L-PBF – built AlSi10Mg.

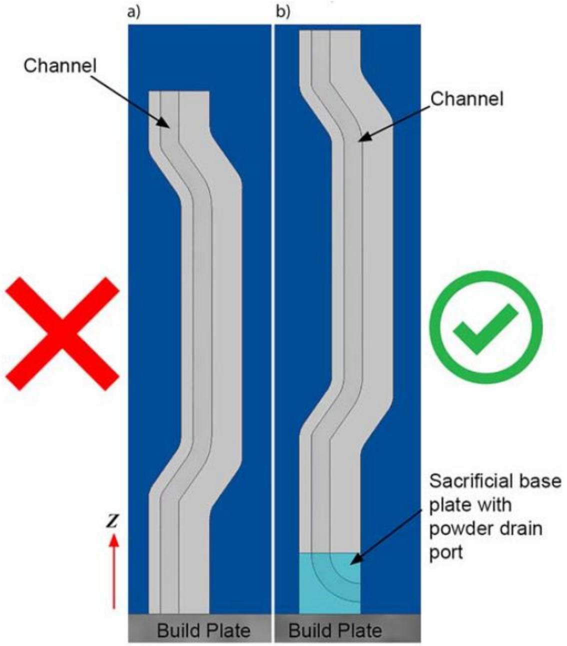


Fig. 7.26 a) Channel terminating at the build plate and b) base plate with powder drain port.

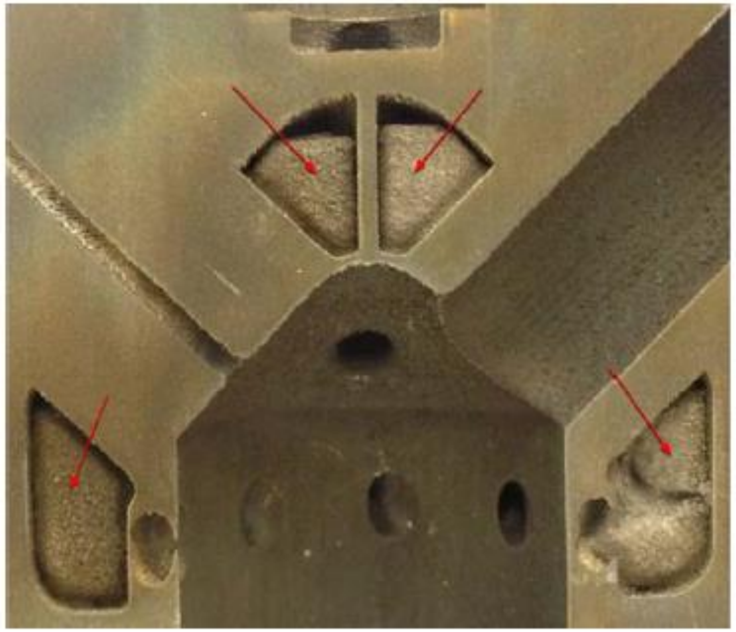


Fig. 5.5 Cross-sectional cut of a part with trapped powder that sintered during stress-relief heat treatment. (Source: NASA.)

DfAM – Orientation and Placement

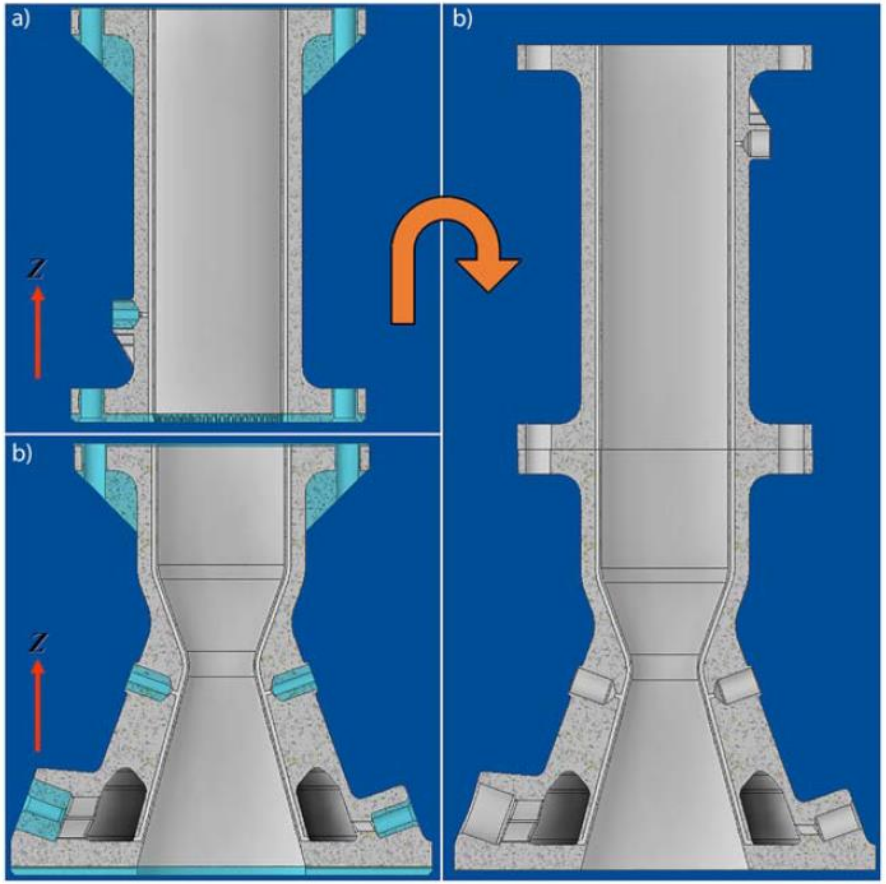


Fig. 7.29 a-b) Each L-PBF part orientation for optimized build. c) Assembly of parts.

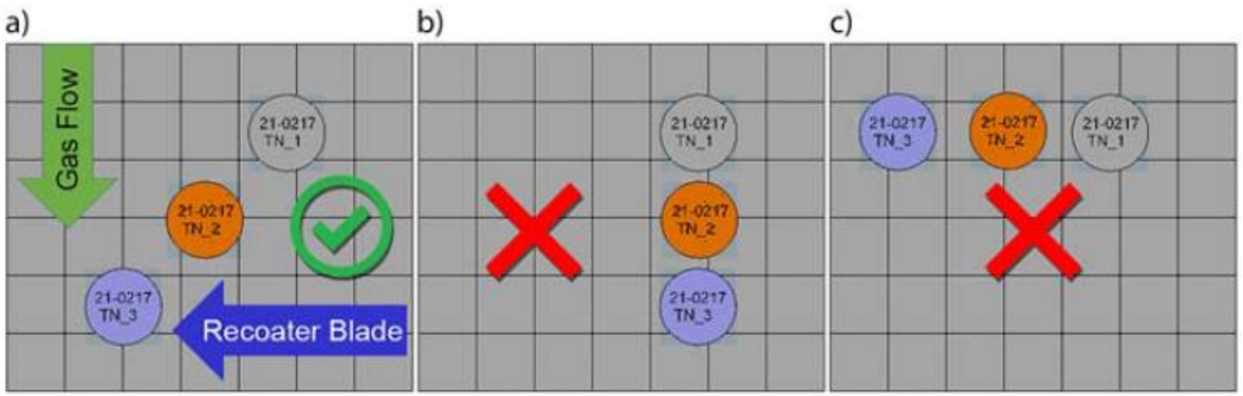


Fig. 7.31 Specimen placement relative to recoater and gas directions.

DfAM – Supports

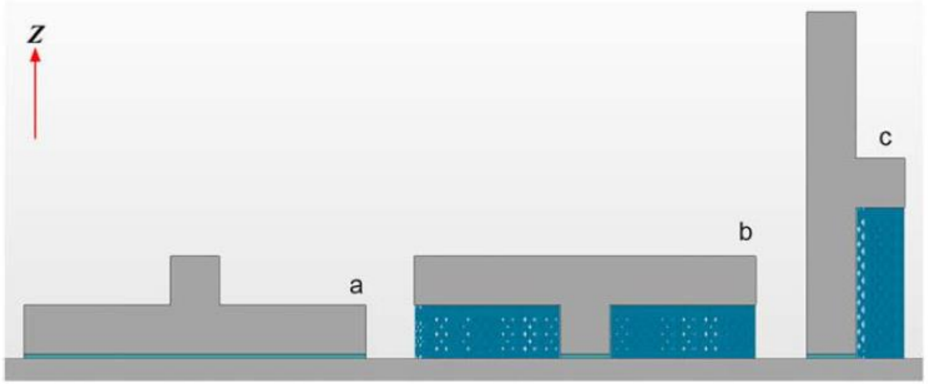


Fig. 7.22 Placement and volume of support structures (blue regions) are highly dependent on part orientation.

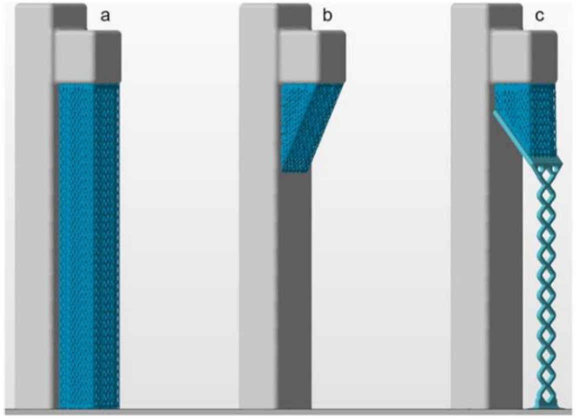


Fig. 7.23 Perforated block supports: a) full length, b) 30° angle, and c) projected onto a user-designed support scaffold.

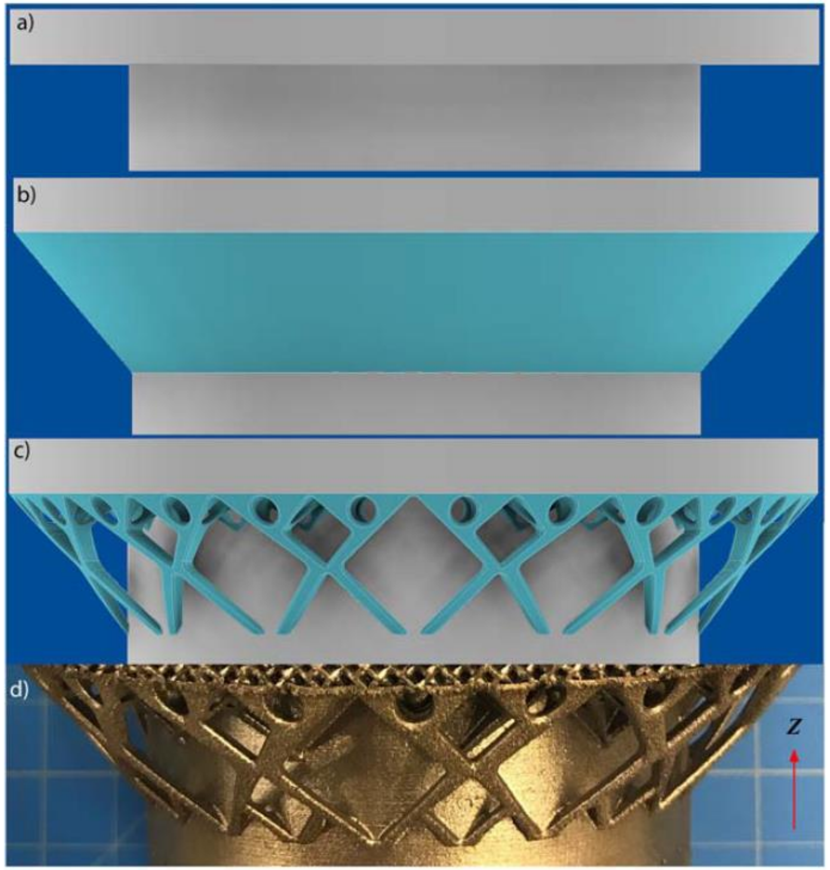


Fig. 7.25 Comparison of a) unsupported overhang flange, b) 40° sacrificial support, c) crown support, and d) Inconel 718 crown support made by L-PBF.

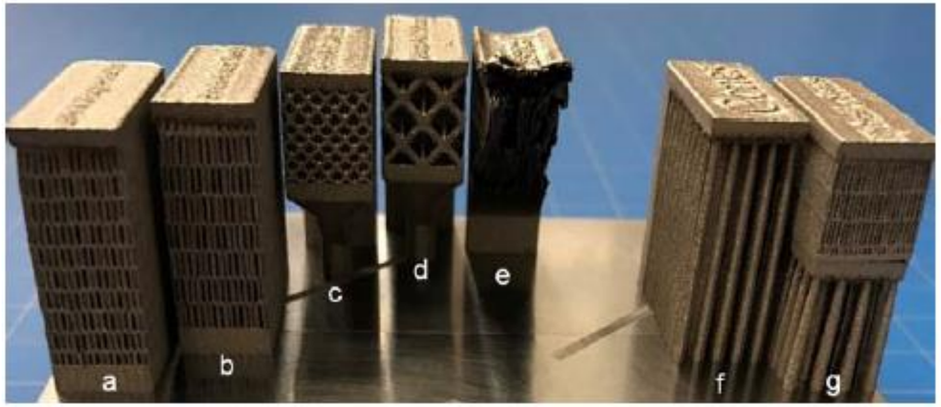


Fig. 5.12 L-PBF support examples. (Source: NASA.)

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

DfAM – Case Study

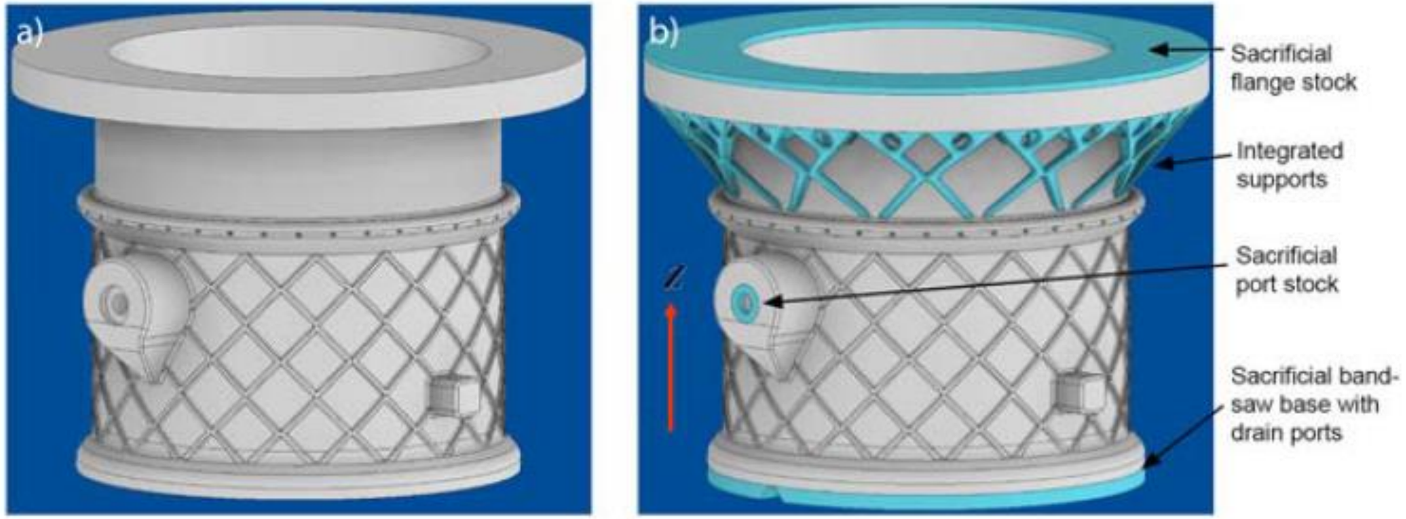


Fig. 7.28 Part a) in final machined condition and b) integrated supports, stock added to interfaces, and drain ports.

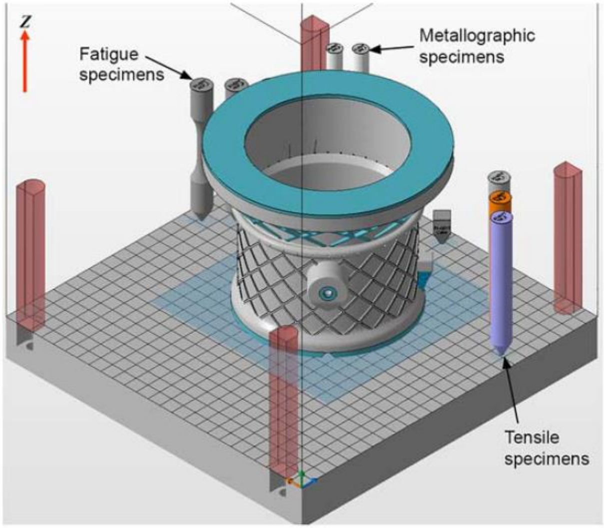


Fig. 7.30 Build layout of a part, support structures, and serialized witness specimens.

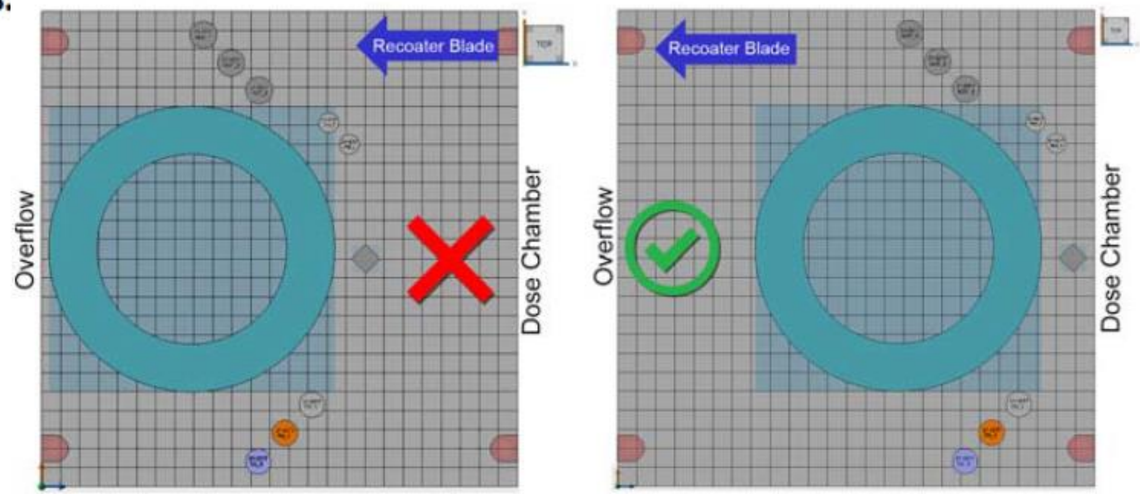


Fig. 7.32 Component placement relative to the dose chamber and recoater blade path.

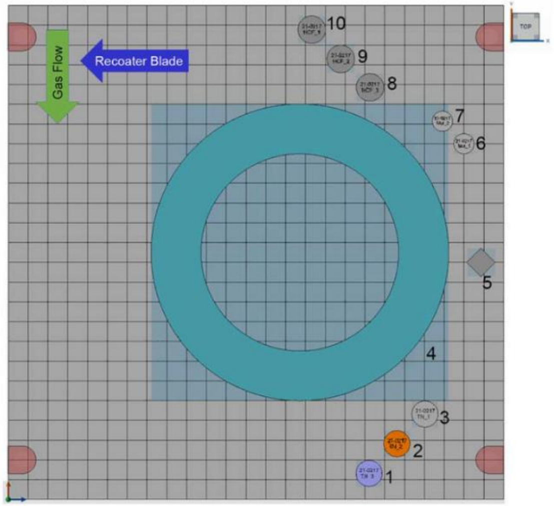
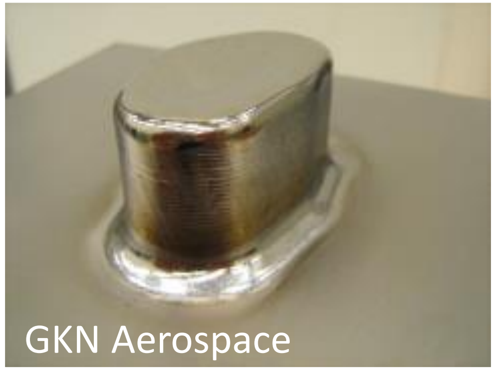
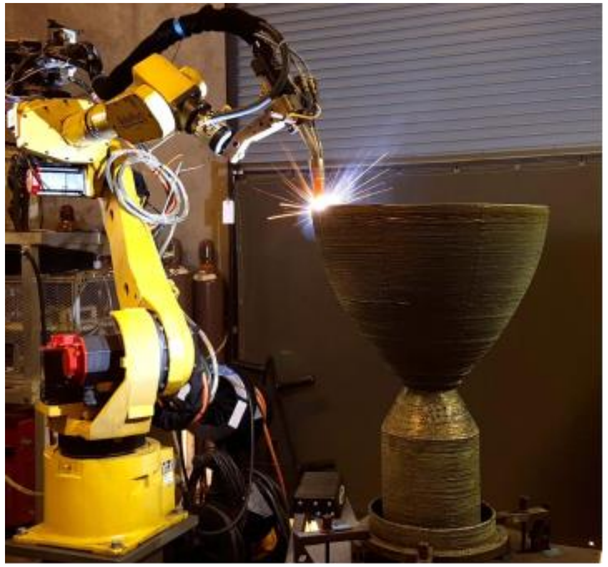


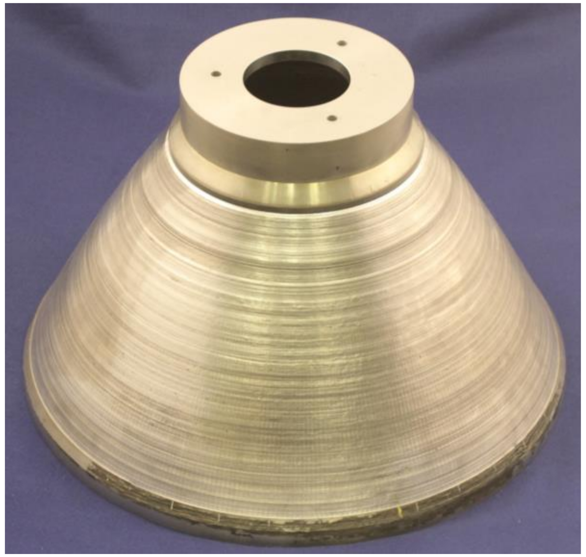
Fig. 7.33 Build layout top view with part positions and scan order optimized for a machine platform with perpendicular gas flow and recoater blade.

Huge Variety of Geometries


GKN Aerospace


DM3D/NASA






DM3D/NASA


RPMI


RPMI/NASA

Design for DED Considerations

Substrate
- Size, Material, Temper
- Integral or Sacrificial?

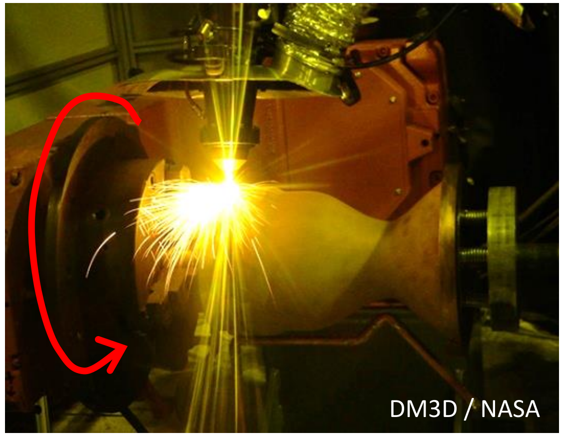
Material
- Chemistry and form
- Material feedstock effect on surface finish

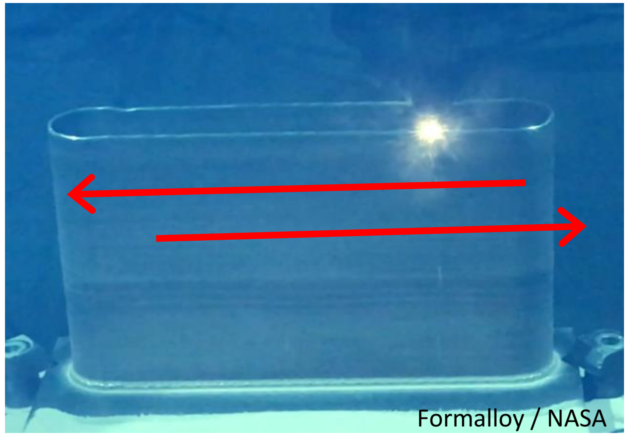
Deposition Strategy and Parameters
- Melt pool size and bead width/height
- Motion platform degrees of freedom and self-supporting angles
- Start / Stop / Transition locations and impact on properties

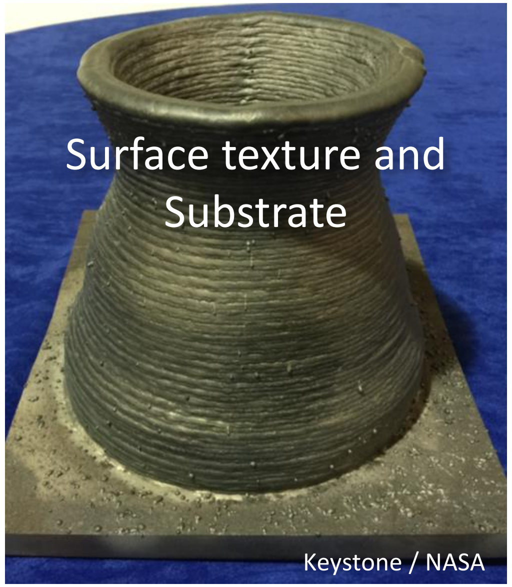
Machining
- Fixturing and datum locations

Inspection
- Surface interface with NDE and/or geometry compatibility

Example: Deposition Strategies


DM3D / NASA

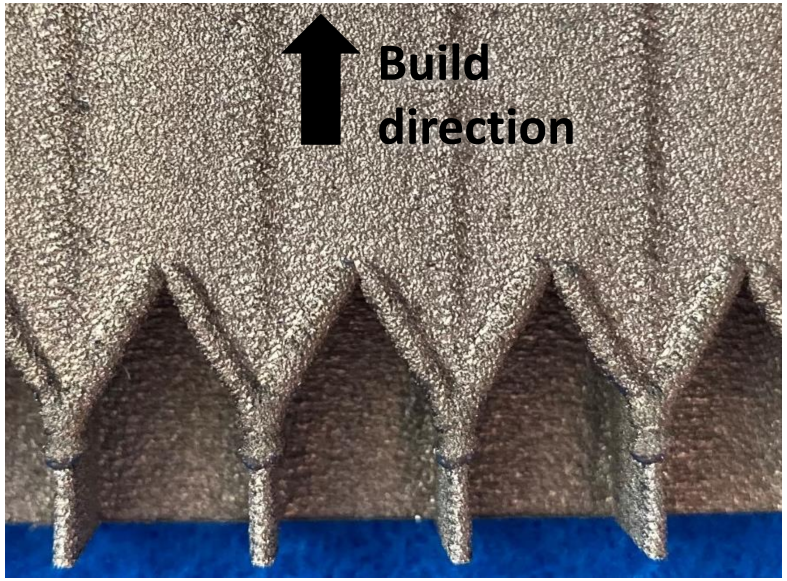

Formalloy / NASA

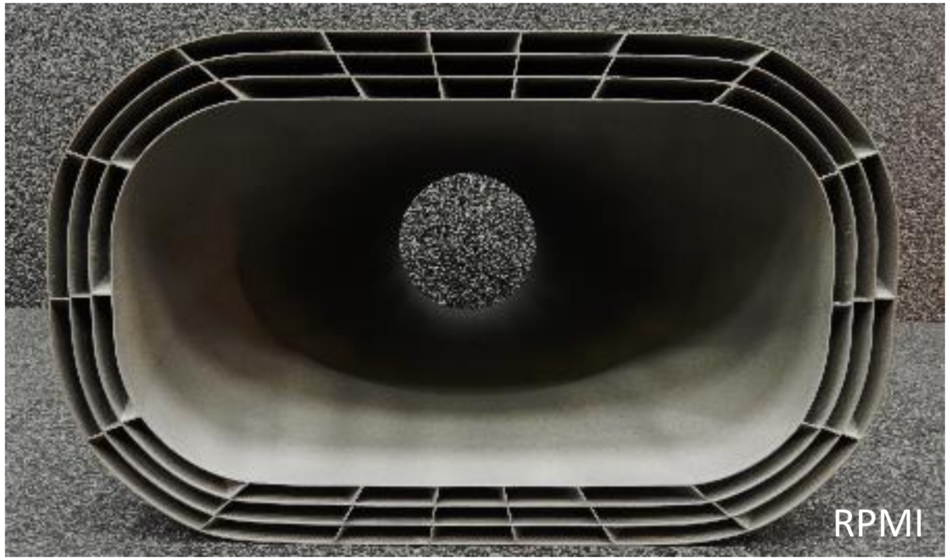


Keystone / NASA

Wall Thicknesses and Geometry Limitations

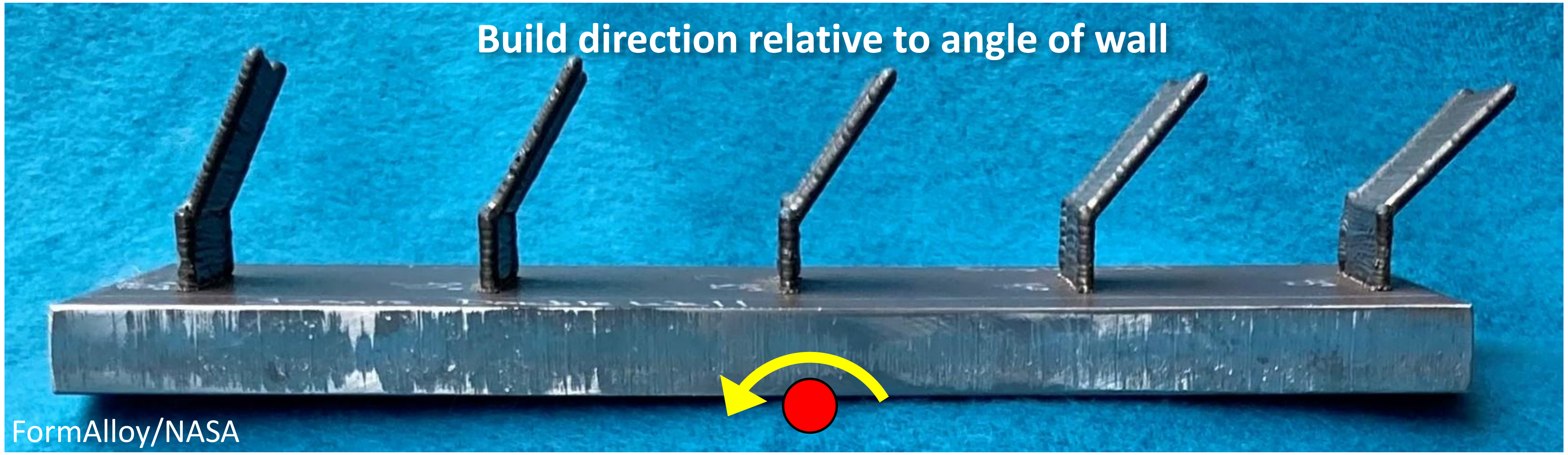
- Wall thicknesses of 1 mm are easily accomplished with LP-DED and LW-DED
- Thinner walls possible, but build angles severely limited and deposition rate reduces significantly
- Internal and complex features are feasible, but within build angle confines
  - Build angles are dependent on the build strategy – 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





Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

Build Angles depend on strategy



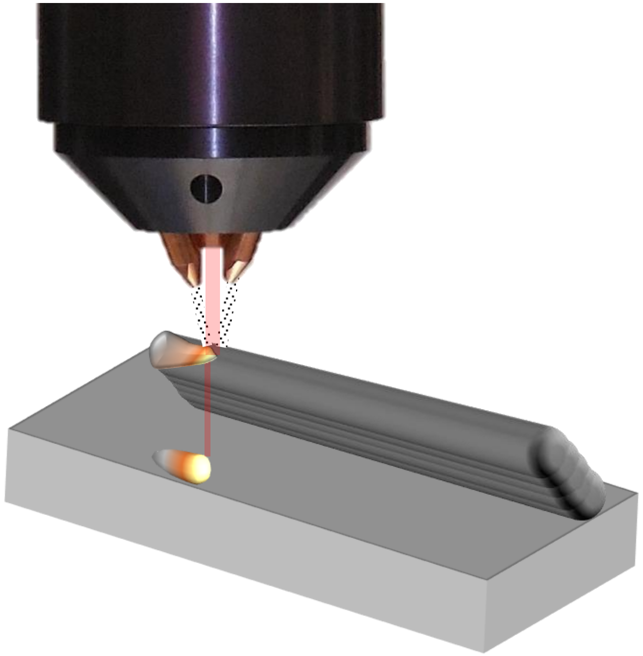


*Image courtesy of RPMI

Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

Freedom in DED design and deposition strategies

Ability to use multiple axes for complex features fabricated locally

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

Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

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

FEATURE RESOLUTION ⟷ DEPOSITION SPEED

Courtesy: RPM Innovations

Gradl, P.R., Mireles, O.R., Protz, C.S. and Garcia, C.P., 2022. Metal Additive Manufacturing for Propulsion Applications. https://arc.aiaa.org/doi/book/10.2514/4.106279

Post-Processing

General Process Flow (Post-Processing)

Powder Removal or Part Cleanup → Support, Build Plate, or Stock Removal → Heat Treatments (Thermal Processing) → Final Processing and Inspections

Powder Removal or Part Cleanup
- Powder Removal
- Verification
- Cleaning of Residual Powder

Support, Build Plate, or Stock Removal
- Removal of Supports
- Build Plate Removal
- Excess Stock Removal

Heat Treatments (Thermal Processing)
- Stress Relief
- Hot Isostatic Pressing (HIP)
- Homogenization
- Solutionizing
- Aging

Final Processing and Inspections
- Inspections
- Final Machining
- Polishing
- Welding
- Brazing

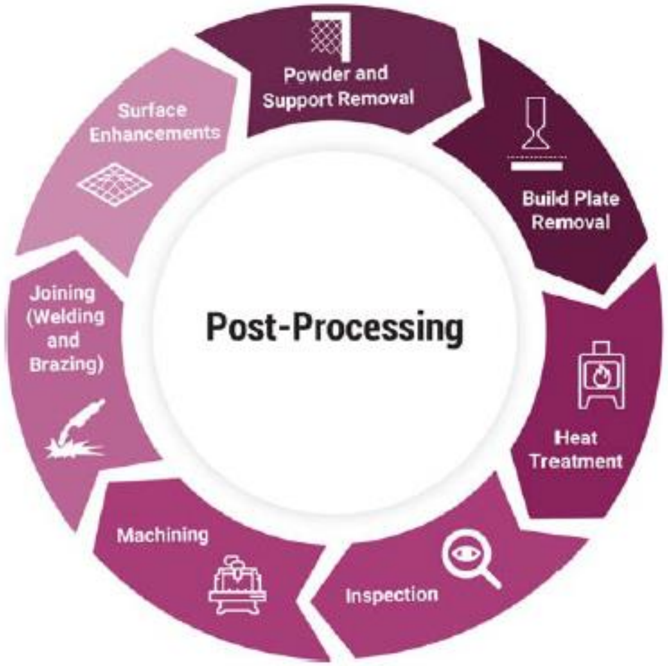


Fig. 5.1 General post-processing steps. The iterative aspect should be considered during the design phase.

Post-Processing

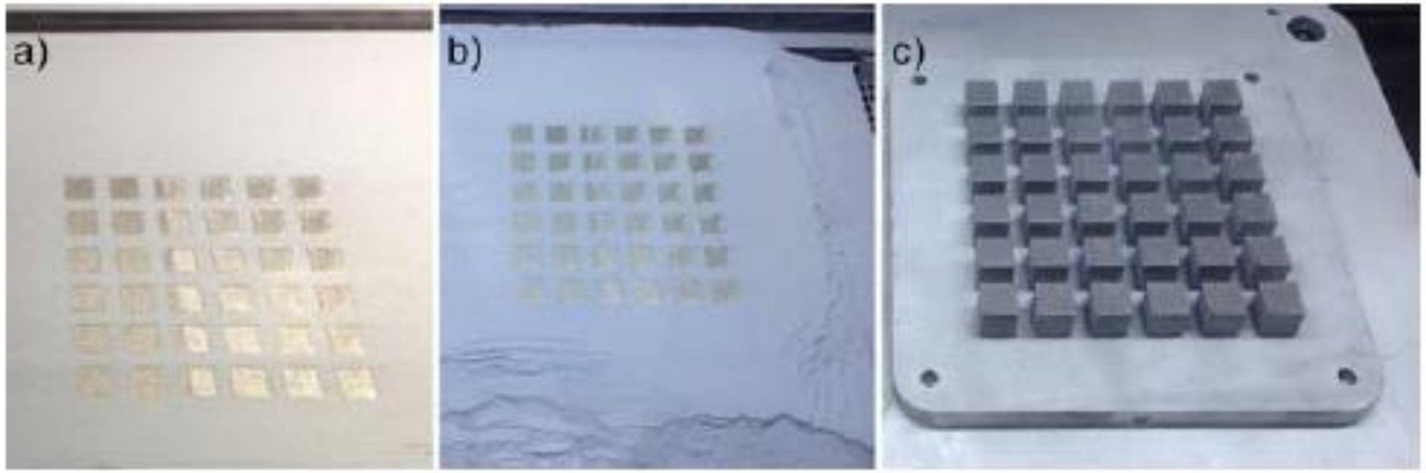


Fig. 5.3 Unpacking example: a) Build completion. b) Build plate raised. c) Powder removed.

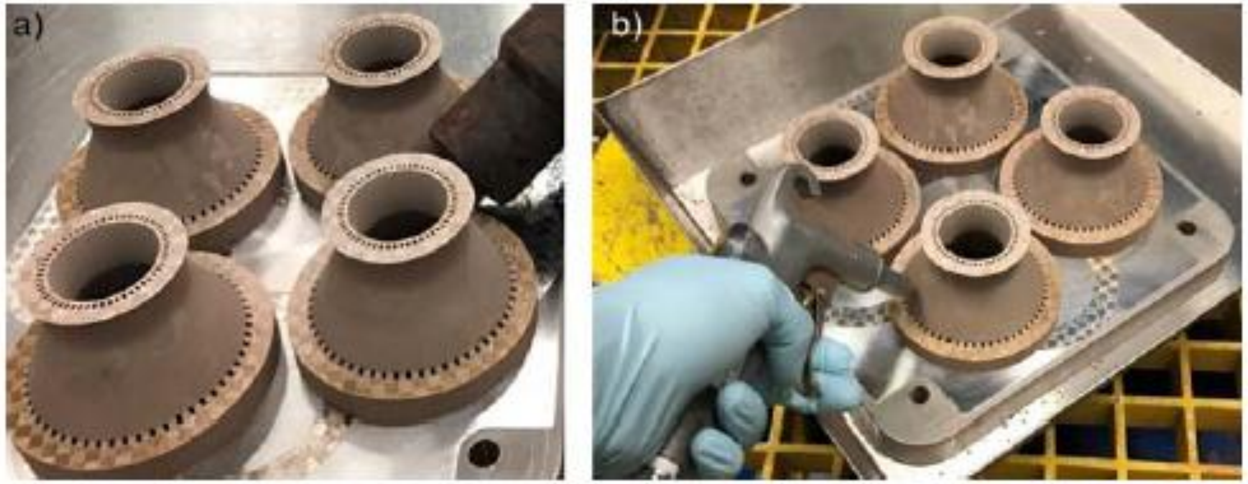


Fig. 5.8 Powder removal with a) a powder vacuum and b) compressed air. (Source: NASA.)

Post-Processing

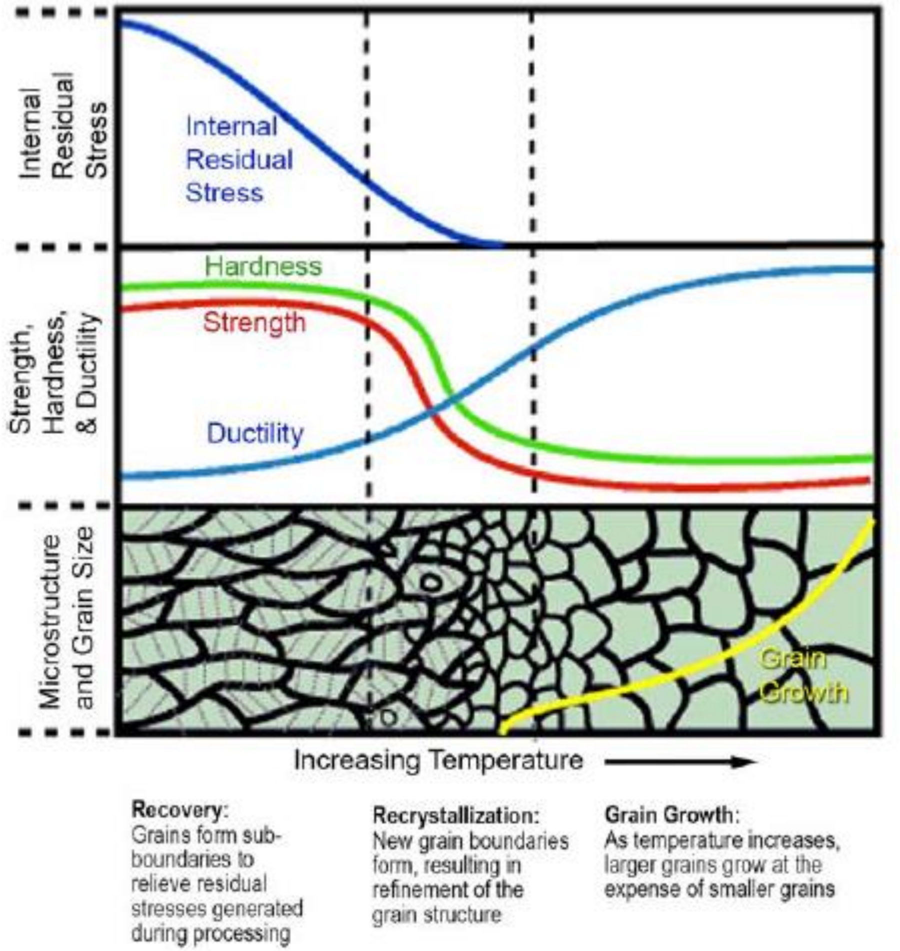


Fig. 4.20 Effects on metal alloy properties of the temperature-dependent recovery, recrystallization, and grain growth regions. (From GATE Metallurgical Engineering [58]; reprinted with permission of GATE Metallurgical Engineering.)

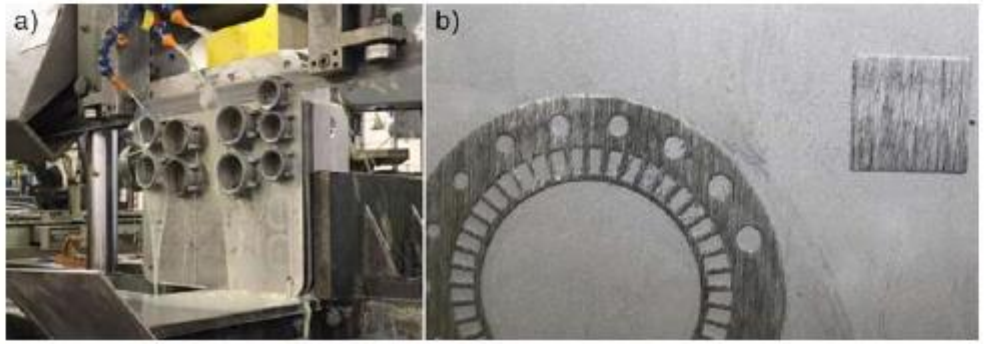


Fig. 5.22 a) Band saw cutting parts from build plate. b) Build plate surface after parts removed.

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

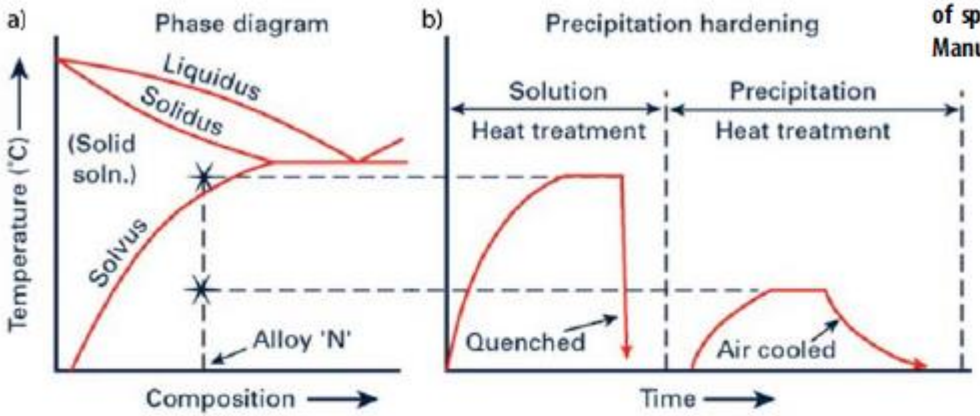


Fig. 4.22 a) General phase diagram and b) corresponding heat-treatment schedule for precipitation hardening. (From Ogunsanya et al. [67]; reprinted under the Creative Commons Attribution-Noncommercial 3.0 Unported License [CC BY-NC 3.0] license, https://creativecommons.org/licenses/by-nc/3.0/.)

Post-Processing

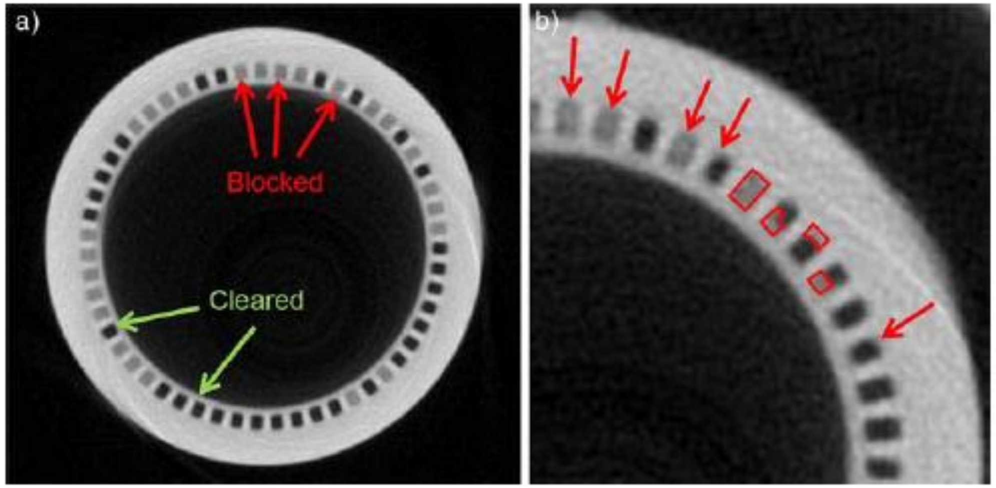


Fig. 5.11 X-ray images of a GRCop-84 chamber with trapped powder in channels. (Source: NASA.)

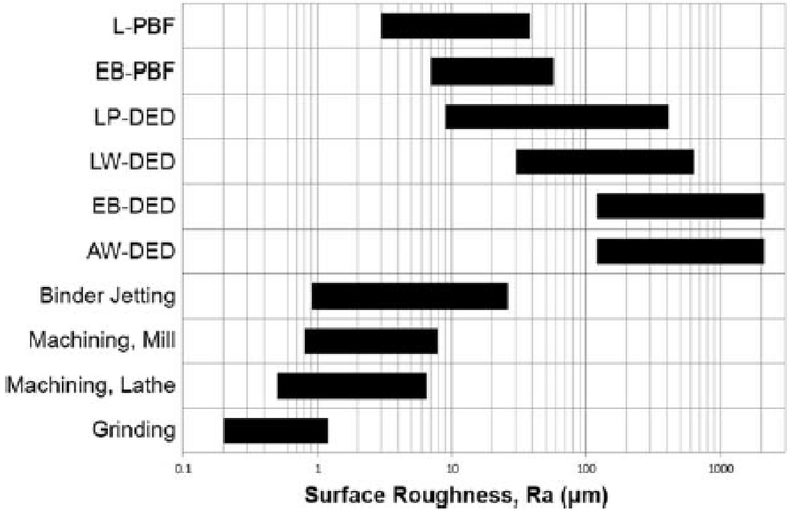


Fig. 5.50 General surface roughness values for selected metal AM processes.

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

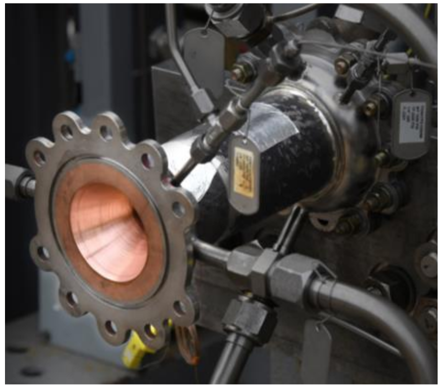
Post-Processing Summary

	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

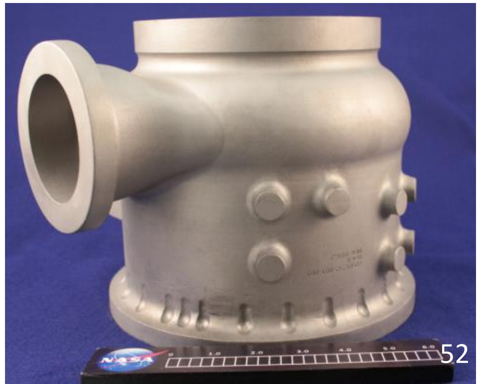
Y = Requires operation
N = Does not require
O = May Require

Summary

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





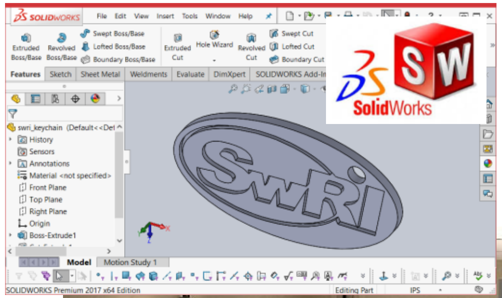
Examples

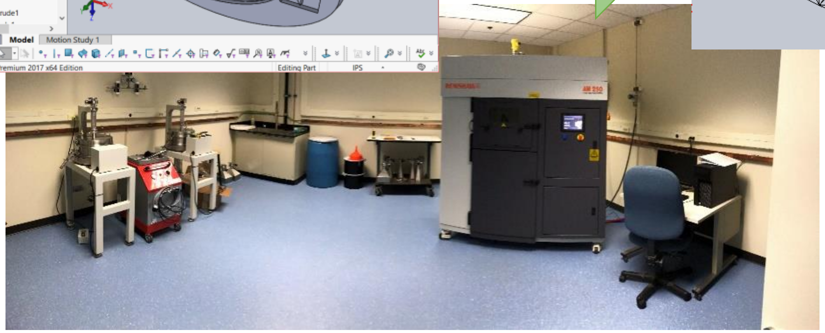
A simple printing exercise can demonstrate the typical workflow

Your widget will change the world……..how can you print it?

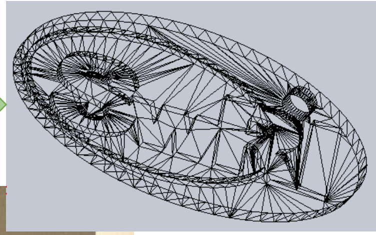
Progression from your design to the machine

Create CAD

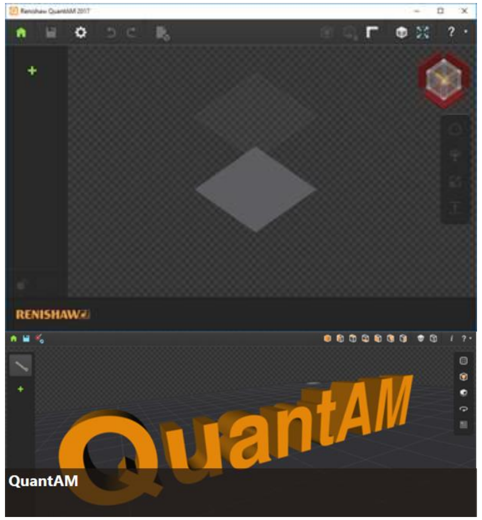




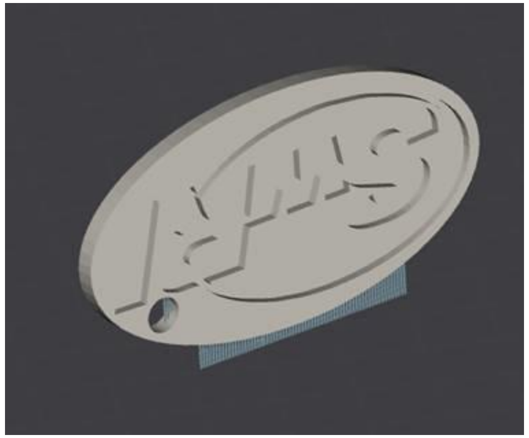
Generate STL



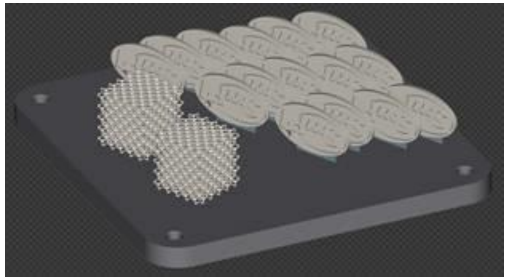
Build Software



Create Single Part Layout

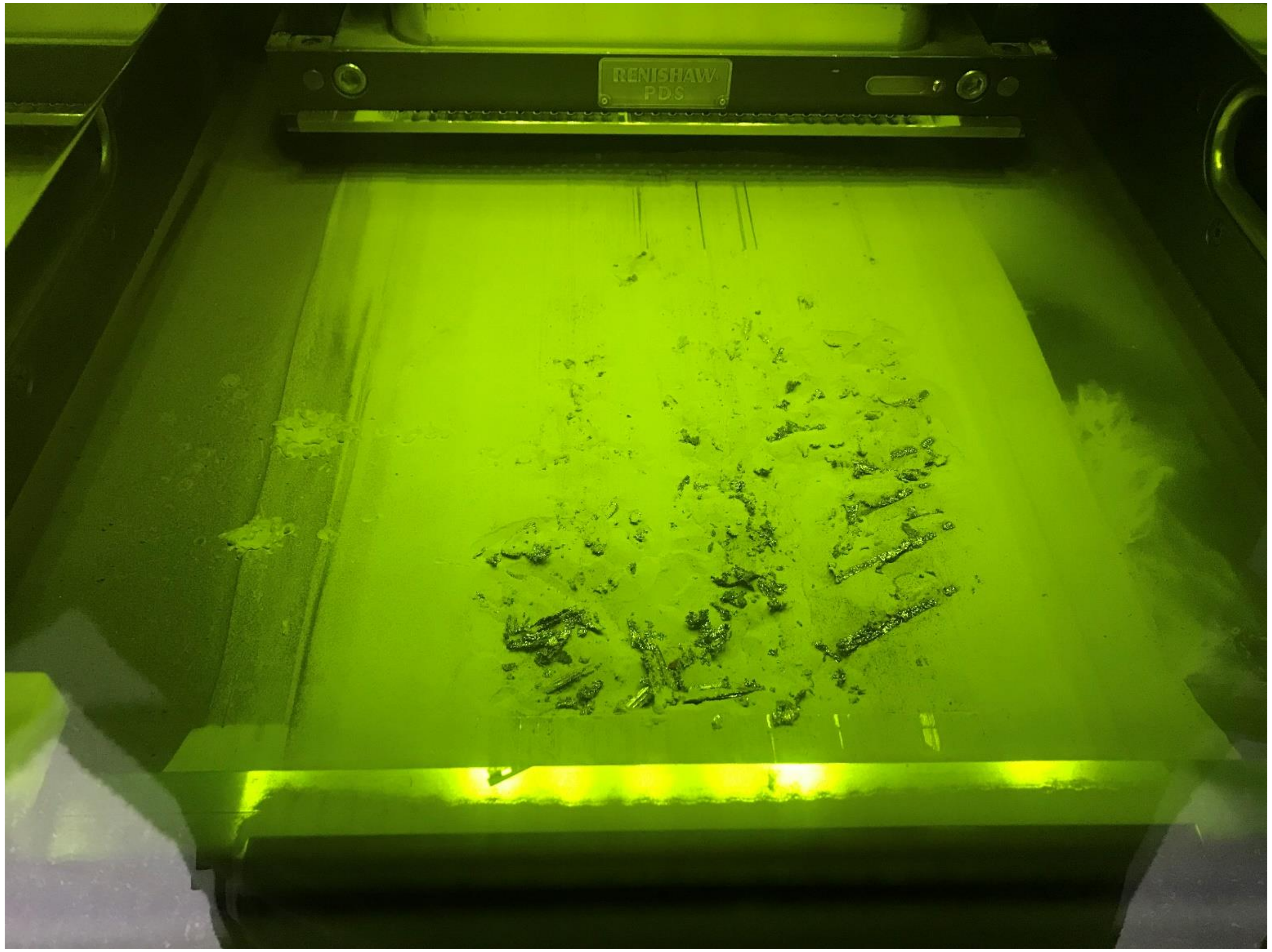


Create Build Layout

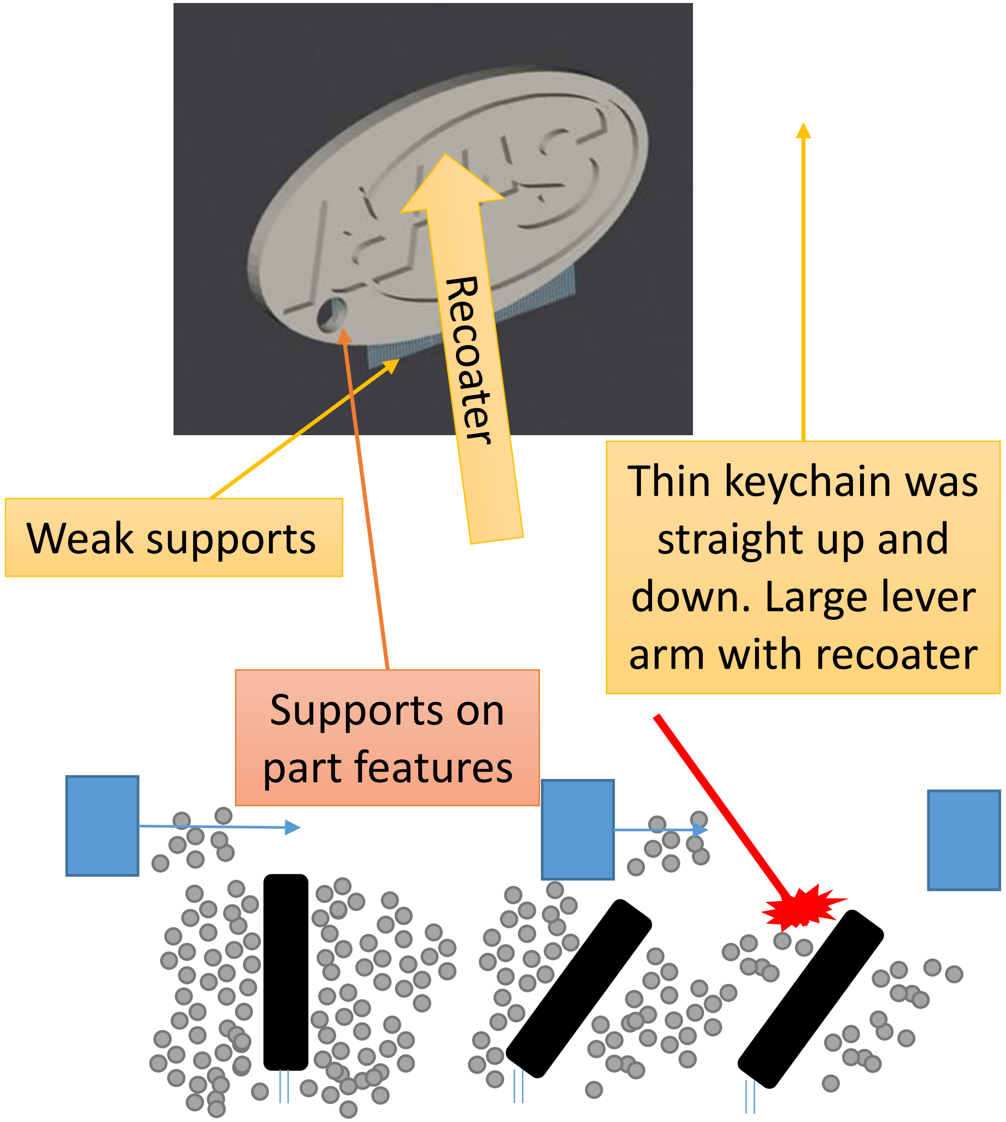


Off to the Machine!

Unexpected results should be expected

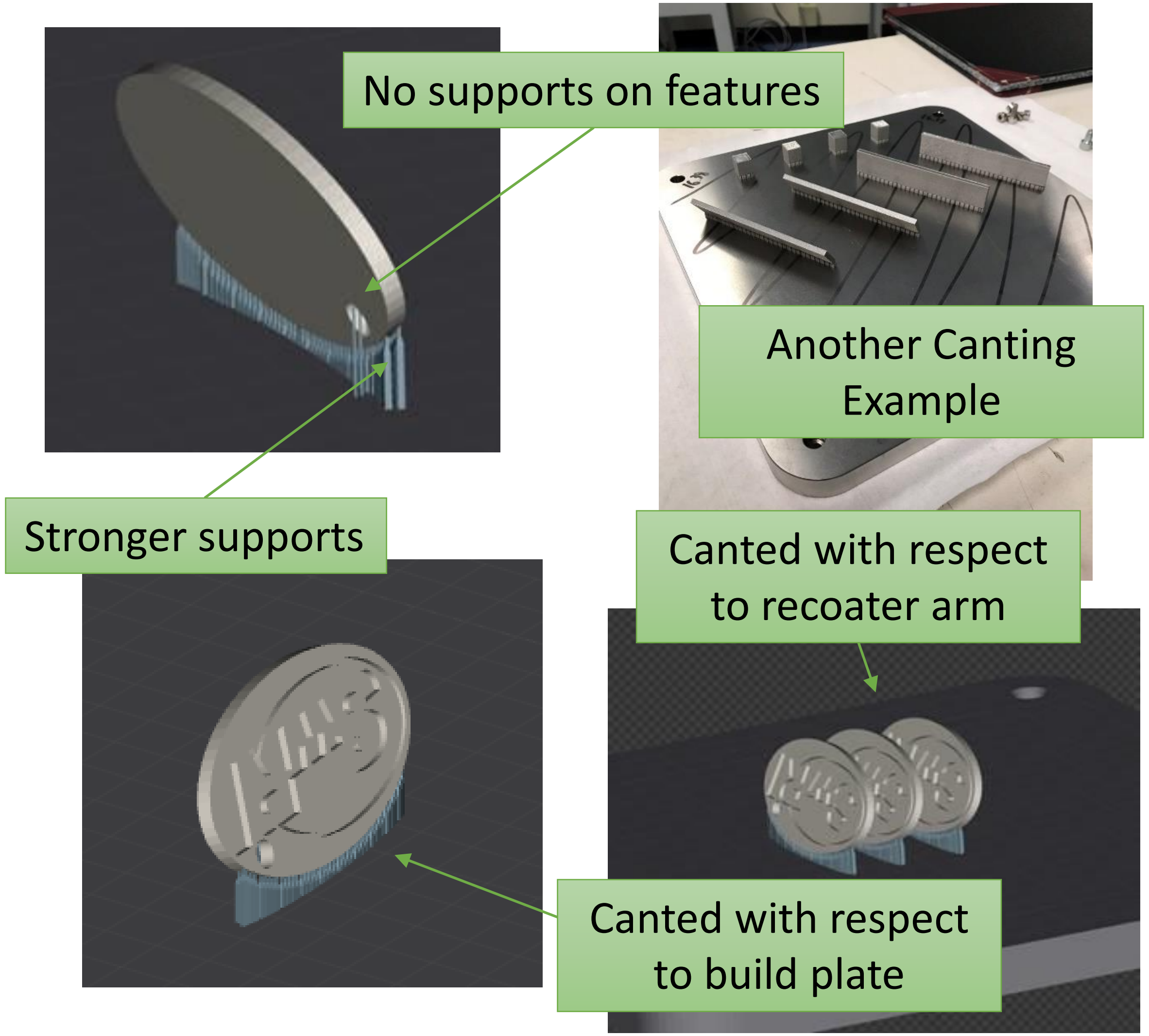


What happened?!?!



Taking your time and thinking ahead can save headache

Improvements to build plan

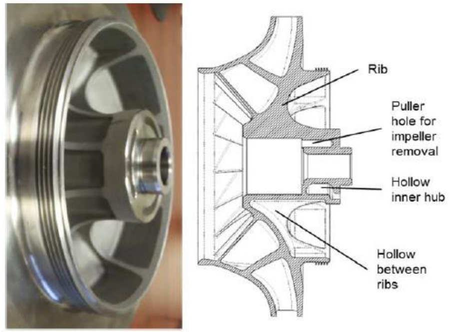


Successful build!

A real AM workflow example: Closed Impeller

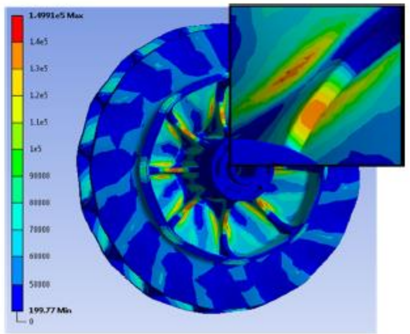
…Almost… A real AM workflow example: Closed Impeller

Design for AM

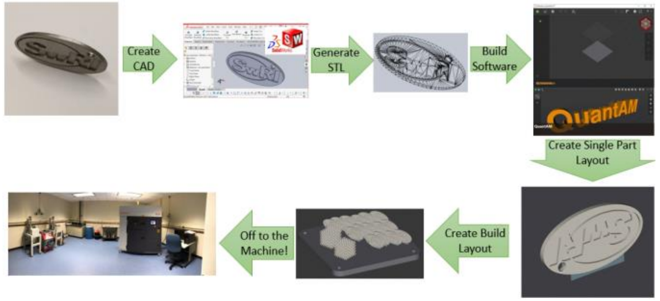


Closed Centrifugal Compressor Impellers

Material:
SS 17-4 PH

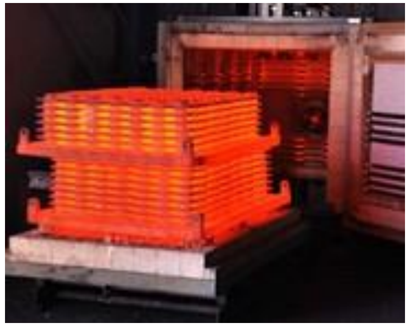


Prepare for Printing

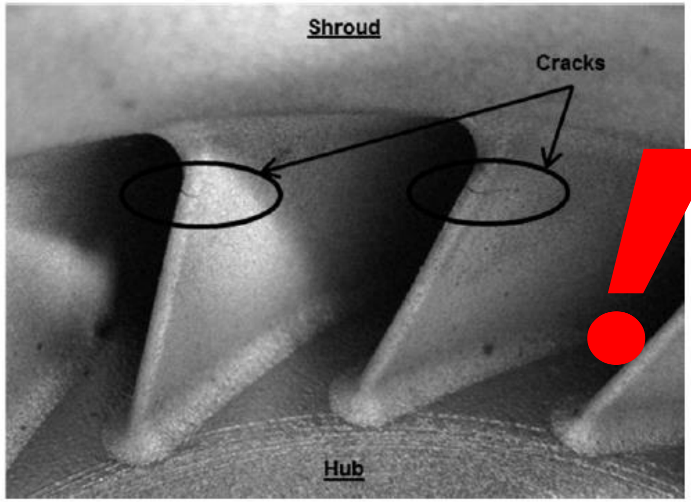


Print and Remove Part

Post Process



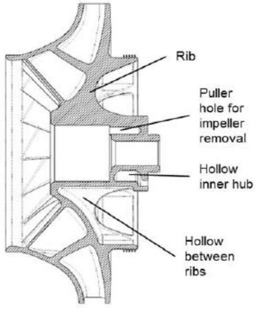
Inspect



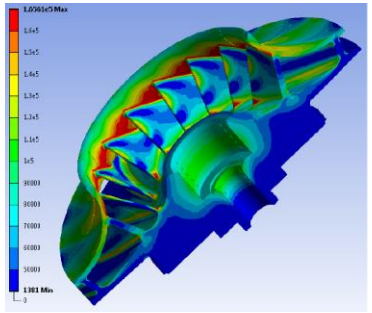
What happened?!?!

The component was redesigned using new material and successful prints were taken off the machine

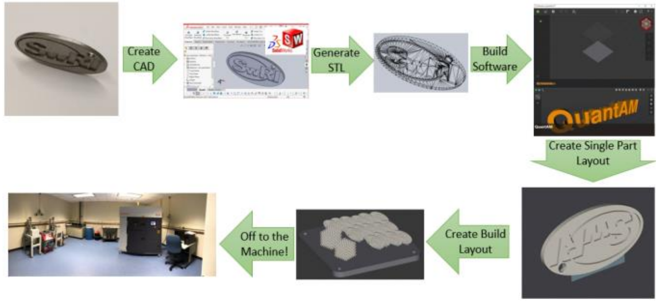
Design for AM



Materials:
Inconel 718
Ti-6Al-4V

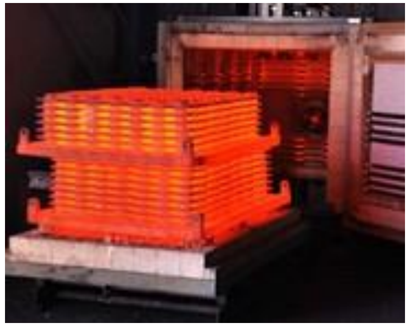


Prepare for Printing



Print and Remove Part

Post Process



Inspect

Looks good! So it must be right…..How can we make sure?

Geometric and material characterization of the printed component was completed

Non-Destructive Evaluations

Support material remains after extrude hone finish

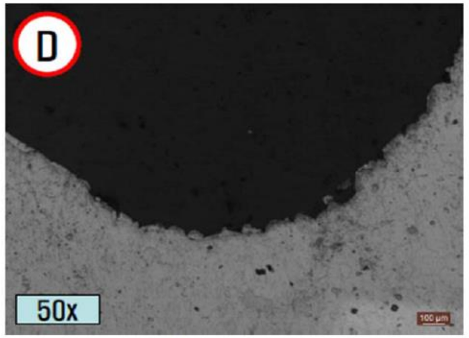


Figure 12. Magnified View of Fillet Region Between Impeller Blade and Shroud

Destructive Evaluation

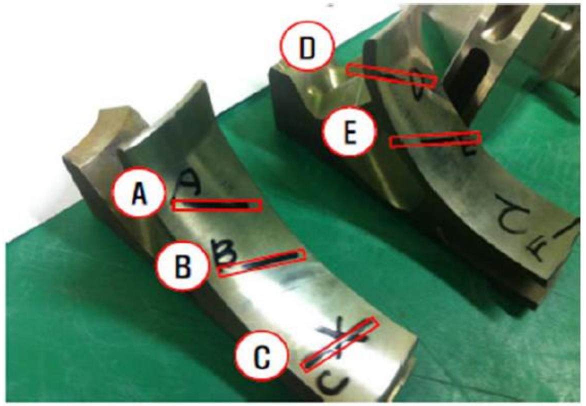


Table 2. Dimensional Accuracy of Manufactured Impellers

Impeller	Impeller Exit Width Accuracy (inches)	Flow Path Surface Roughness (R_a)
1st Generation 0.08 ϕ Impeller	+0.011	NA
1st Generation 0.11 ϕ Impeller	NA	NA
2nd Generation 0.08 ϕ Impeller Variation 'a'	-0.015 to -0.010	63-125
2nd Generation 0.08 ϕ Impeller Variation 'b'	-0.011 to -0.005	7-32
2nd Generation 0.08 ϕ Impeller Variation 'c'	-0.005 to +0.000	16
2nd Generation 0.11 ϕ Impeller Variation 'a'	-0.014 to -0.012	63-125
2nd Generation 0.11 ϕ Impeller Variation 'b'	-0.005	63-125
2nd Generation 0.11 ϕ Impeller Variation 'c'	-0.003	16-92

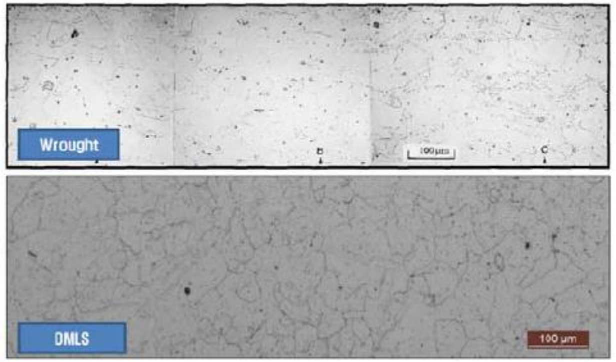


Figure 13. Comparison of Grain Size Between Wrought Inconel 718 and DMLS Inconel 718

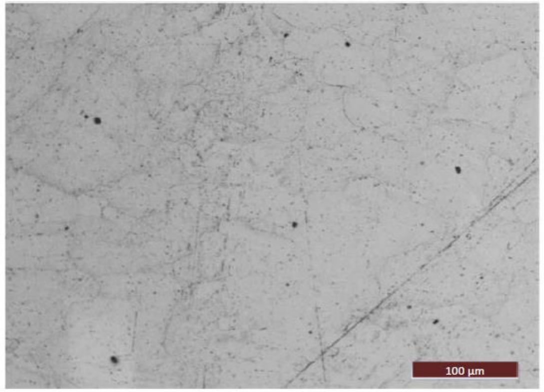


Figure 14. Magnification of DMLS Inconel 718 Sample Showing Micro-Porosity

Allison et. al. "Manufacturing and Testing Experience with Direct Metal Laser Sintering for Closed Centrifugal Compressor Impellers", 2014

Application Testing

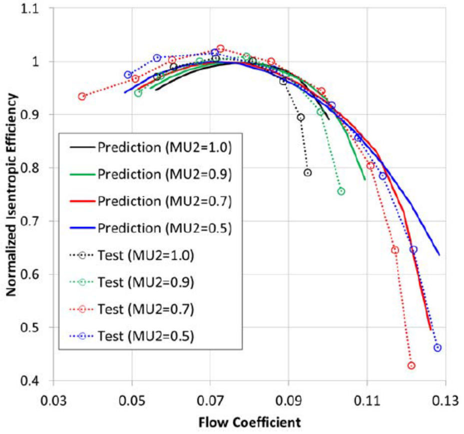


Figure 18. Comparison of Predicted and Tested Normalized Isentropic Efficiency vs. Flow Coefficient

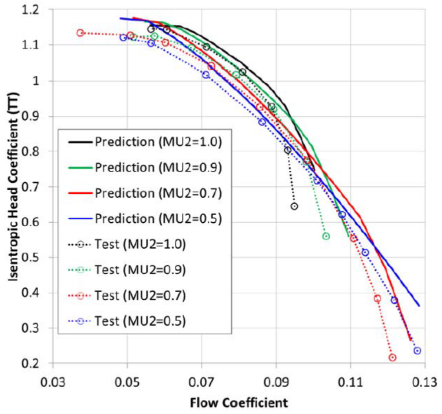
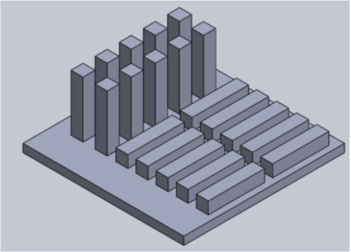


Figure 17. Comparison of Predicted and Tested Head vs. Flow Coefficient

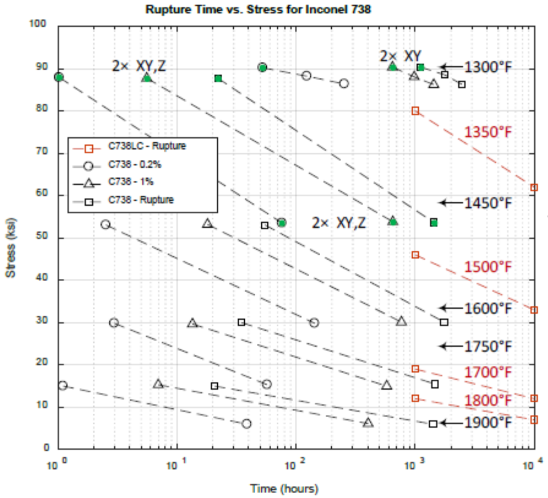
Mechanical property characterization of printed IN738 were measured for high-temperature applications

Specimens



Post Process

Historical Cast In738 Data



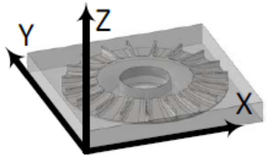
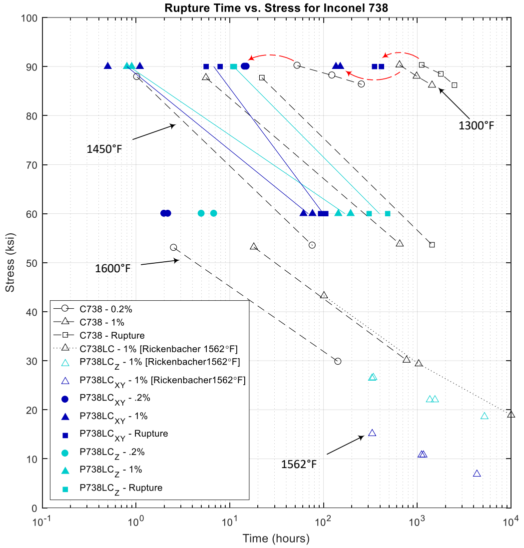
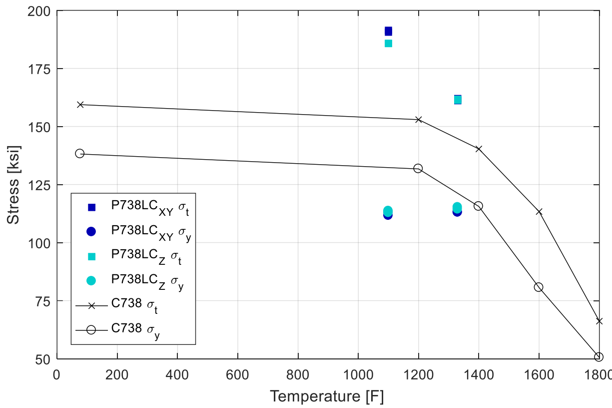


Figure 2: Cast Inconel 738 Creep Sample Data and Associated Test Points (Denoted by Green Accent), Heat Treat - 2050F, 2 hrs, AC +1550F, 24 hrs, AC (data taken from [8])

Wilkes et. al. "Creep and Tensile Properties of DMLS Printed Inconel 738 Coupons and Comparison to Cast Properties", 2018

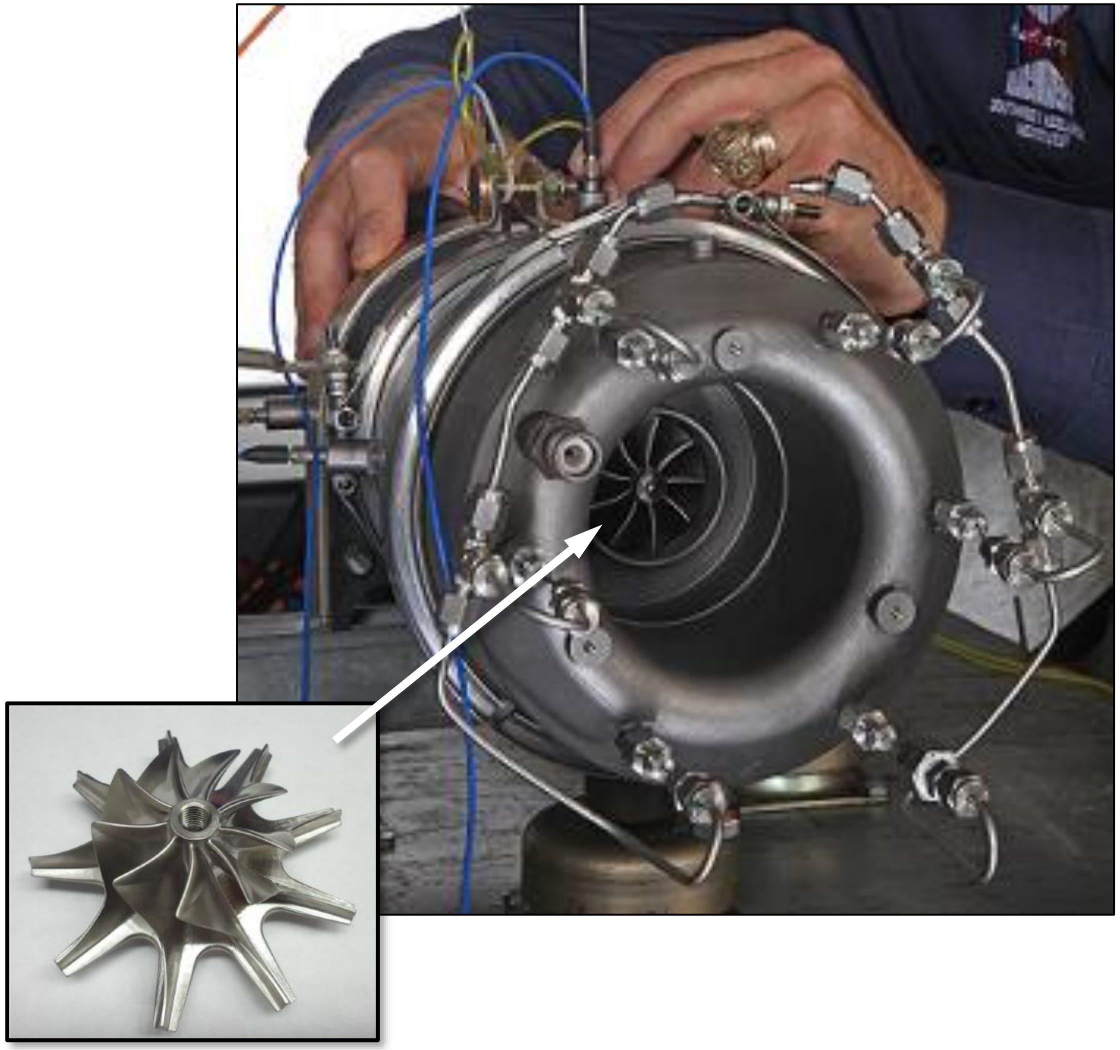
Printed In738LC Data

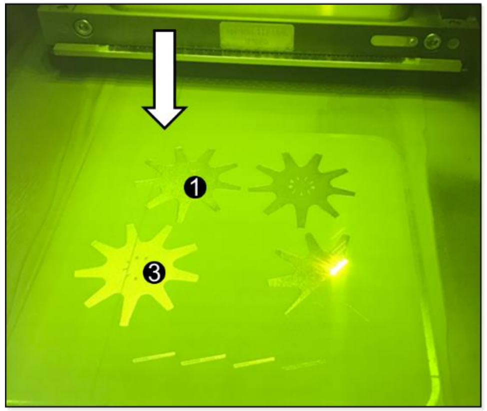


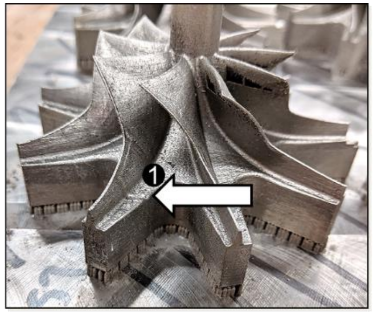


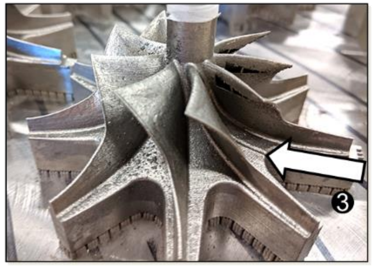
Specimen ID	Test Temper	Diameter (Inches)	Ultimate Strength	Yield Strength	Elongation (%)	Reduction Of Area (%)	Fracture Location
S1	1330	0.2507	162,000	113,000	17.5	27.1	Gage
S2	1330	0.2493	161,100	113,000	16.8	23.9	Gage
S3	1100	0.2498	190,600	111,600	15.4	23.5	Gage
S4	1100	0.2496	191,400	113,100	15.6	22	Gage
R1	1330	0.2507	161,300	114,300	21.6	34.1	Gage
R2	1330	0.2507	161,700	115,200	23.4	37.3	Gage
R3	1100	0.2509	185,800	113,600	15.2	23.1	Gage
R4	1100	0.251	185,700	112,800	14.6	22.1	Gage

The AM Process Lifespan





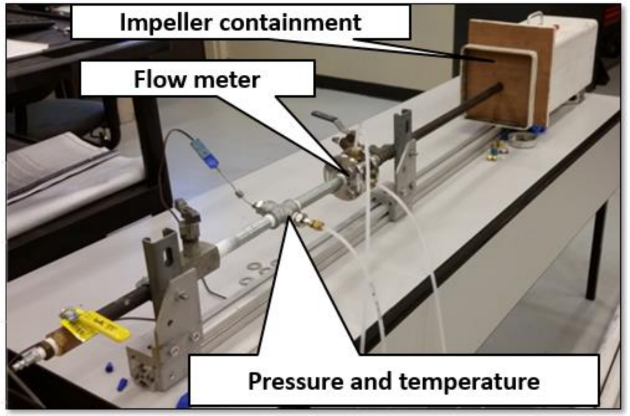




Successful AM application needs access to all the processes

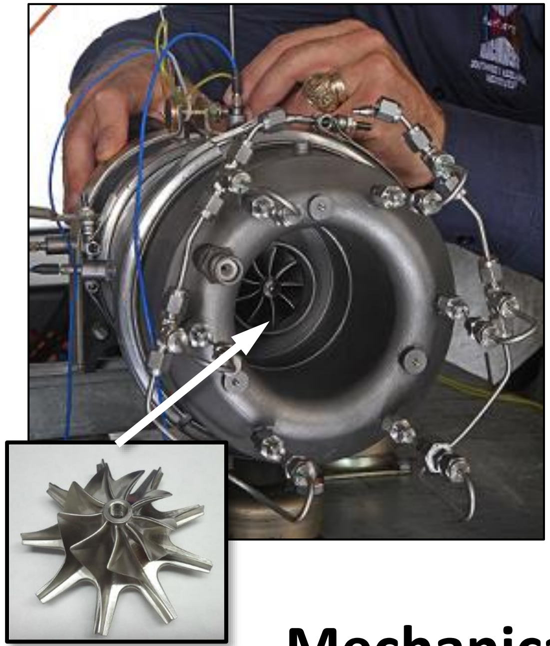
Component Testing: Pressurized Coolant Flow Test Rig

- Shop air (~100 psi)
- Measure pressure drop
- Measure flow rate



Printing Capability: Renishaw AM250

- 273mm x 273mm build area
- IN 718 capable

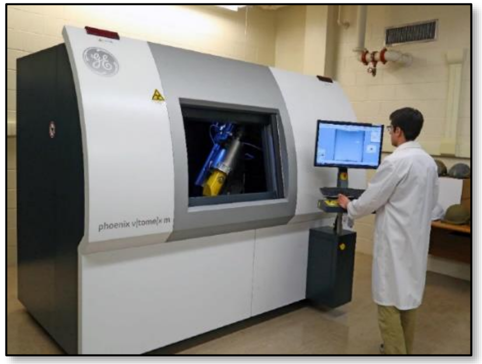


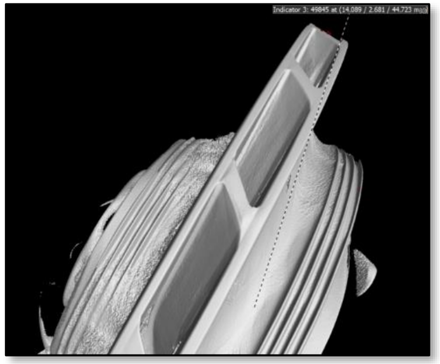
Application: 12.5kW Gas Turbine

- 118,000 rpm
- Material IN718
- 90mm diameter

Inspection Capability: CT Scan

- Non-destructive evaluation of impeller



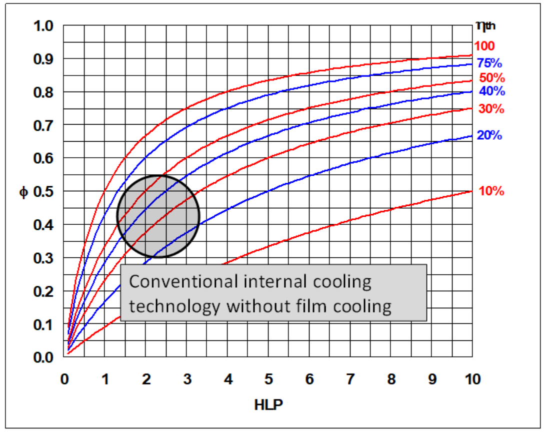


Mechanical Testing & Characterization Lab

- Surface characterization
- Destructive evaluation tests

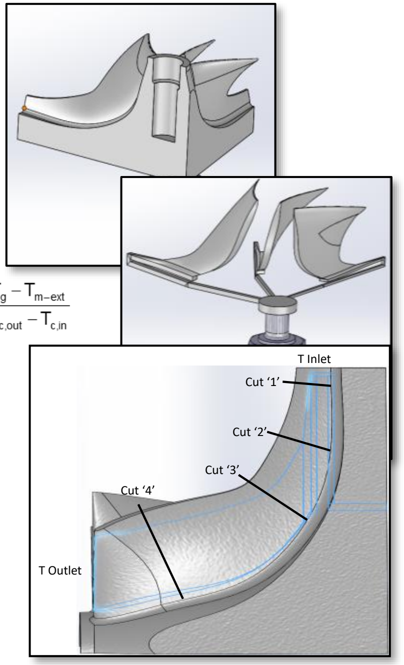
Design was functionally considered for AM benefits

1D heat transfer analysis to determine passage size to achieve 550°C metal temperature using available compressor bleed air



$$\phi_m = \frac{T_g - T_{m,ext}}{T_g - T_{c,in}}$$

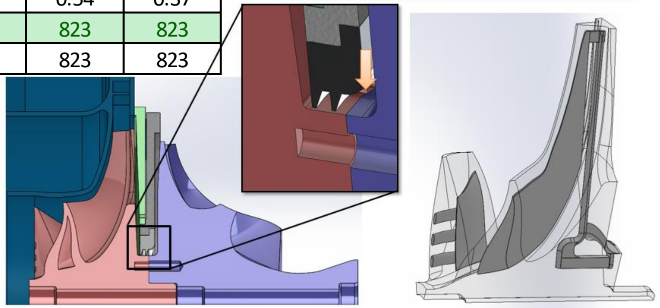
$$HLP = \frac{W_c C_p}{h_g A_g} = \frac{T_g - T_{m-ext}}{T_{c,out} - T_{c,in}}$$



The turbine cooling requirements are defined to achieve conventional cooling effectiveness values

	Case 1	Case 2	Case 3	Case 4
Inlet Channel Width [mm]	0.5	0.6	0.75	1
Cooling Split [%]	0.75%	1.08%	1.35%	1.79%
Flow Check [KPa]	-1	40	121	135
Max Mach # []	0.92	0.93	0.54	0.37
Tm-ext Max [K]	835	823	823	823
Tm-ext Target [K]	823	823	823	823

Cooling flow sourced from compressor discharge

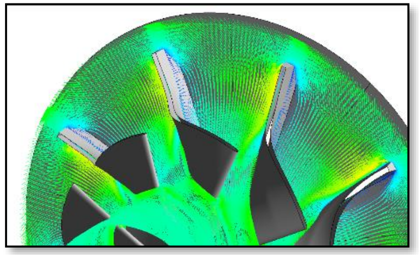


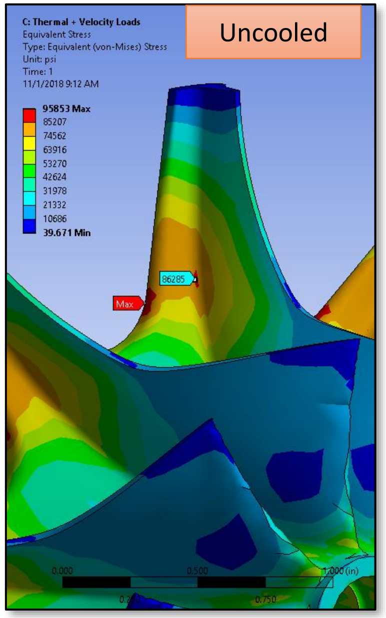
3D heat transfer and mechanical analysis to determine mechanical integrity and life

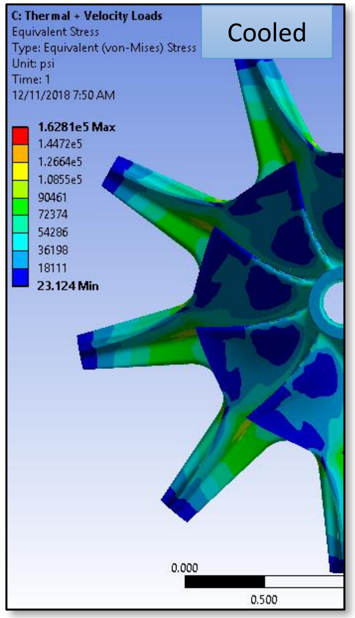
118,000 rpm
Fixed axial displacement
Shaft cylindrical support
Assume 550°C-370°C

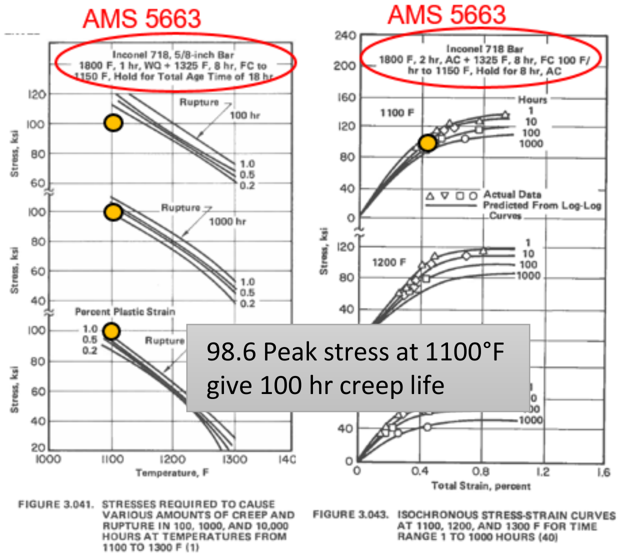
1202°F Property	Wrought	Printed
Modulus Elasticity	3016.8 ksi	2538.1 ksi
Yield Strength	169.7 ksi	161.0 ksi
Ultimate Strength	204.5 ksi	195.8 ksi

Printed material properties for heat treated IN718 from Strobner et al. 2015 and Deng et al. 2017



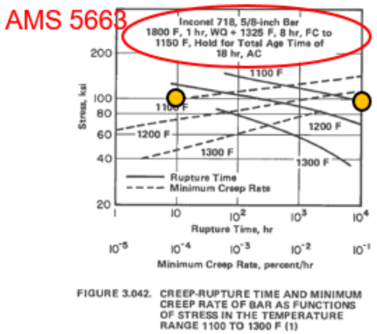






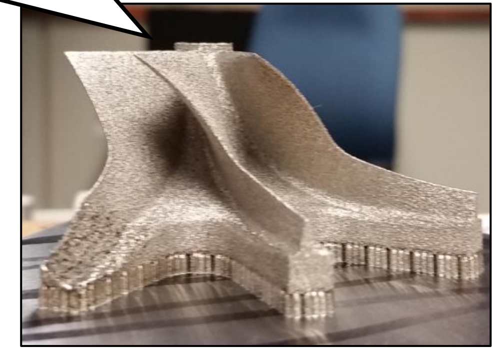
98.6 Peak stress at 1100°F give 100 hr creep life

Ref: 1996, Aerospace Structural Metals Handbook, Purdue University Center for Information and Numerical Data Analysis and Synthesis.



Several test prints have been completed to determine AM print capabilities and considerations of the design

Quarter geometry for blade angles



Quarter geometry for cooling channel thickness

What if we account for build distortions?

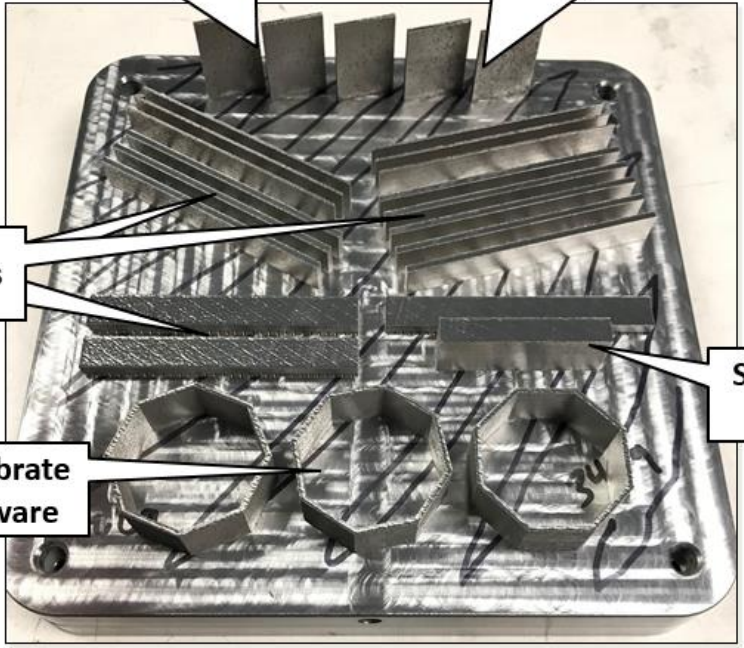
What if we make the blades thicker?

Build CAD geometry using supports (Baseline)

What if we build the impeller directly on the build plate?

Coupons for channel roughness

Coupons for cooling turbulators



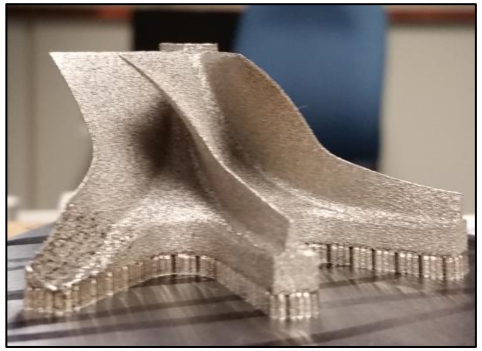
Tensile coupons

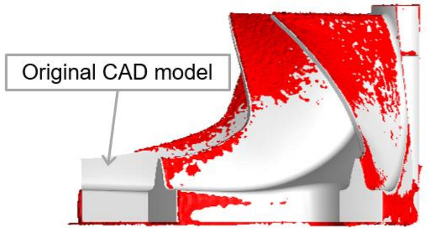
Solid block to calibrate distortion software

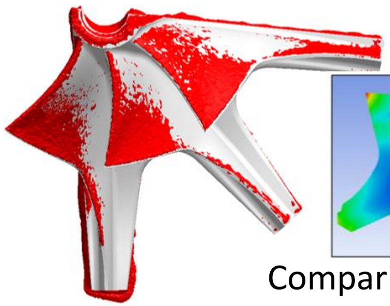
Polygons to calibrate distortion software

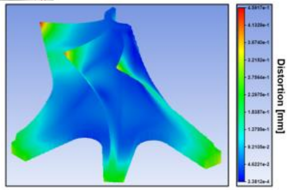
Non-destructive evaluations were used to determine printability of features and expected distortions

Coordinate Measurement Machine (CMM) inspections show geometric distortions





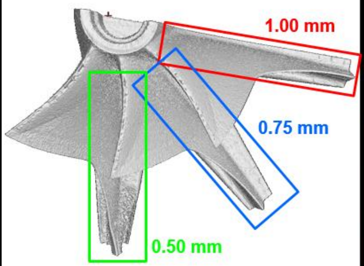


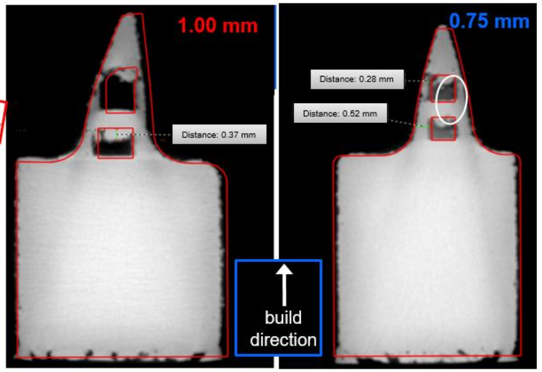


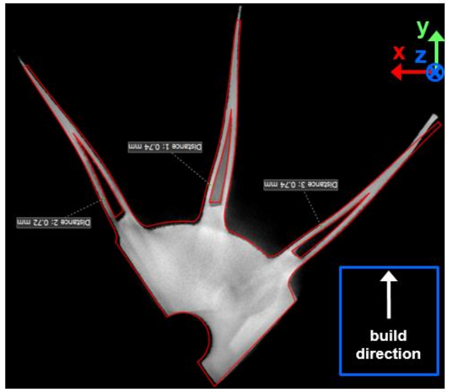
Location	Measured Distortion
1	0.51 mm
2	0.43 mm
3	0.31 mm
4	0.39 mm
5	0.24 mm
6	0.34 mm

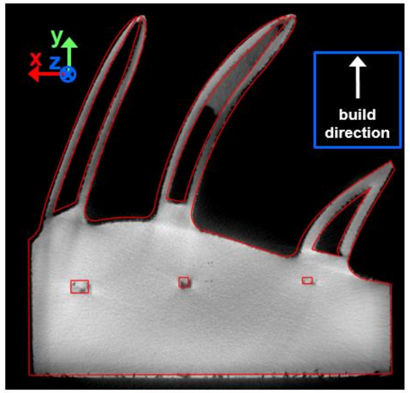
Comparison performed with ANSYS Additive®

X-Ray CT Inspections show 0.75 mm cooling channels are repeatable

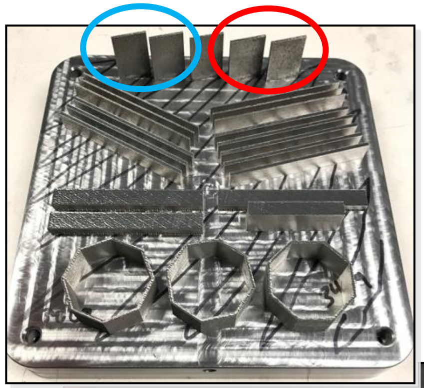


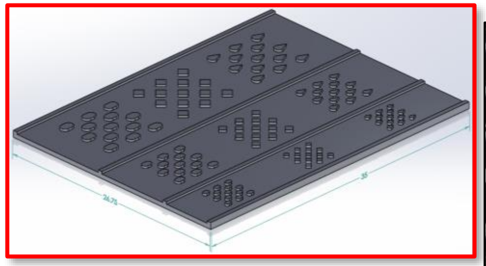


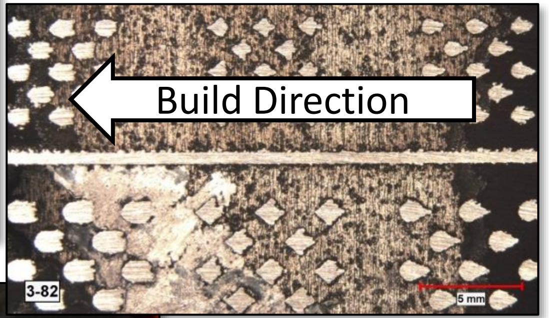


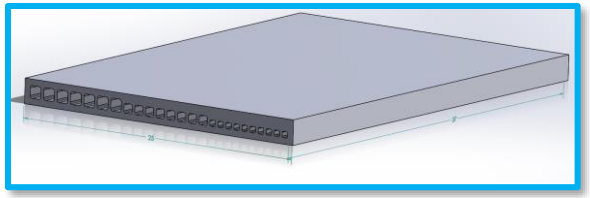


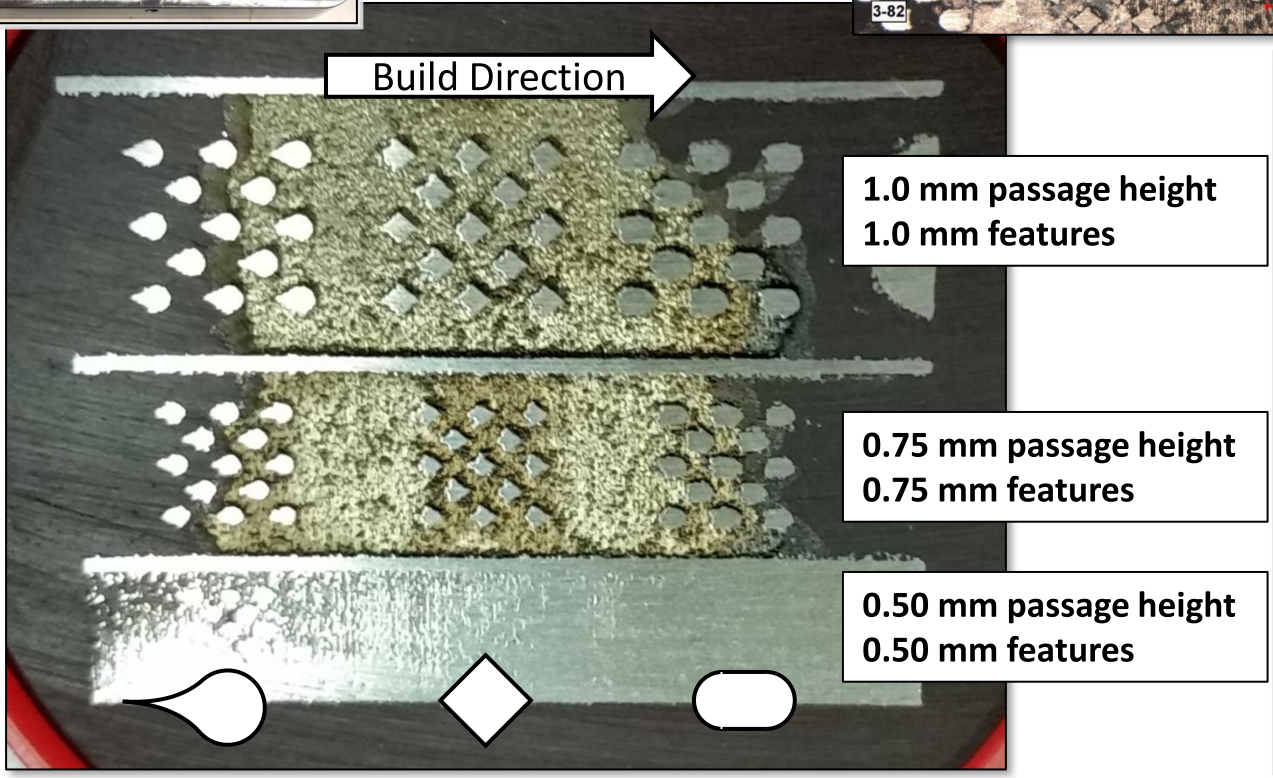
Teardrop-shaped turbulators had the best build resolution, which is also the most aerodynamic, and 0.75 mm was the minimum repeatable passage width

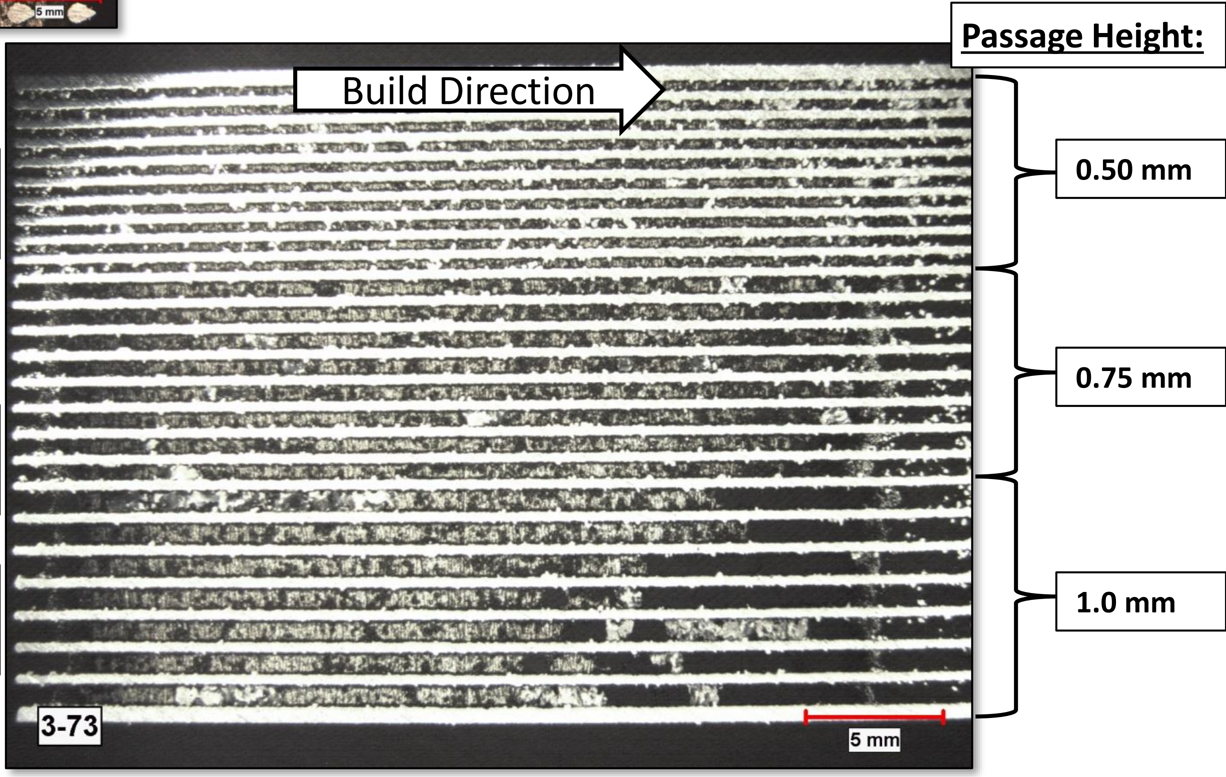






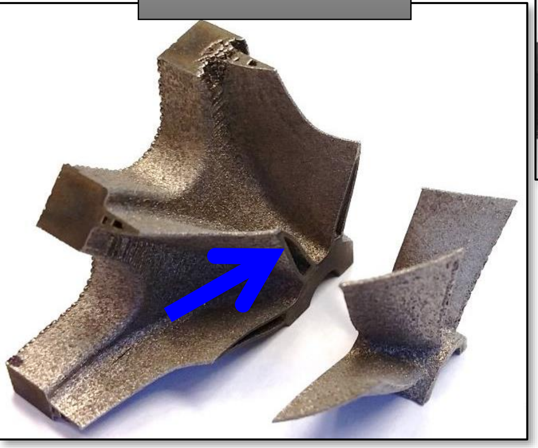


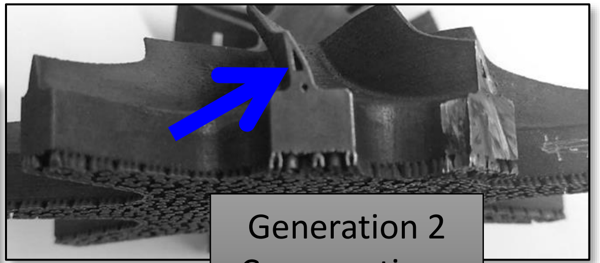




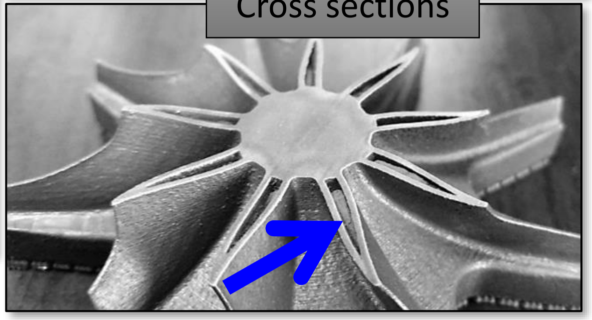
The cooling passages are modified to allow easy removal of powder prior to stress relief

Generation 1
Cross sections

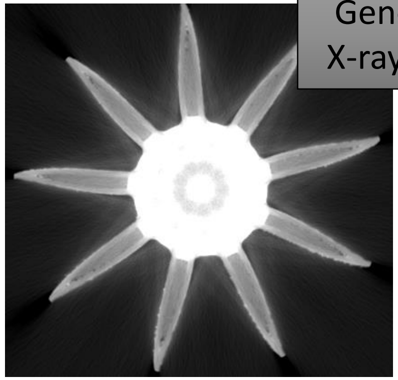


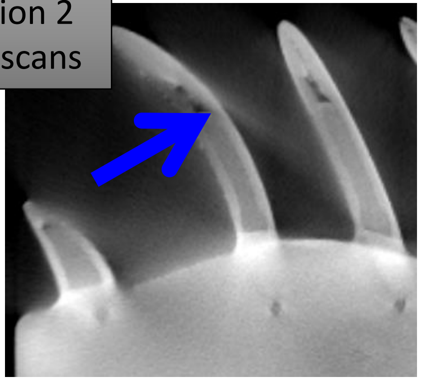


Generation 2
Cross sections



Generation 2
X-ray CT scans



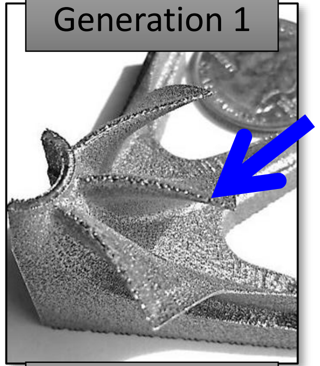


Generation 3 will utilize vibration apparatus

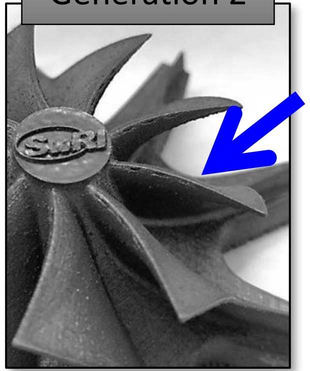
Vibration & Mechanical Removal

Gradl, P., Mireles, O., and Andrews, N., 2018, "Intro to Additive Manufacturing for Propulsion Systems."

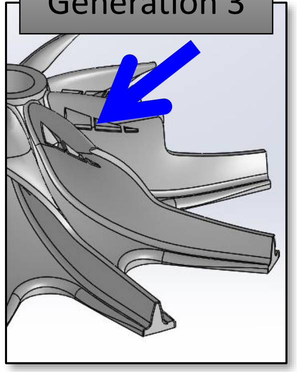
Generation 1



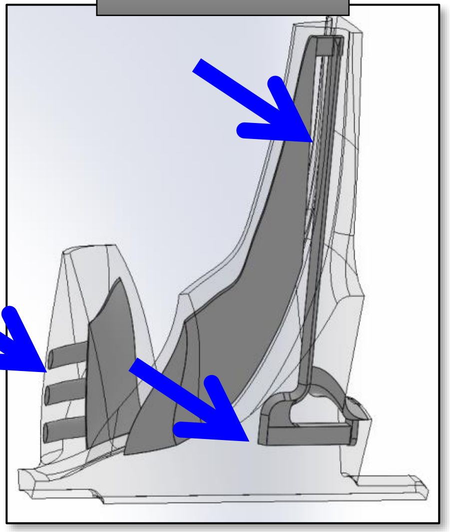
Generation 2



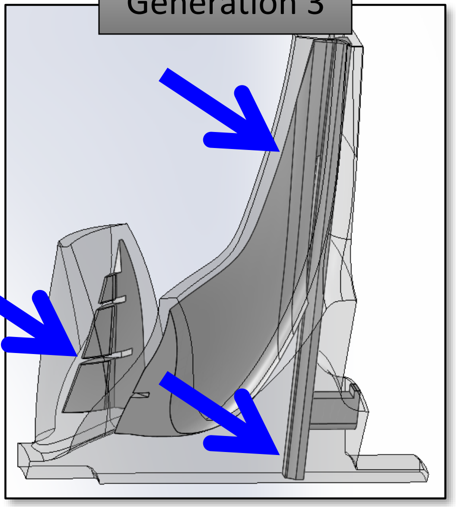
Generation 3



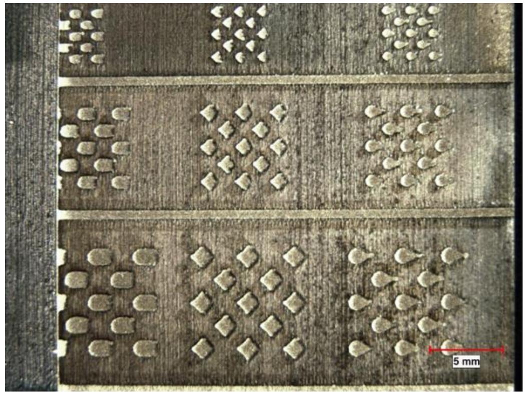
Generation 2



Generation 3



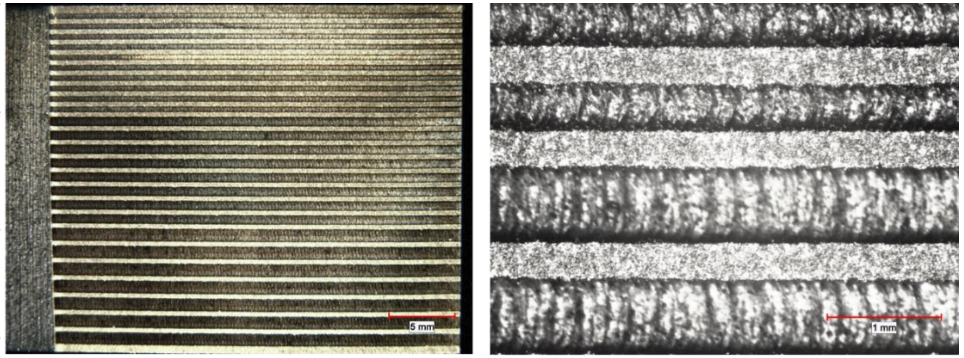
Improved powder remove processes revealed cleaner and more precise capabilities



0.50 mm

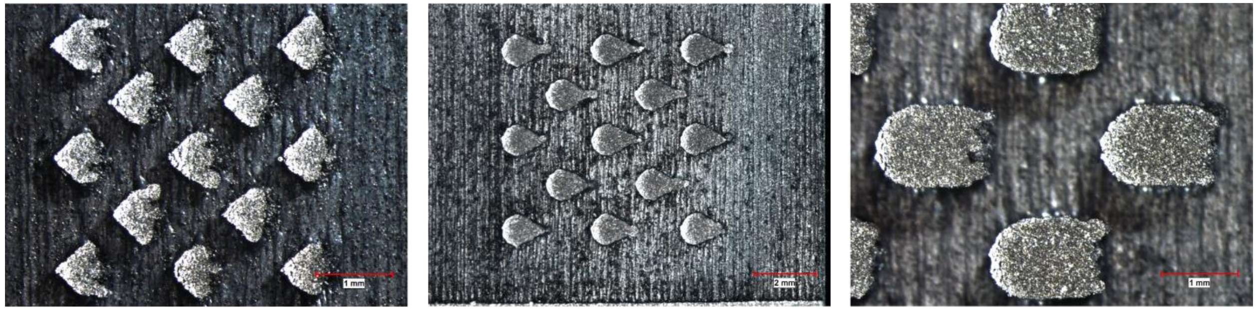
0.75 mm

1.0 mm



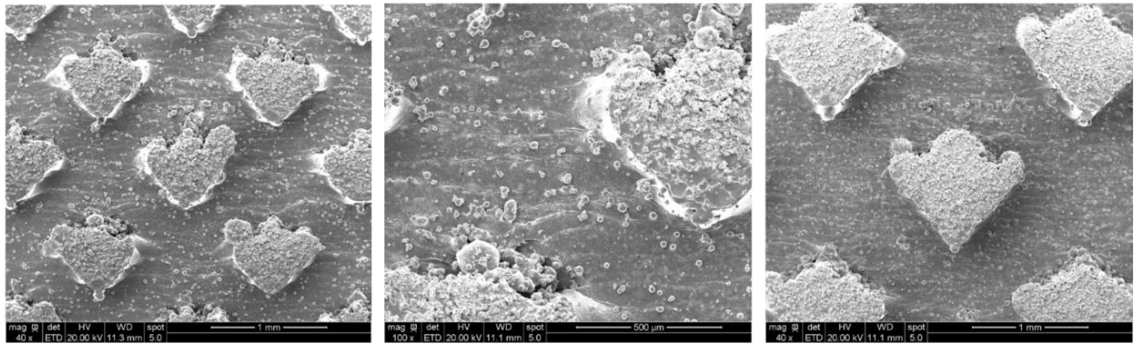
Build direction

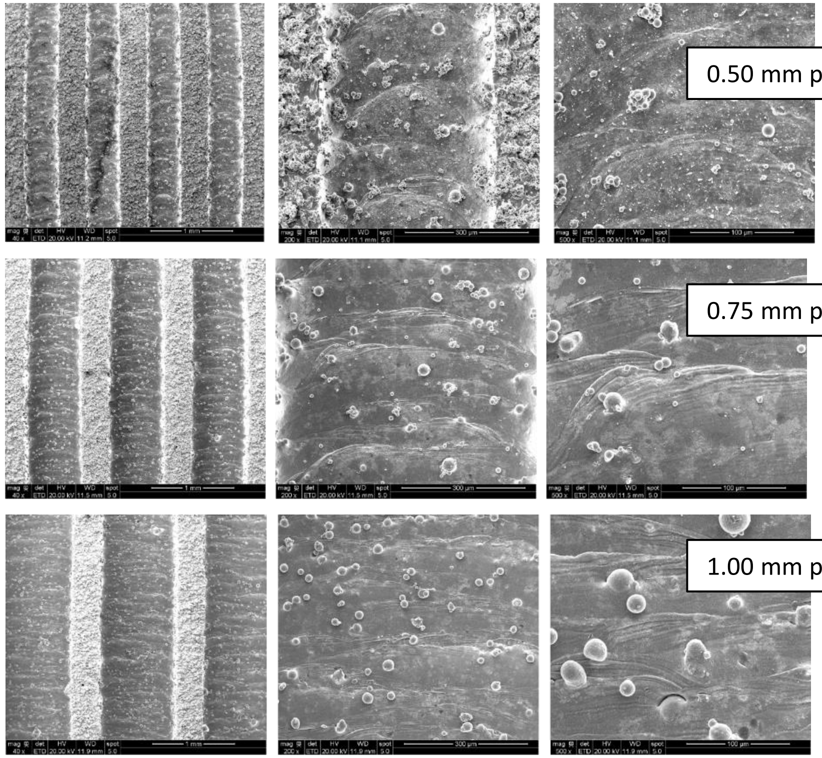
Build direction



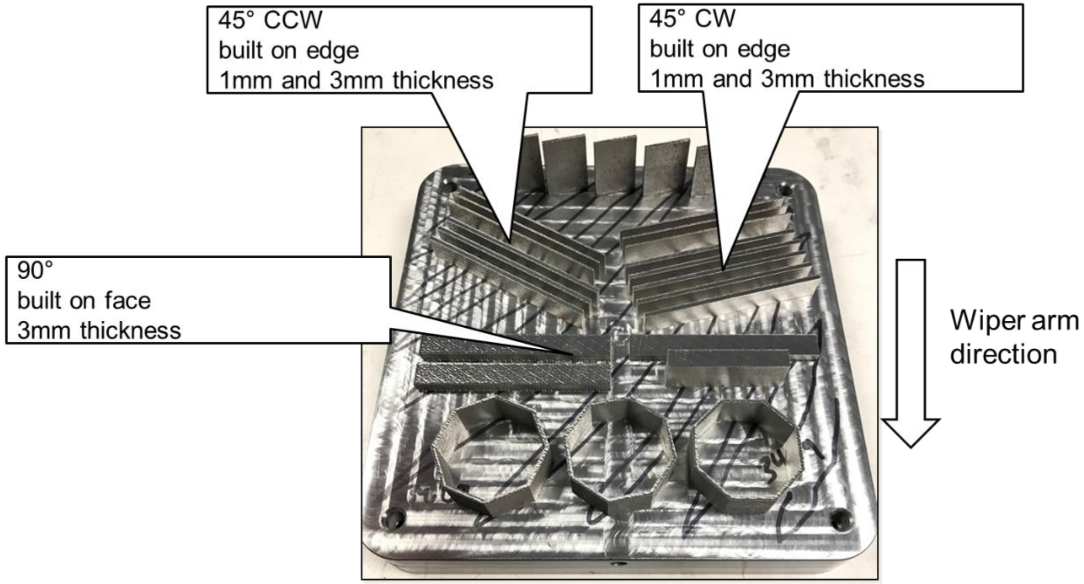
Build direction

Build direction





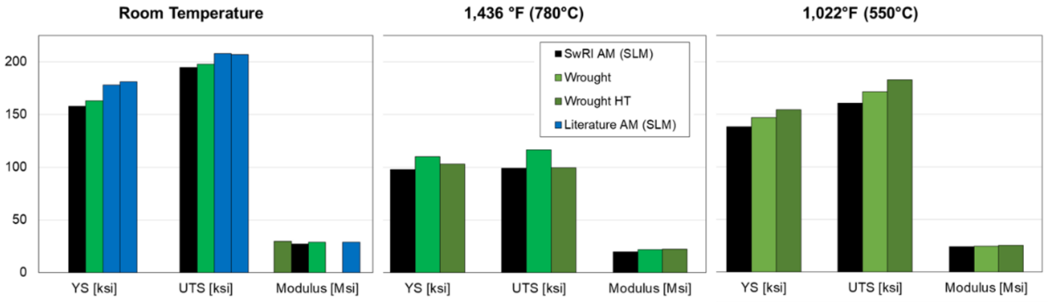
Two separate heat treatments and different build orientations studied



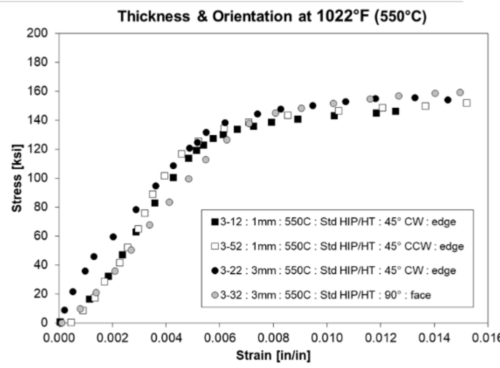
Process	#1	#2
Description	***Combined HIP+Heat Treat***	***Separate HIP and Heat Treat***
HIP Vendor (std)	Quintus (ASTM F3055-14a)	KittyHawk (ASTM F3055-14a)
Heat Treat (HT)Vendor (std)	Quintus	Texas Heat Treat (AMS 5663N)
HIP process	>14.5 ksi @ 2050°F-2165°F ±25°F for 4h ±1h hold in inert atmosphere; Cool below 800°F	
Solution HT process	1725°F-1850°F hold within ±25F for time commensurate with cross-sectional thickness. Cool at a rate equivalent to air cool or faster	
Aging HT process	1325-1400°F ±15°F hold for **6h**; Cool 100°F ±15°F per hr to 1150-1200°F; Hold ±15°F for **2h** and air cool.	1325-1400°F ±15°F hold for 8h; Cool 100°F ±15°F per hr to 1150-1200°F; Hold ±15°F for 8h and air cool. May furnace cool at any rate provided the time at 1150-1200°F is adjusted to give **18h total**

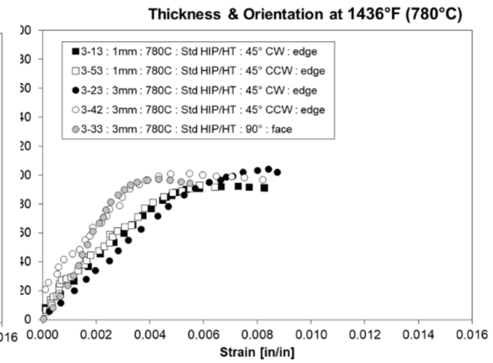
ID #	Part Description
3-11	1mm thick tensile coupon, built on edge 45deg CW Rotation
3-12	1mm thick tensile coupon, built on edge 45deg CW Rotation
3-13	1mm thick tensile coupon, built on edge 45deg CW Rotation
3-21	3 mm thick tensile coupon, built on edge 45deg CW Rotation
3-22	3 mm thick tensile coupon, built on edge 45deg CW Rotation
3-23	3 mm thick tensile coupon, built on edge 45deg CW Rotation
3-31	3 mm thick tensile coupon, built on face No Rotation
3-32	3 mm thick tensile coupon, built on face No Rotation
3-33	3 mm thick tensile coupon, built on face No Rotation
3-41	3 mm thick tensile coupon, built on edge 45deg CCW Rotation
3-42	3 mm thick tensile coupon, built on edge 45deg CCW Rotation
3-43	3 mm thick tensile coupon, built on edge 45deg CCW Rotation
3-44	3 mm thick tensile coupon, built on edge 45deg CCW Rotation
3-45	3 mm thick tensile coupon, built on edge 45deg CCW Rotation
3-51	1mm thick tensile coupon, built on edge 45deg CCW Rotation
3-52	1mm thick tensile coupon, built on edge 45deg CCW Rotation
3-53	1mm thick tensile coupon, built on edge 45deg CCW Rotation

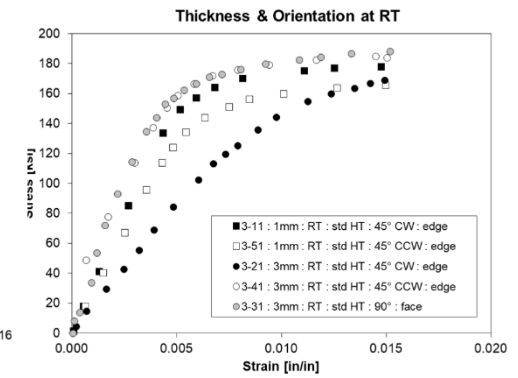
Orientations and heat treatments do show some sensitivity



SwRI AM printed materials are typically within 10% of wrought properties and early estimates.

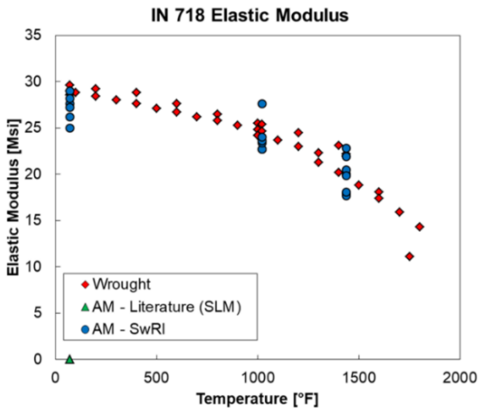


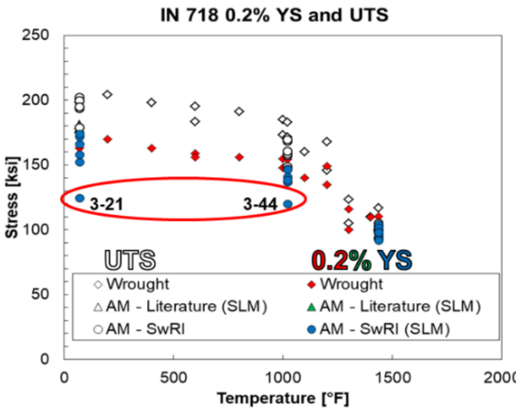




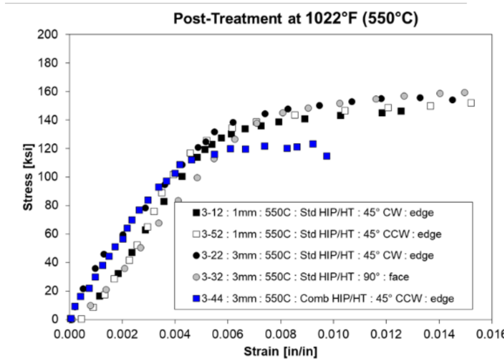
Effects of build orientation and thickness can be neglected at elevated temperatures.

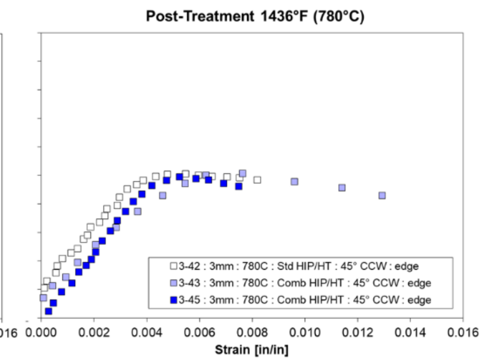
Build orientation and thickness can show sensitivity



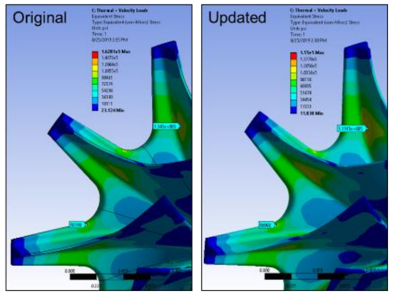


The printed materials are consistent with literature and wrought properties for all temperatures.



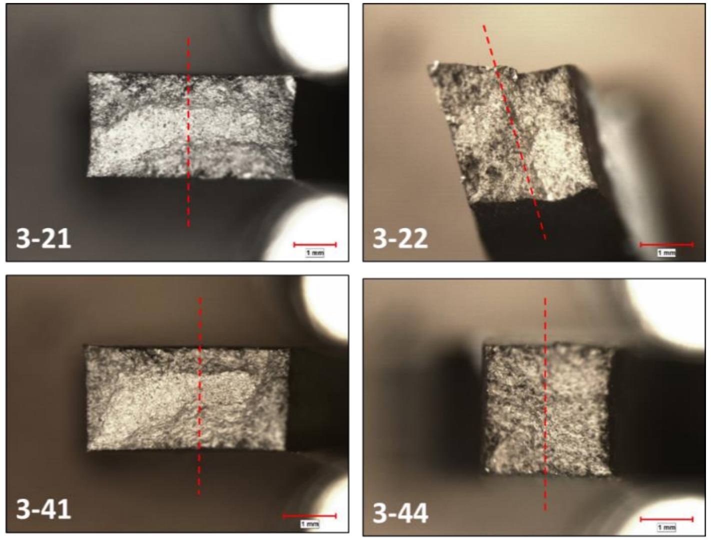


Post-treatment has little effect on material response at 780°C, but YS at 550°C is lower for the combined HIP/HT process.

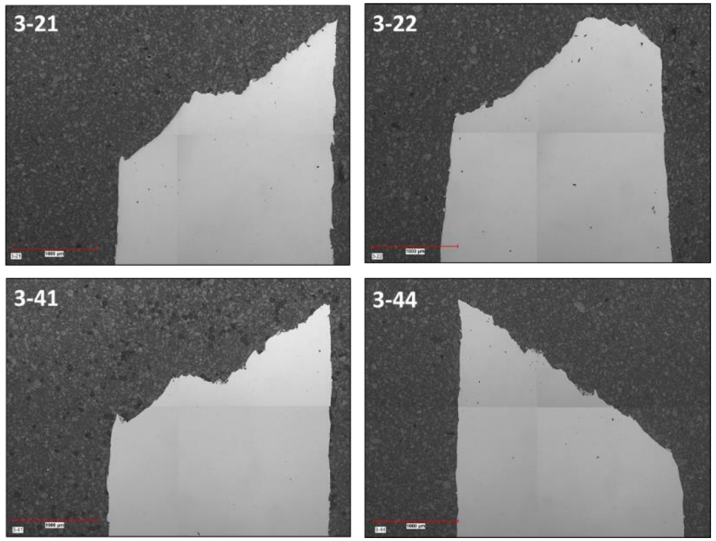


Don’t forget to update analysis predictions with the new data!

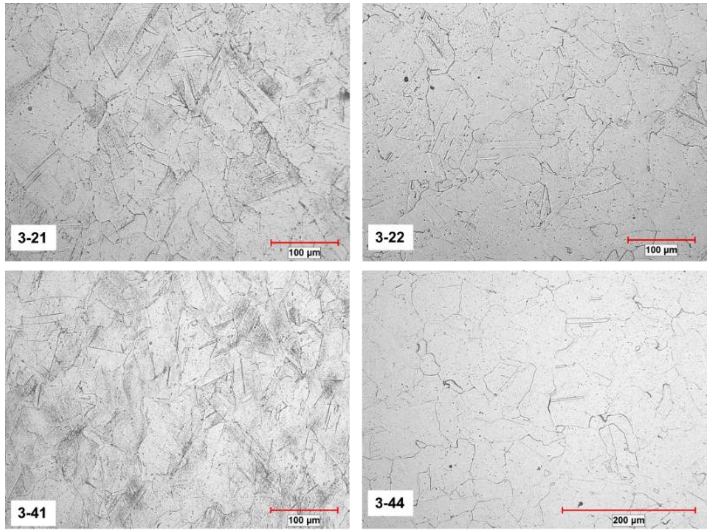
Deeper investigations made to examine anomalies



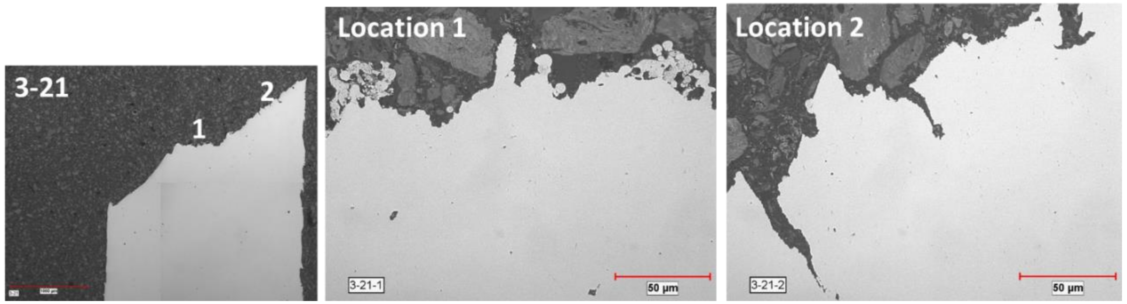
The specimens were sectioned at the fracture location for analysis.



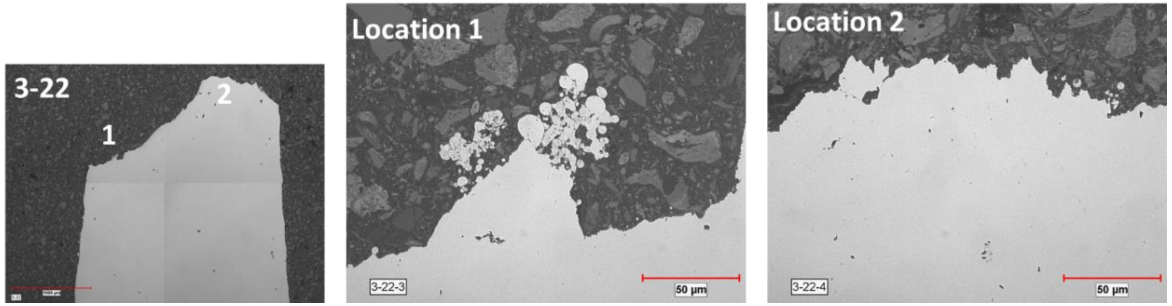
3-41 has least porosity.



No significant differences in microstructure were observed in the specimens.

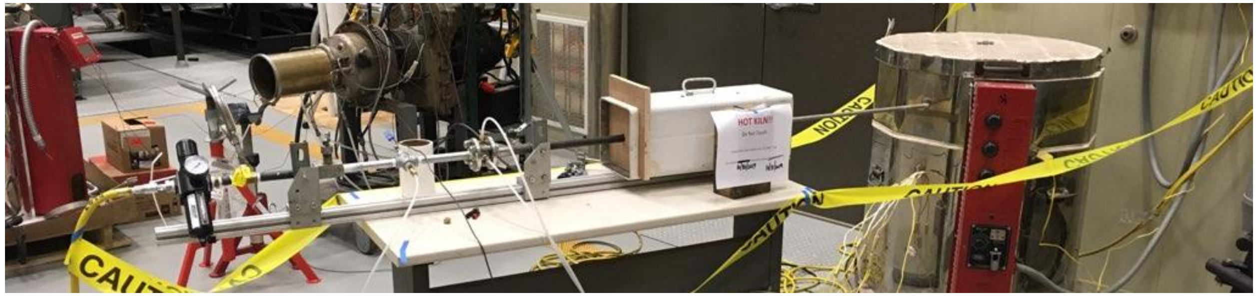


Specimen 3-21 exhibited areas of melting and partial fusion along the fracture surface.

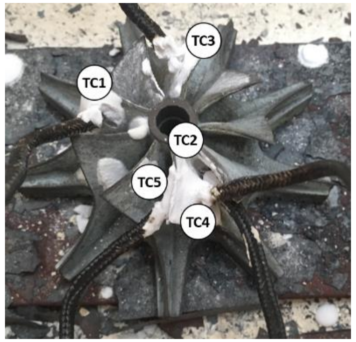


Enhanced images of the fracture surface of specimen 3-22, 3-44, and 3-41 did not indicate significant secondary cracking.

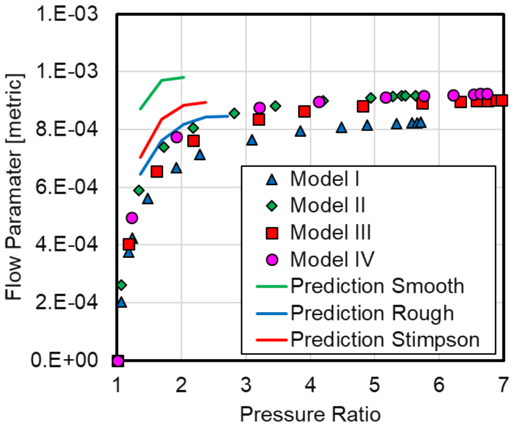
Application testing confirms form, fit and function



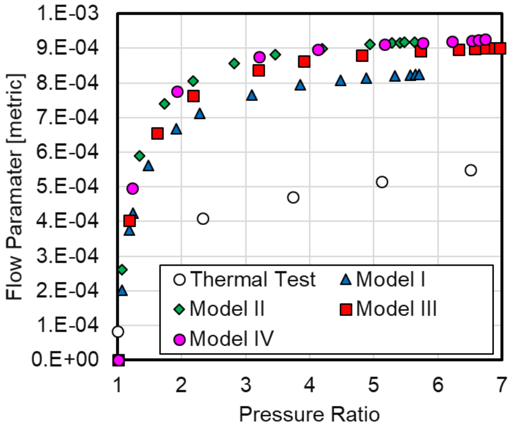
Build orientation and thickness can show sensitivity



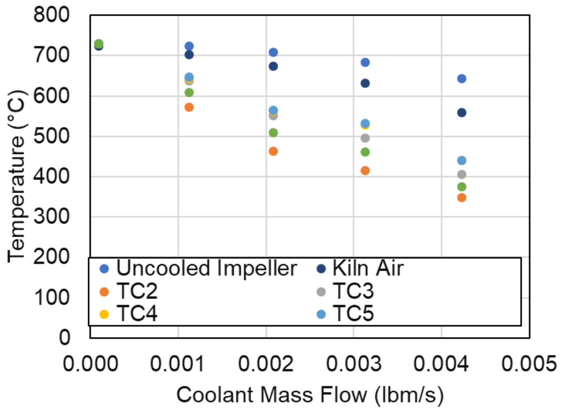
One impeller was cooled while the other impeller in the kiln served as a baseline.



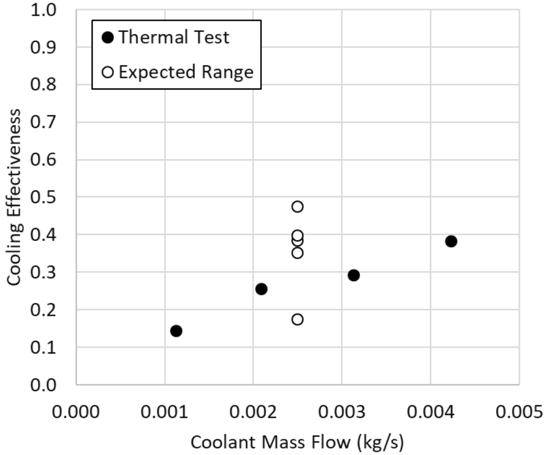
Impeller models II through IV had good flow agreement and all impeller tests indicated higher than expected surface roughness.



The flow in the thermal test was much lower than measurements recorded while the impellers were on the build plate.



Increasing the mass flow lowered the temperatures of both impellers, as expected.



The cooling effectiveness measured in the thermal test is within the expected range of the one-dimensional thermal design calculations.

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

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- AP&C
- Keystone Synergistic
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  Keegan Jackson
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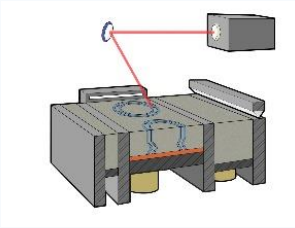
Metal Additive Manufacturing for Propulsion Applications

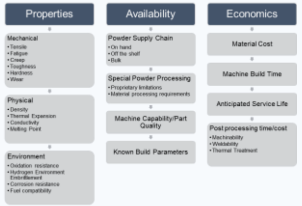
Editors: Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia

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

Chapter 1
Introduction and Applications of Additive Manufacturing for Propulsion



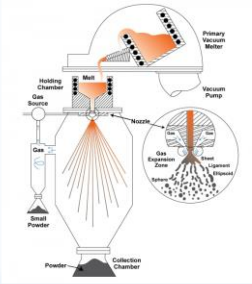
Chapter 2
Metal Additive Manufacturing Processes and Selection



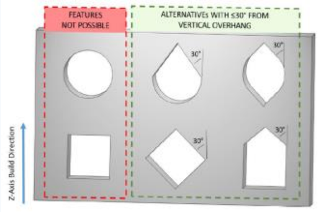
Chapter 3
Selection and Overview of Additive Manufactured Metals and Metal Alloys

Chapter 4
Microstructure and Properties of Additively Manufactured Metal Alloys

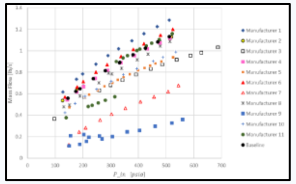
Chapter 5
Post-Processing of Metal Additively Manufactured Components



Chapter 6
Feedstock for Metal AM

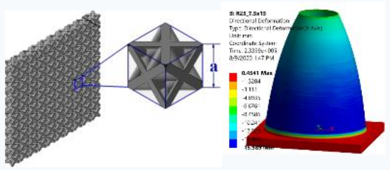


Chapter 7
Functional Design for Metal Additive Manufacturing



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