National Aeronautics and Space Administration

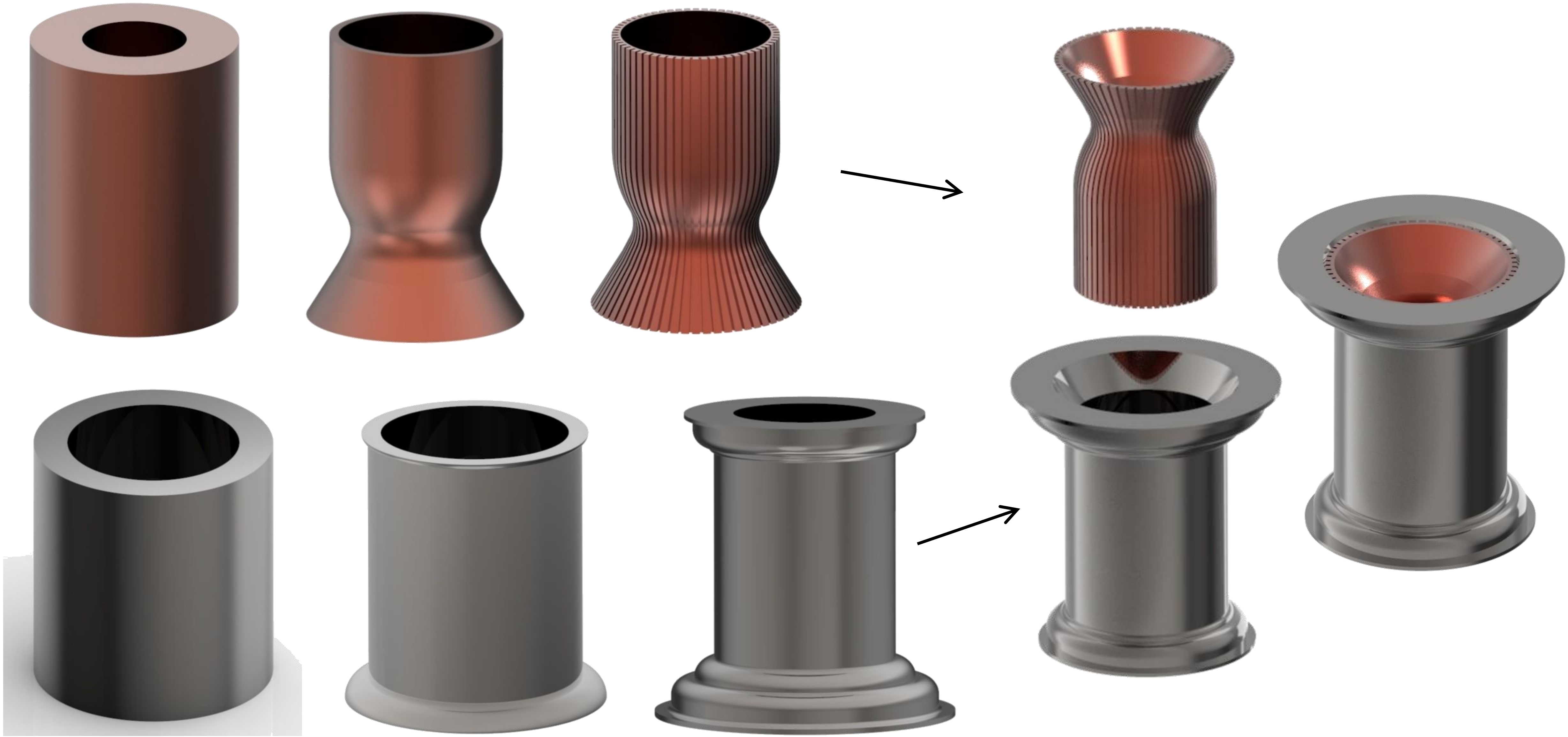
Metal Additive Manufacturing for Rocket Engines: Successes and Failures

Paul Gradl
National Aeronautics and Space Administration (NASA)

24 April 2023

Southwest Emerging Technology Symposium 2023

Traditional Manufacturing…Forging to final assembly



A rocket combustion chamber case study for AM

<table>
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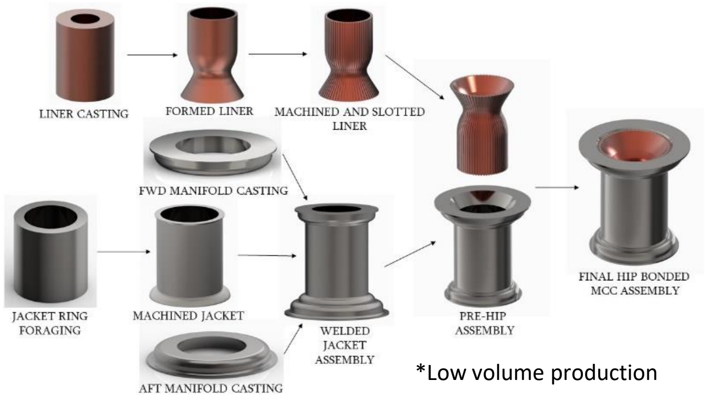
<td colspan="2">
*Low volume production</td>
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<tr>
<th>Category</th>
<th>Traditional Manufacturing</th>
<th>Initial AM Development</th>
<th>Evolving AM Development</th>
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<tr>
<td>Design and Manufacturing Approach</td>
<td>Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly</td>
<td>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</td>
<td>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</td>
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<tr>
<td>Schedule (Reduction)</td>
<td>18 months</td>
<td>8 months (56%)</td>
<td>5 months (72%)</td>
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<tr>
<td>Cost (Reduction)</td>
<td>$310,000</td>
<td>$200,000 (35%)</td>
<td>$125,000 (60%)</td>
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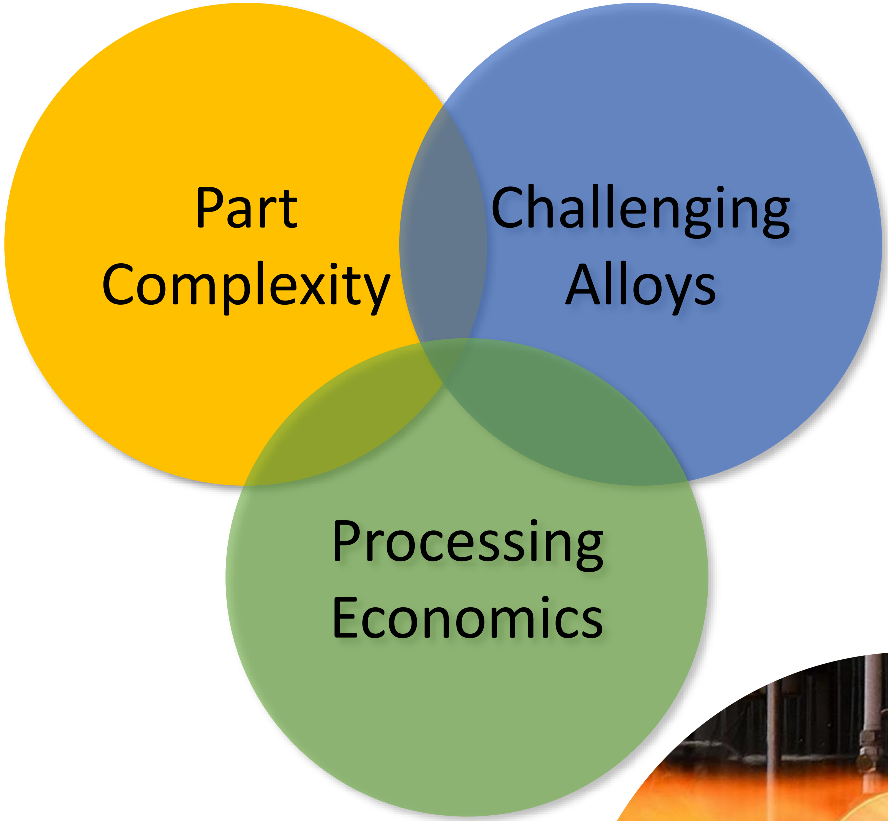
As AM process technologies evolve using multi-materials and processes, additional design and programmatic advantages are being discovered

The Case for Additive Manufacturing in Propulsion

- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities.
- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing.

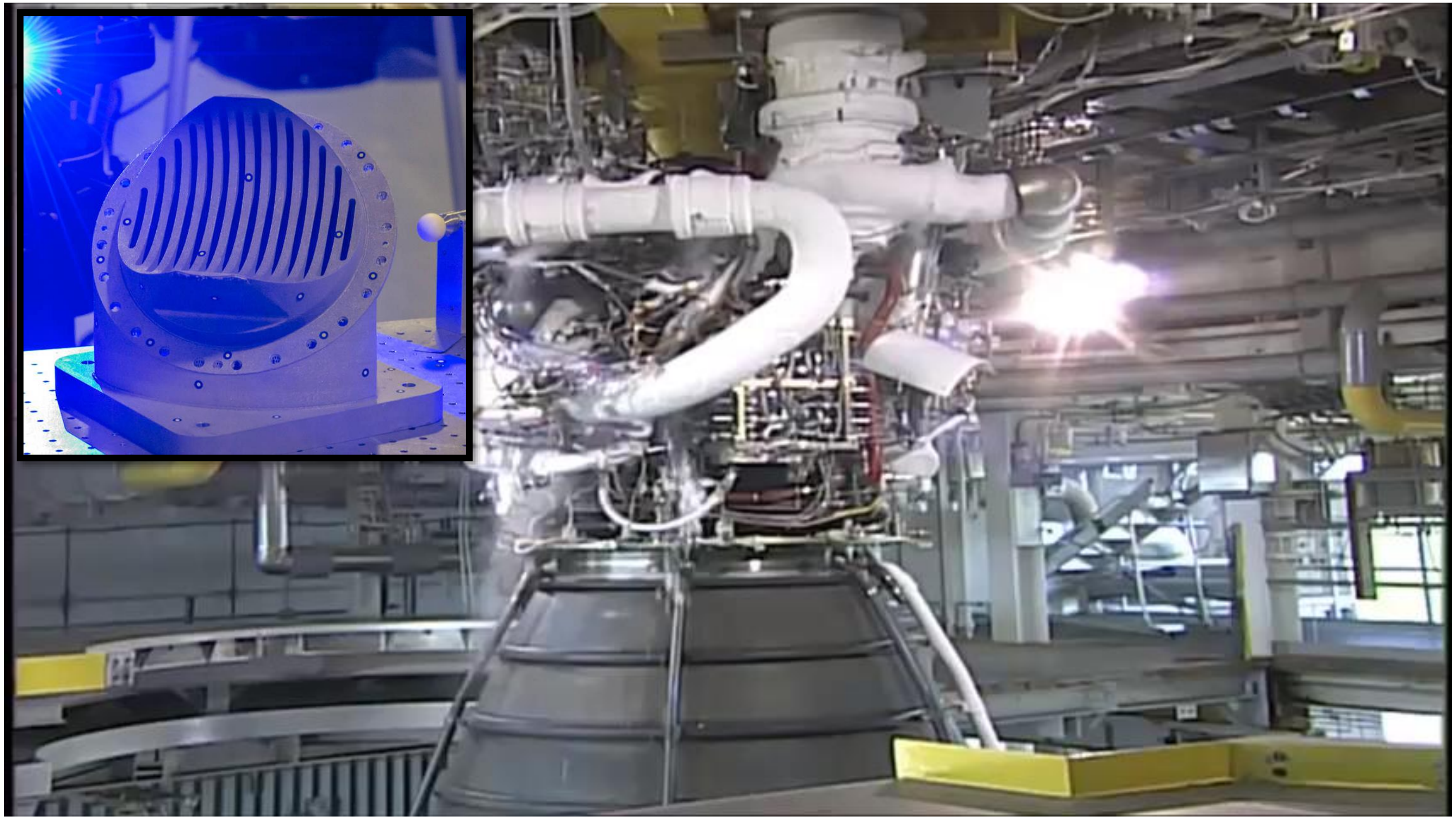


Part Complexity

Challenging Alloys

Processing Economics

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

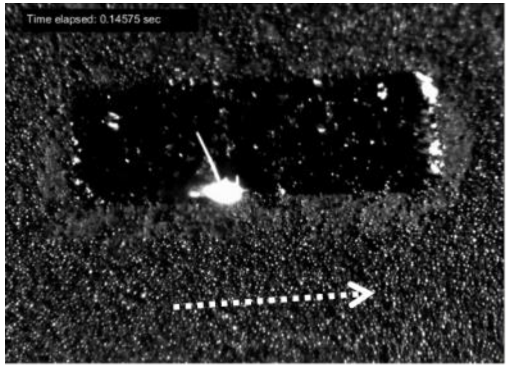


November 15, 2022

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

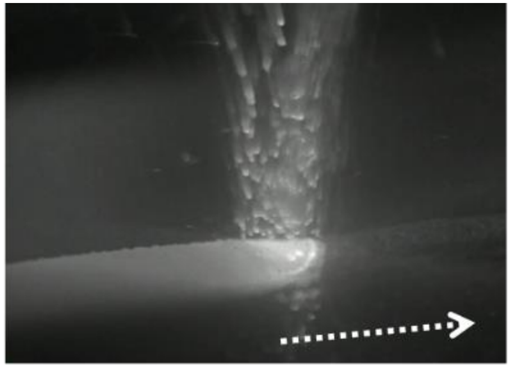
RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from <u>127 welds to 4 welds</u>

AM Processes for various applications

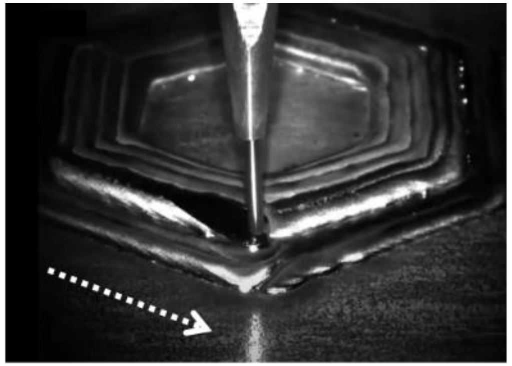


Laser Powder Bed Fusion

Electron Beam Powder Bed Fusion

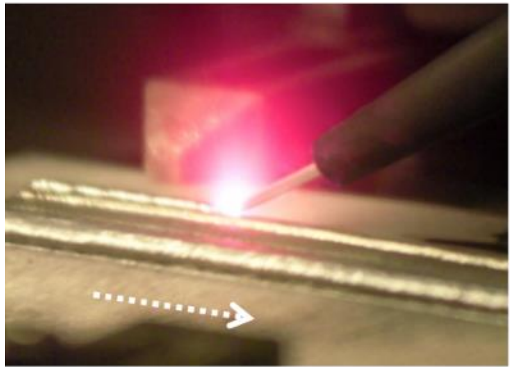


Laser Powder DED

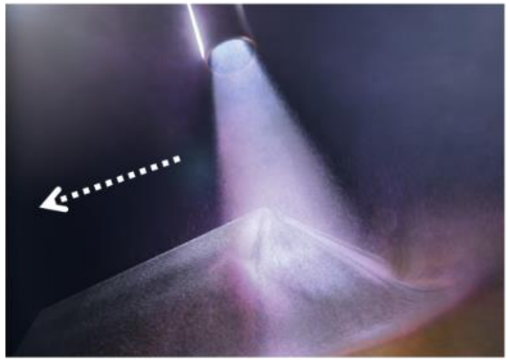


Laser Wire DED

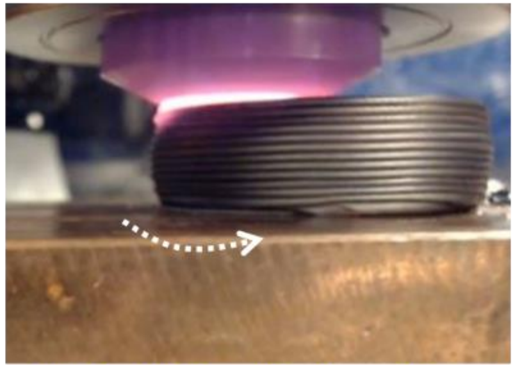
Arc Wire DED



Electron Beam Wire DED



Cold Spray



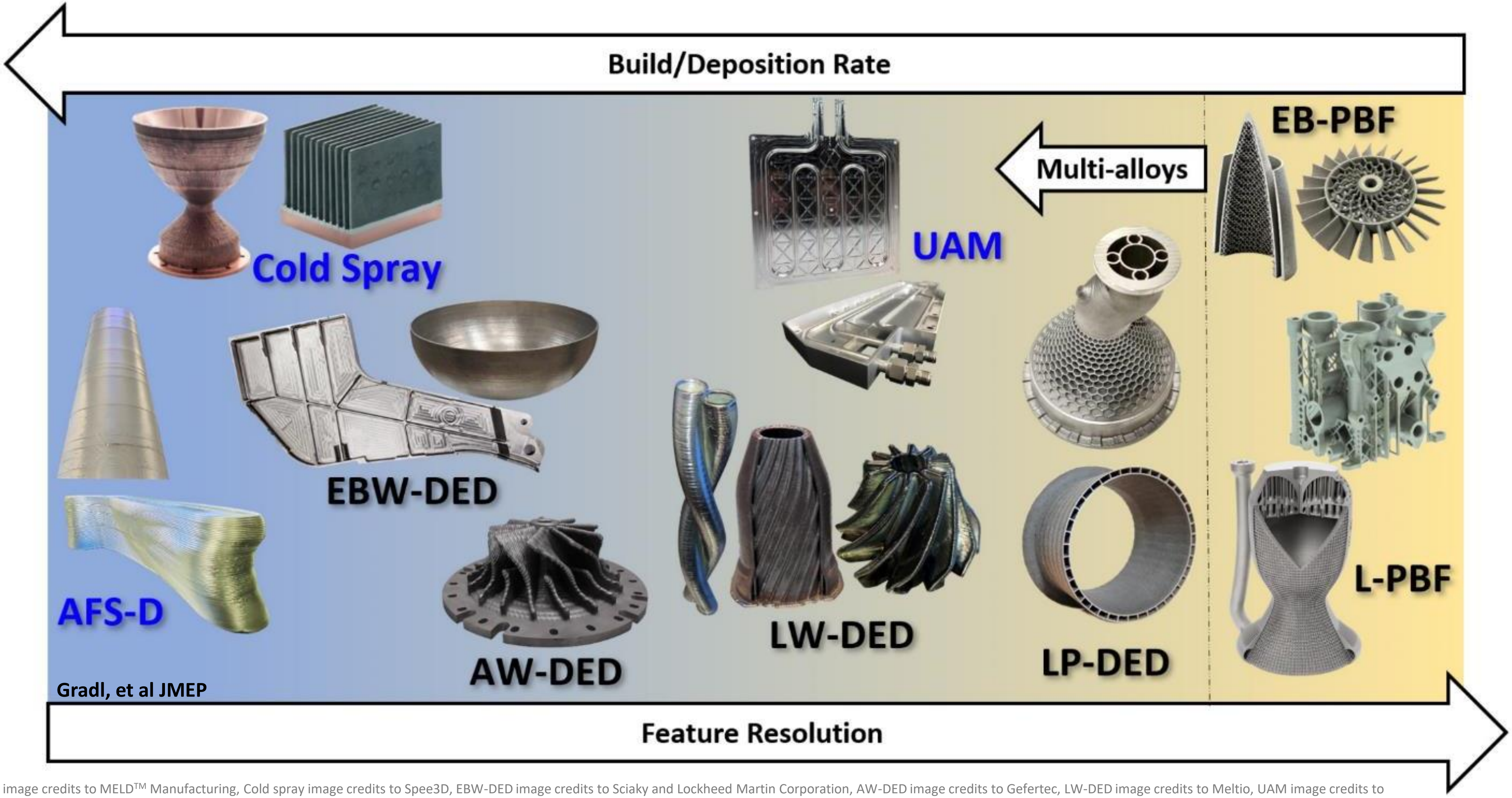
Additive Friction Stir Deposition

Ultrasonic Additive Manufacturing

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

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

Criteria and Comparison Various Metal AM Processes



Build/Deposition Rate

Multi-alloys

Cold Spray

AFS-D

EBW-DED

AW-DED

LW-DED

UAM

LP-DED

EB-PBF

L-PBF

Feature Resolution

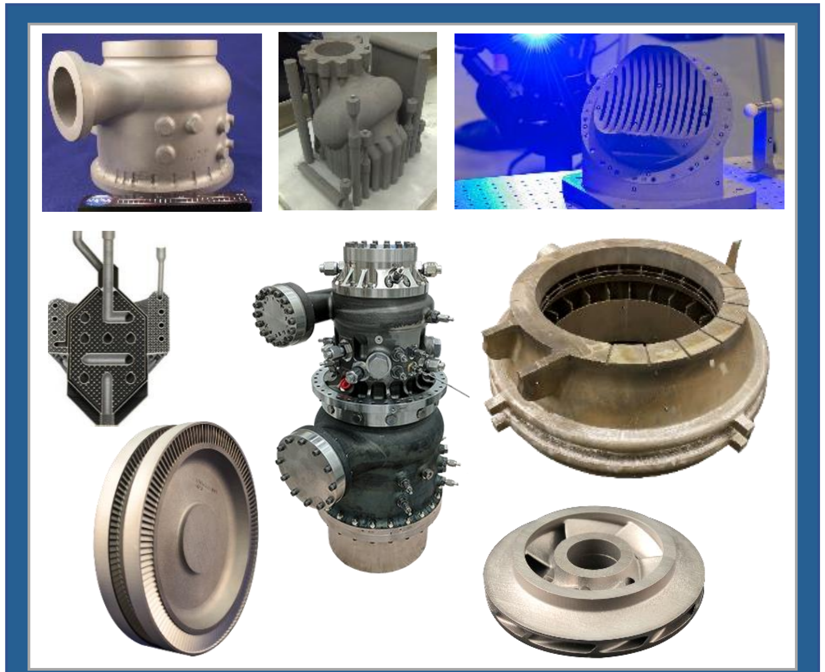
Gradl, et al JMEP

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

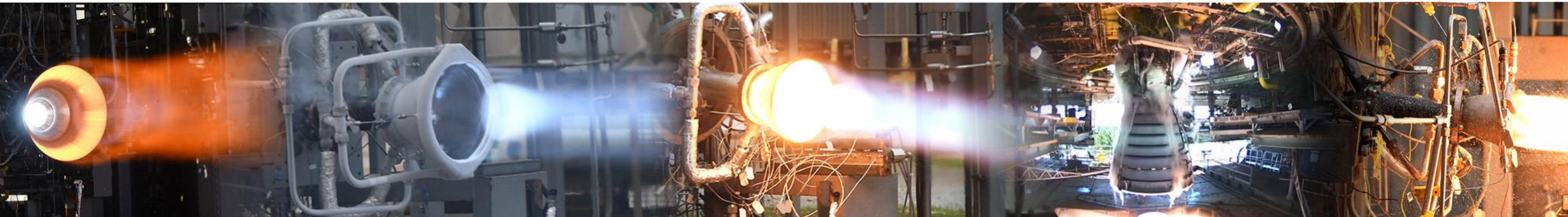
Metal Additive Manufacturing Development for Rocket Engines

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

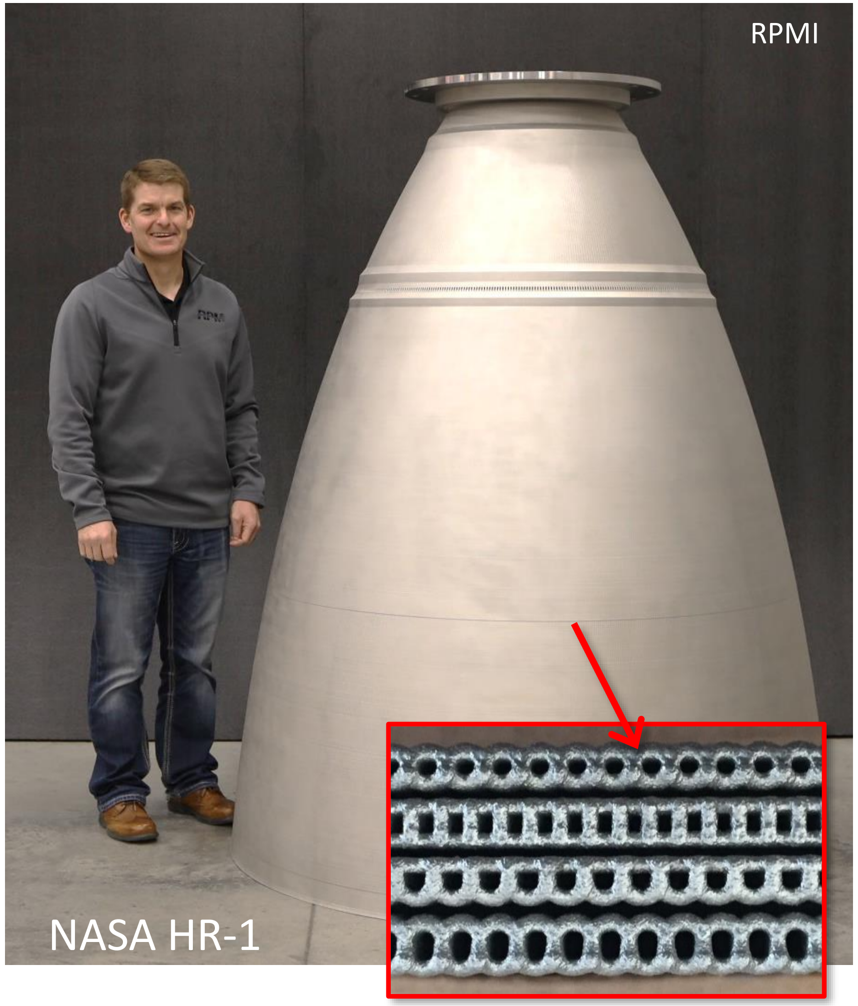
Directed Energy Deposition



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



Large Scale LP-DED Nozzle Development



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

90 day deposition

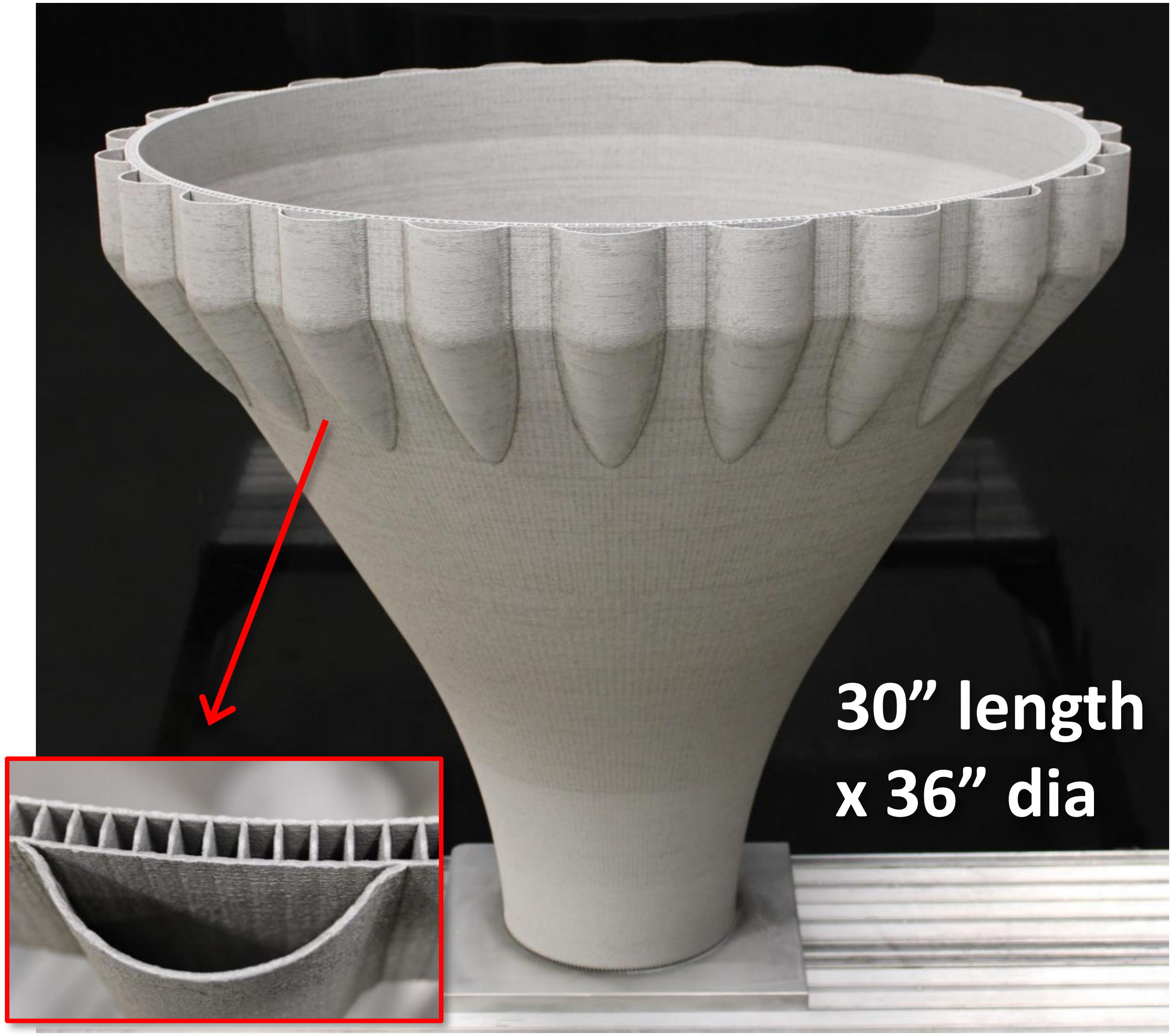
95” (2.41 m) dia and 111” (2.82 m) height

Near Net Shape Forging Replacement

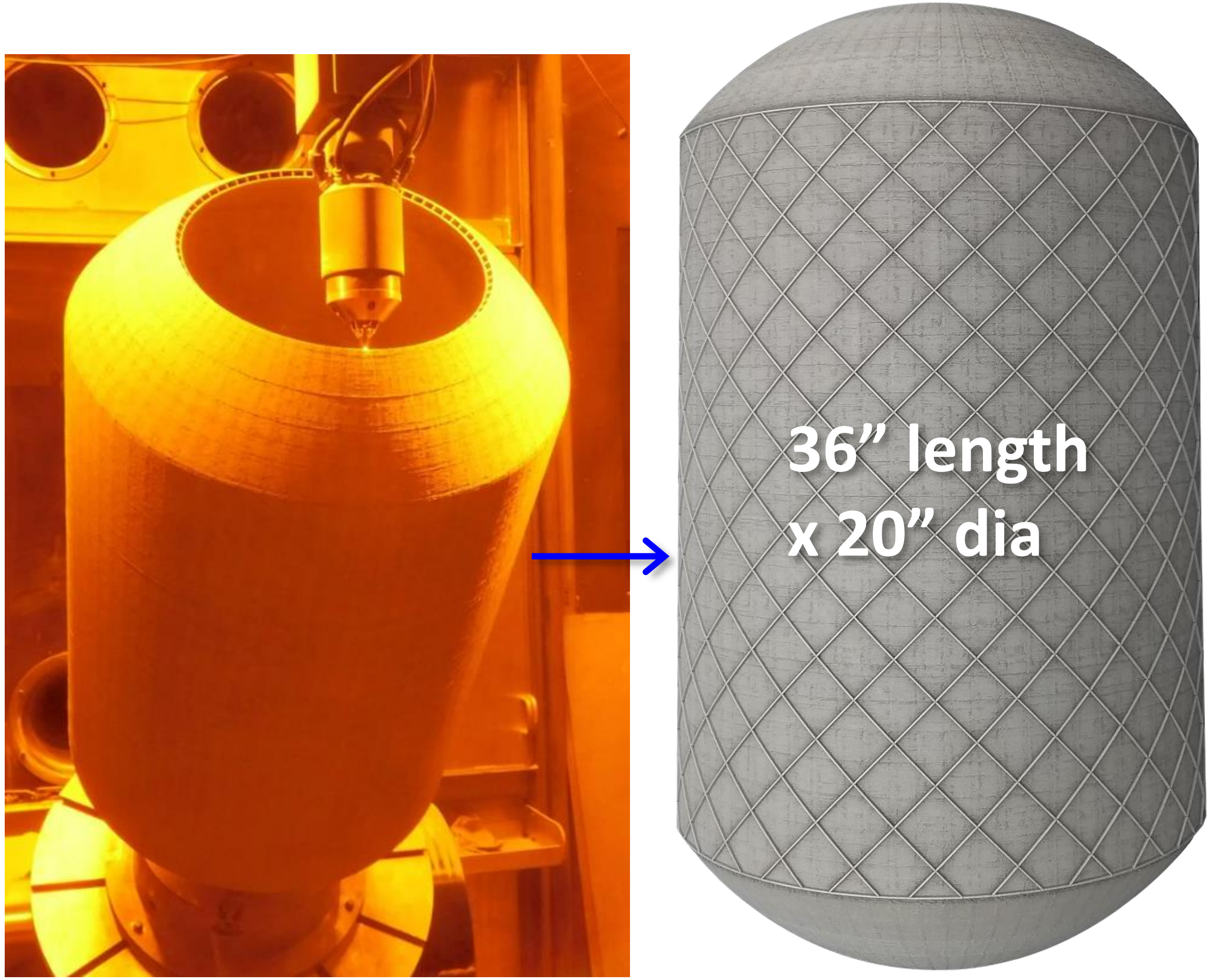
__Reference:__ P.R. Gradl, T.W. Teasley, C.S. Protz, C. Katsarelis, P. Chen, Process Development and Hot-fire Testing of Additively Manufactured NASA HR-1 for Liquid Rocket Engine Applications, in: AIAA Propuls. Energy 2021, 2021: pp. 1–23. https://doi.org/10.2514/6.2021-3236.

Aluminum Development with LP-DED

6061-RAM2 with 1.5 mm single-bead wall thickness

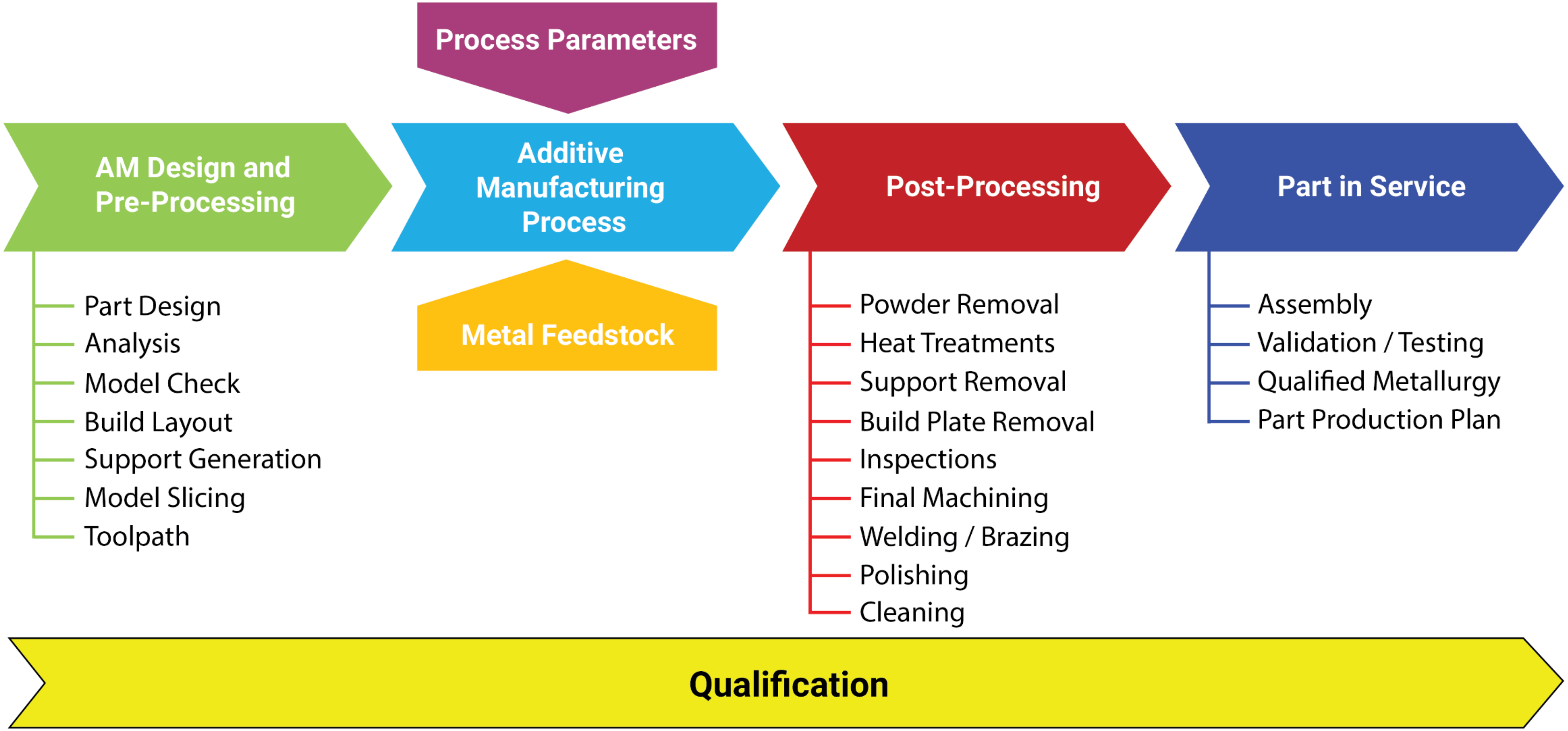


30” length x 36” dia



36” length x 20” dia

Additive Manufacturing Typical Process Flow



Process Parameters

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

Additive Manufacturing Process

Metal Feedstock

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

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

Qualification

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

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

Multi-metallic and multi-process development

Credit: RPMI

L-PBF Liner / LP-DED Jacket

L-PBF Liner / Coldspray Jacket

L-PBF Liner / EBW-DED Jacket

L-PBF GRCop-42 to Inco 625

Direct deposit LP-DED nozzle
(Axial Bimetallic)

NASA’s New Alloy Development

Max. Use Temp. (°C)	Alloy Family	Purpose	Novel AM Alloys	Propulsion Use
200	Aluminum	Light weighting	-	Various
750	**Copper**	**High conductivity; strength at temperature**	**GRCop-42 GRCop-84**	**Combustion Chambers**
800	**Iron-Nickel**	**High strength and hydrogen resistance**	**NASA HR-1**	**Nozzles, Powerheads**
900	Nickel	High strength to weight	-	Injectors, Turbines
1100	**ODS Nickel**	**High strength at elevated temp; reduced creep**	**GRX-810 Alloy 718-ODS**	**Injectors, Turbines**
1850	**Refractory**	**Extreme temperature**	**C-103, C-103-CDS, Mo, W**	**Uncooled Chambers**


GRCop-42 L-PBF


NASA HR-1 LP-DED

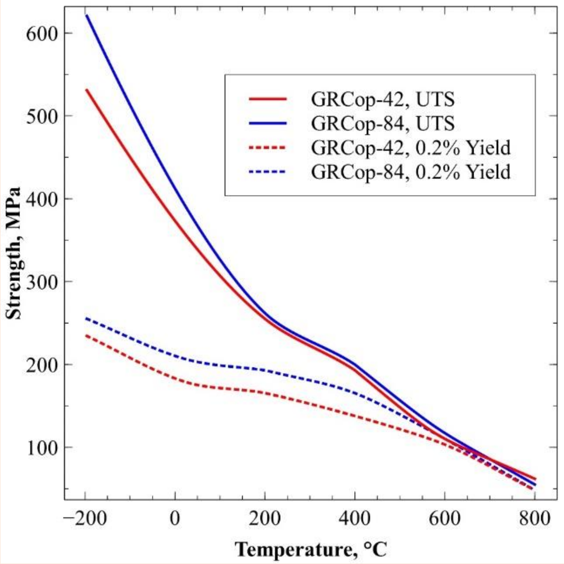

GRX-810 L-PBF

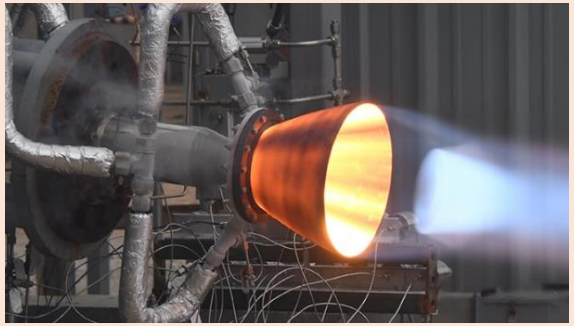

C103 L-PBF

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

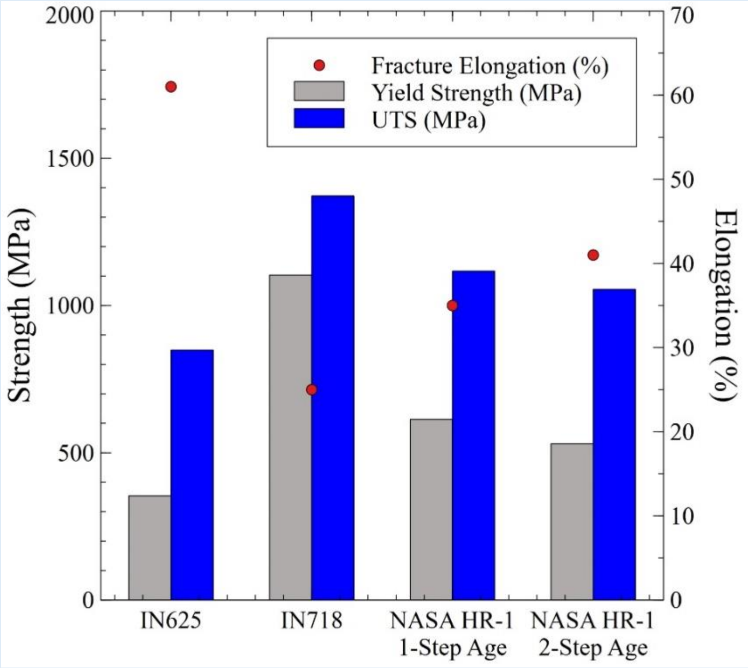
AM Enabling New Alloy Development

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

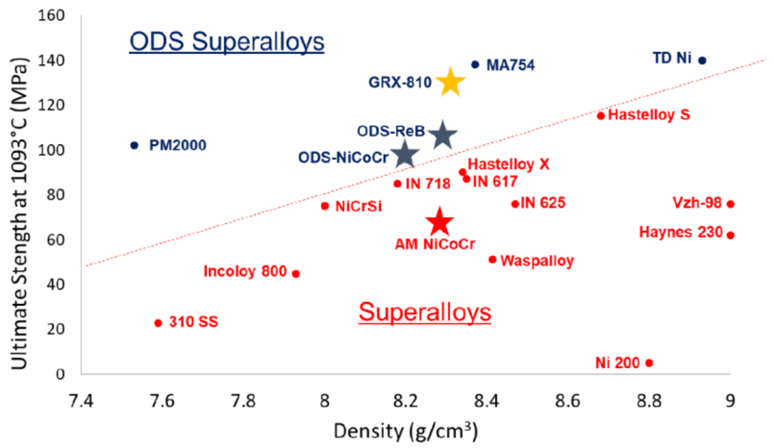




NASA HR-1, high strength superalloy for hydrogen environments



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



Ref: Tim Smith, Christopher Kantzos / NASA GRC

“It’s fine to celebrate success but it is more important to heed the lessons of failure.” —*Bill Gates*

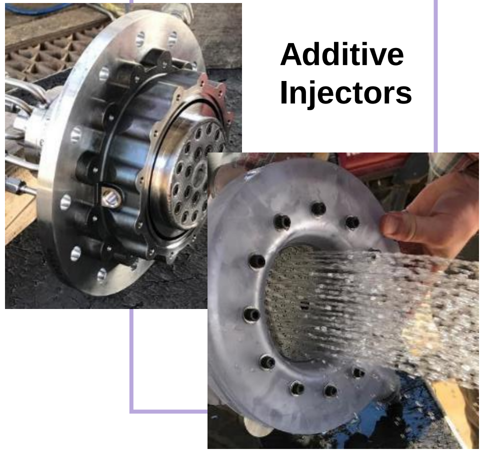
Long Life Additive Manufacturing Assembly (LLAMA) Hardware Overview


L-PBF GRCop-42 Chambers

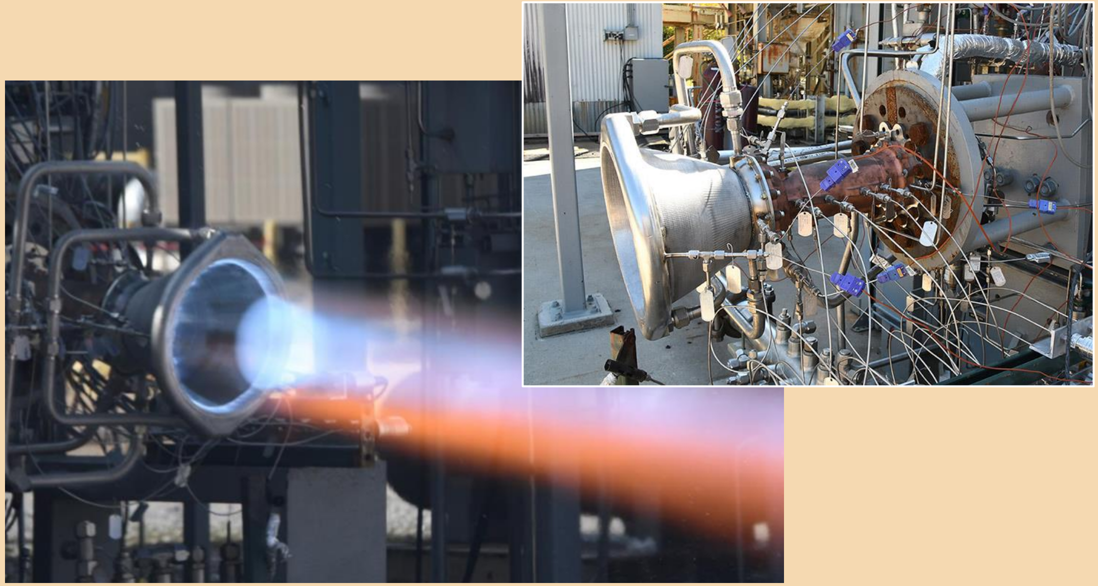
Final DED Regen Nozzle

DED of Integral Channels

Carbon-Carbon Nozzles



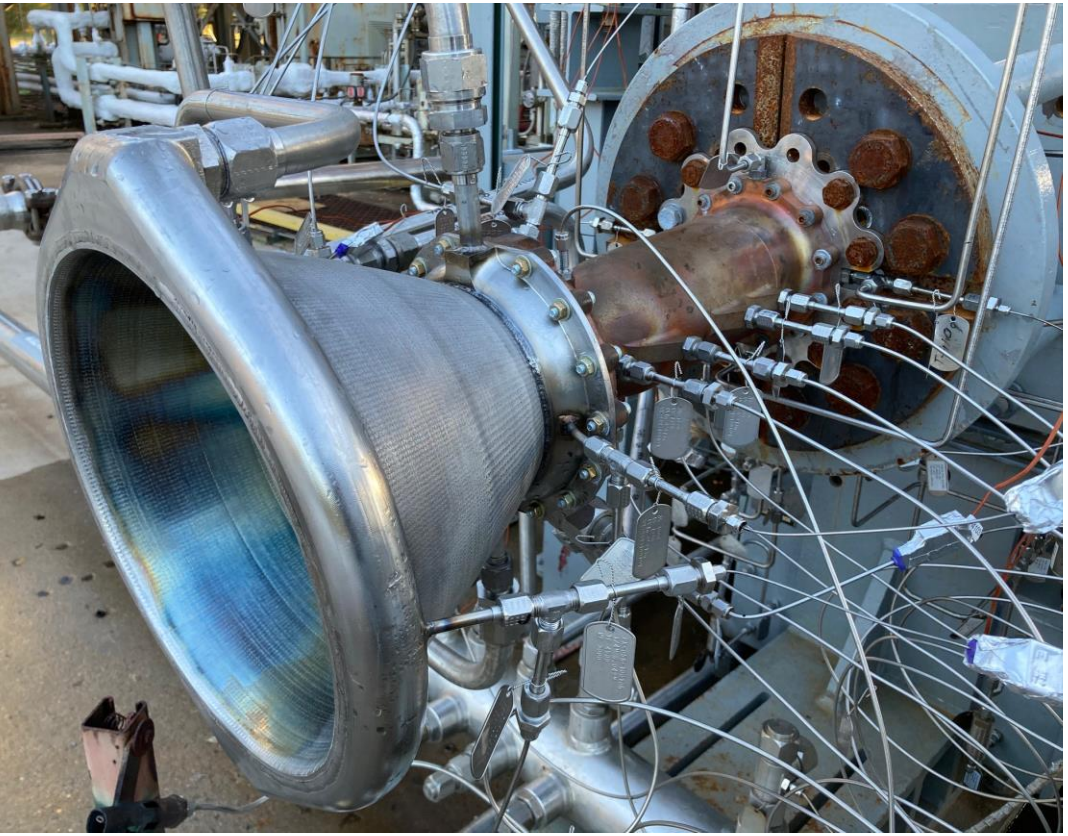
Additive Injectors



7k-lb$_f$ GRCop-42 chamber and Composite Nozzle

Successful Test of “Sister” Chamber – 51 starts

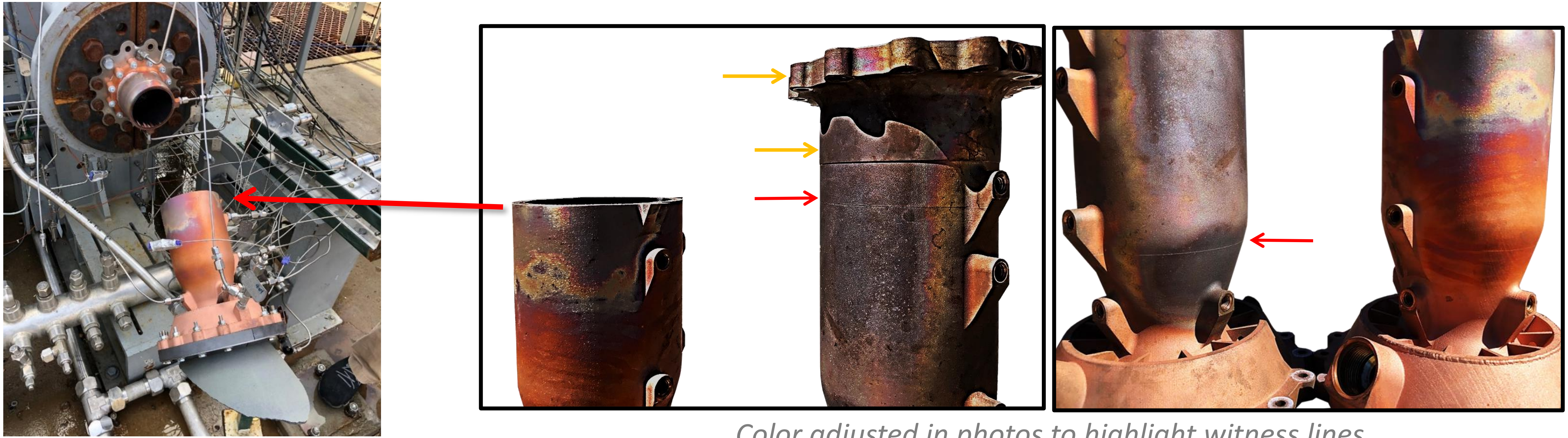
L-PBF GRCop-42 chamber from same build plate and identical processing successfully tested 51 starts and 1,000 seconds



Process Investigation – Build Interruptions

L-PBF GRCop-42 chamber

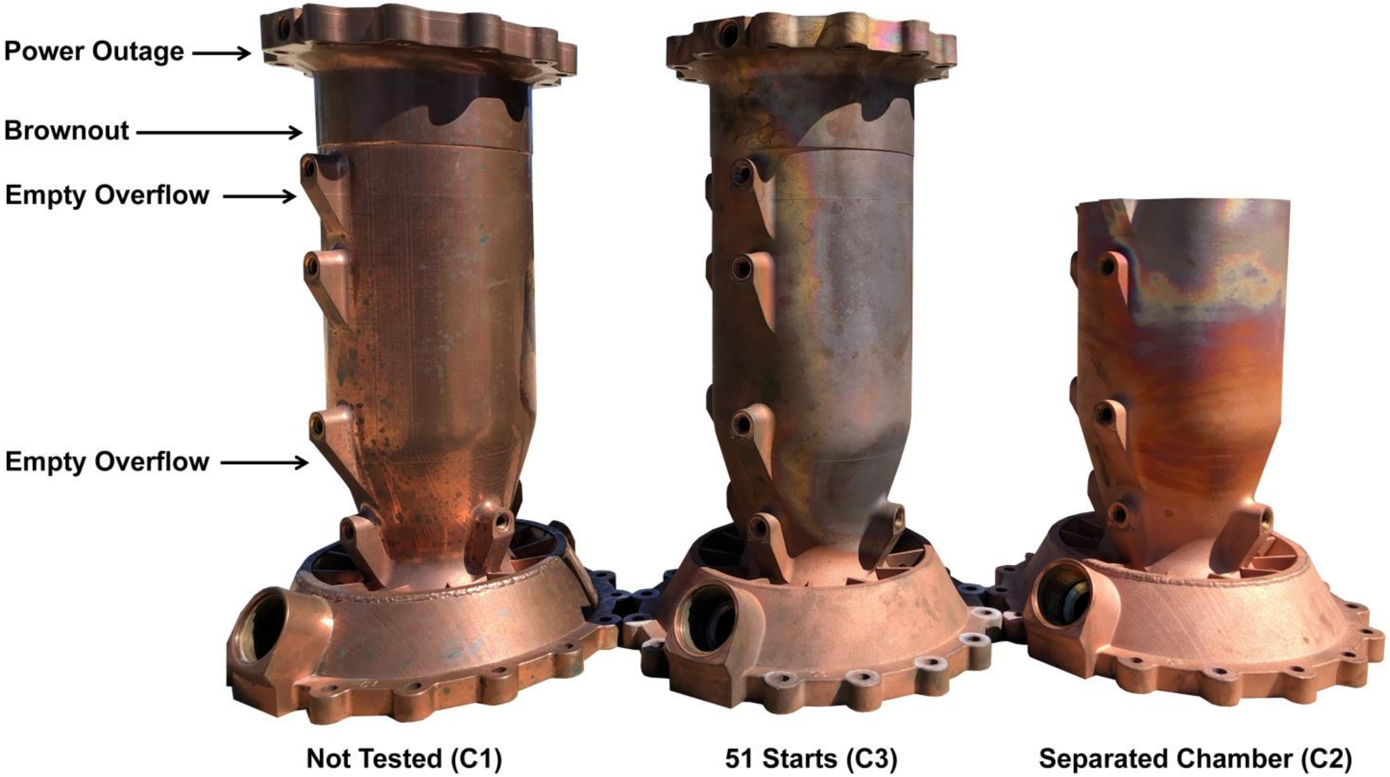
- (4) chambers on the build plate; one other tested 51 times.
- 9 starts and 83.3 sec. accumulated before separation failure.
- No issues observed in prior chamber test data.
- Build interruptions observed (power failure, powder overflow).



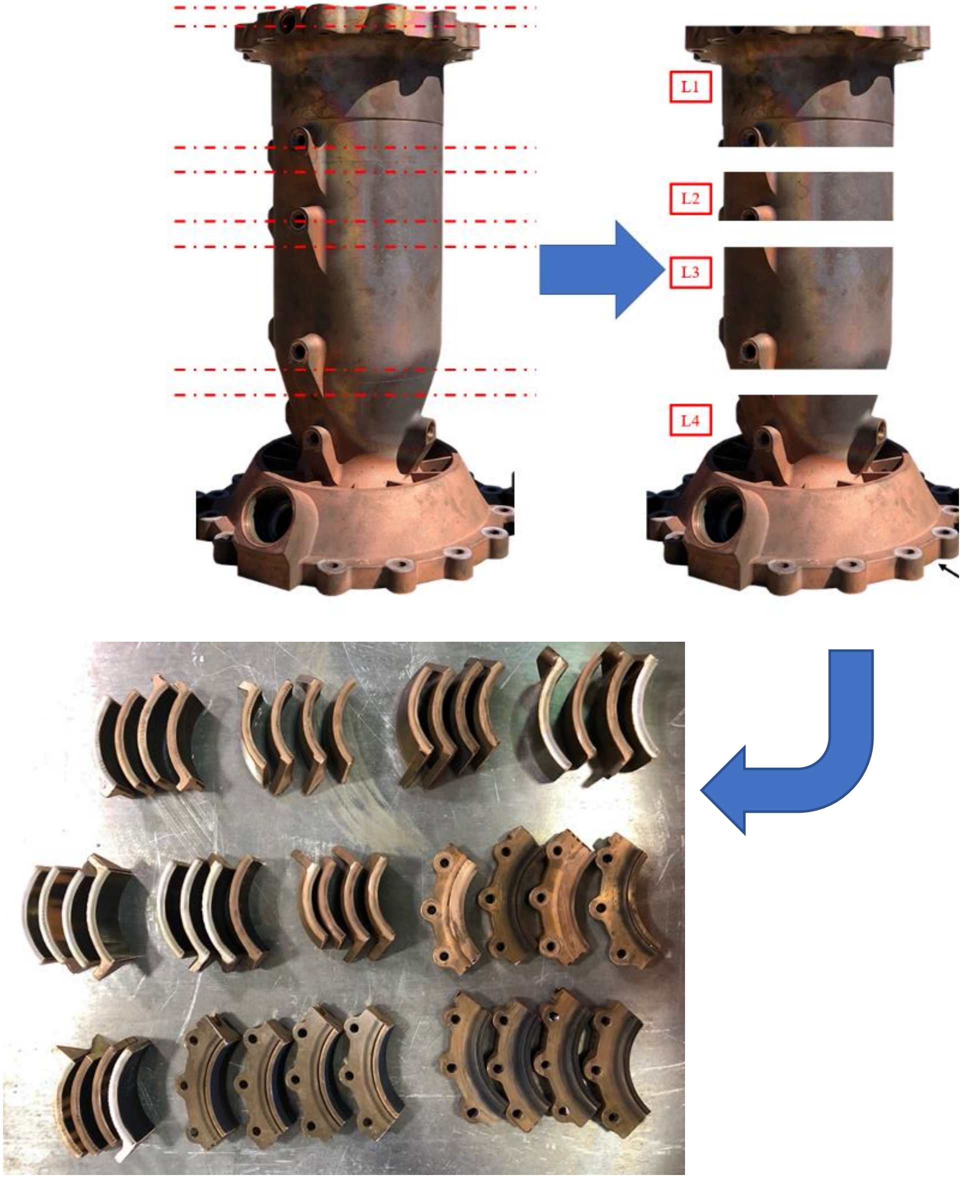
Color adjusted in photos to highlight witness lines

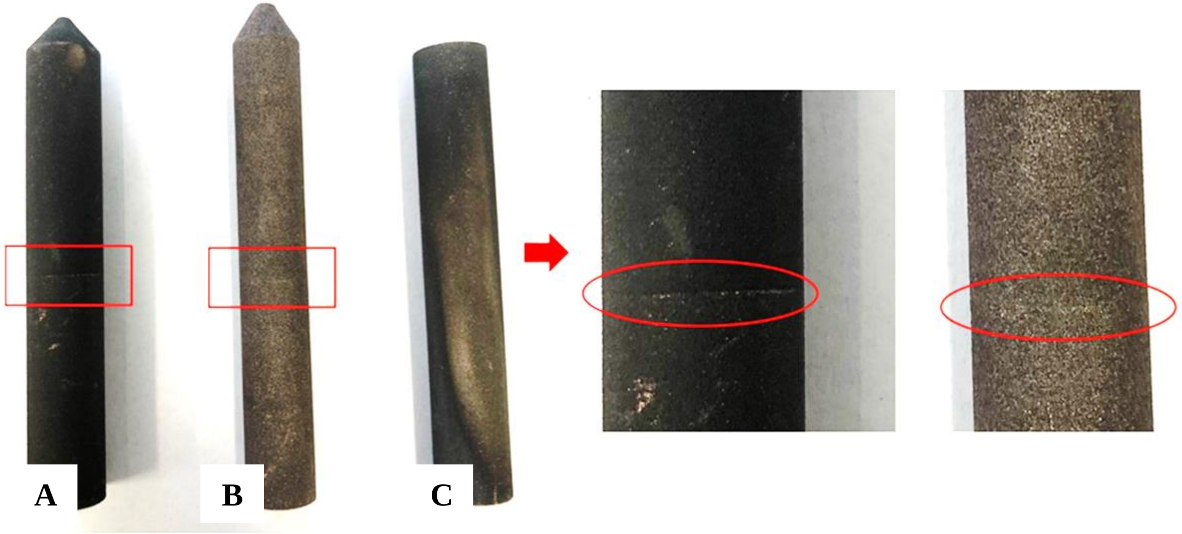
Multiple L-PBF Chambers Built and Tested

- EOS M400 L-PBF printer
  - Certified GRCop-42 powder lot
  - 4 chambers on the build
    - 3 w/ identical designs for LLAMA
- Computed Tomography Scans
  - No observations from data prior to HIP
  - Did not specifically look for witness lines – focused on powder removal verification
- Post-processing
  - C1 – HIP, EB weld manifold, exterior polishing
  - C2 – HIP, EB weld manifold
  - C3 – HIP, EB weld manifold, chemically milled



Test Specimens: Chamber Sectioning, Test Bars

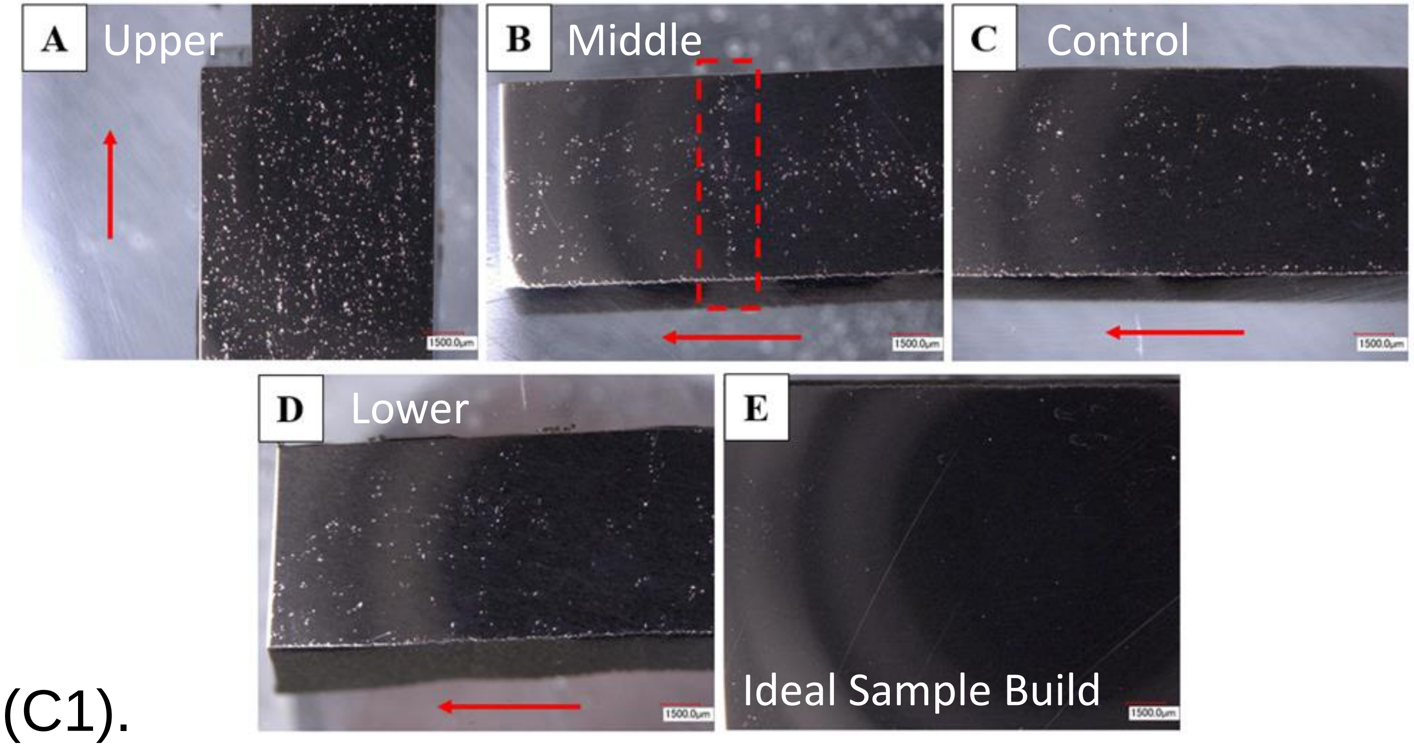




Bar	Chamber Restart Replicated	Witness Line Replicated	Restart
A	None	Control Section	None
B	Empty Overflow	Middle and Lower	Chamber Open
C	Power Outage	Upper	Chamber Closed

Optical Images of Chamber Sections

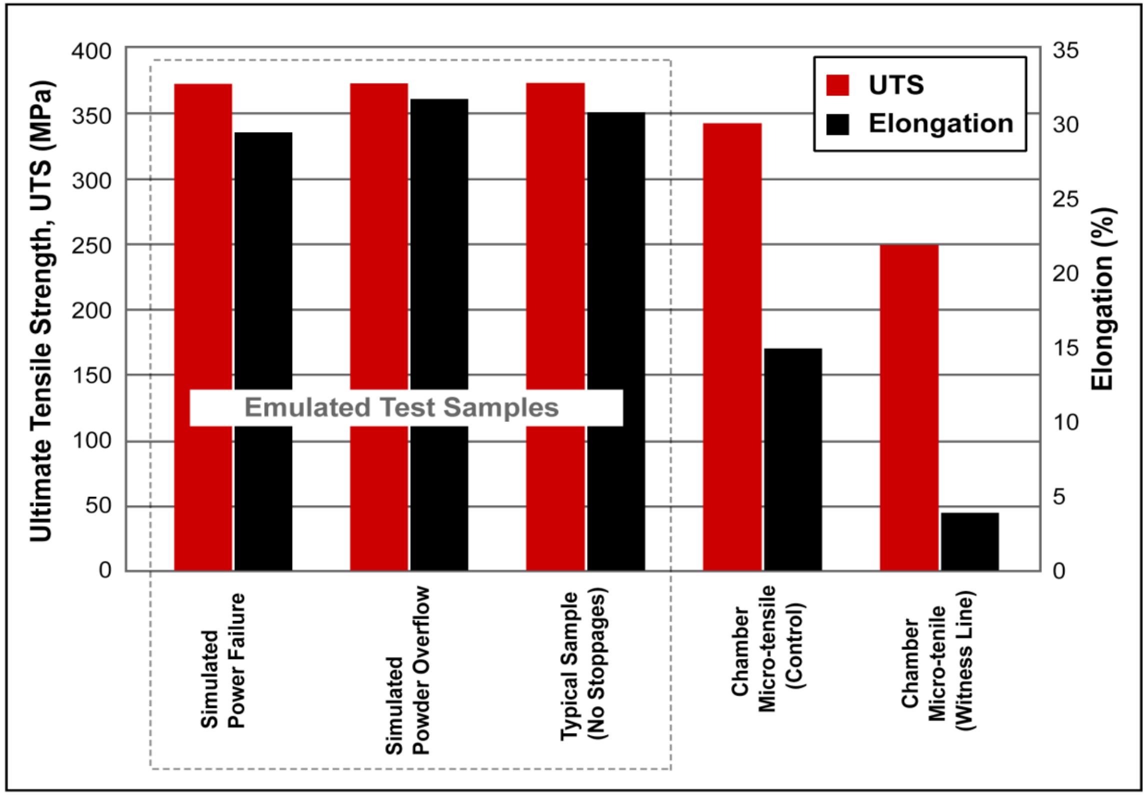
Label	Section	Porosity
A	Upper Witness Line	0.748%
B	Middle Witness Line	1.906%
C	Control Section	0.511%
D	Lower Witness Line	1.743%
E	Tensile Bar	0.006%



- Samples taken from un-tested chamber (C1).
- Tensile bar built separately as part of investigation.
  - Emulated process build interruptions.
- Proper HIP of chambers was confirmed.
- Porosity is evident throughout samples.
- Clear congregation of porosity around witness lines.
- Porosity reduces load bearing capacity (reduced area) and can act as stress concentrators/crack initiators.

Combined Microtensile & Tensile Results

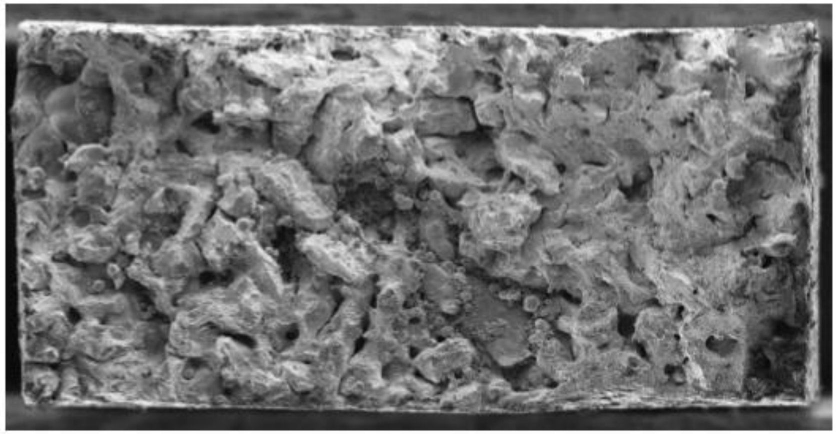
- Room temp tensile testing conducted on ASTM E8 specimens (0.25” dia gage) from witness bars with various restarts
  - Testing at 1200F for ASTM E8 round bars showed similar trends
  - Fracture surfaces appeared similar
- Microtensile testing conducted at room temp on section from chamber (C1 and C3) at witness line and non-witness



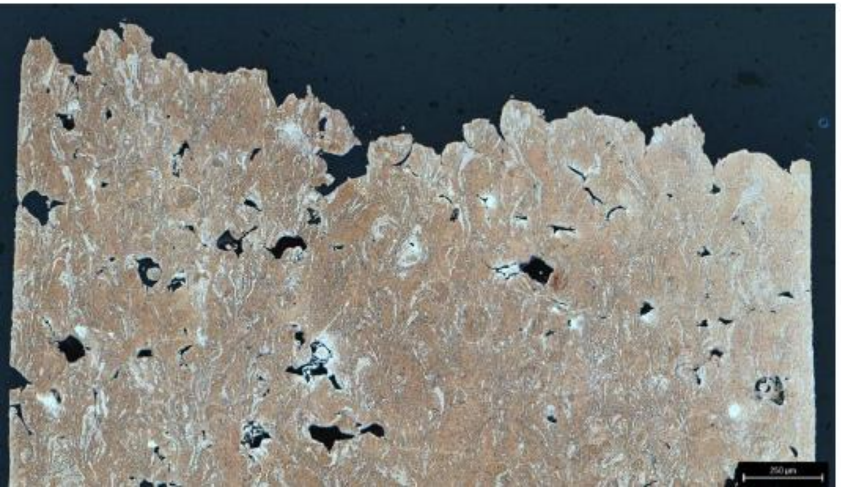
Fractography of Samples after Mechanical Testing

Microtensile

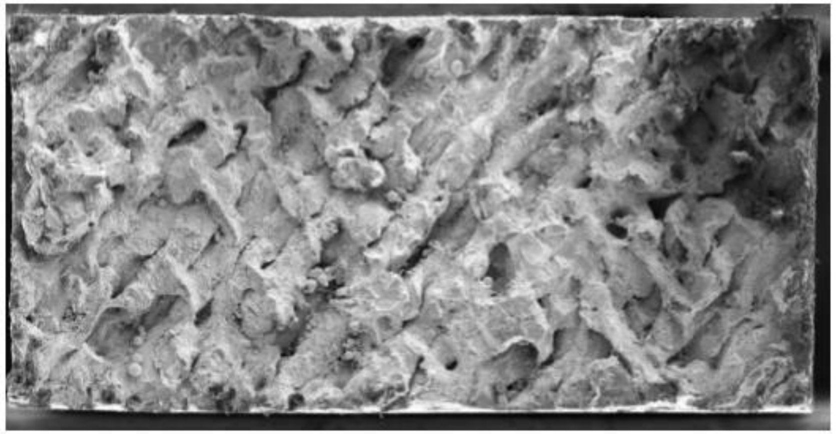
1T1B



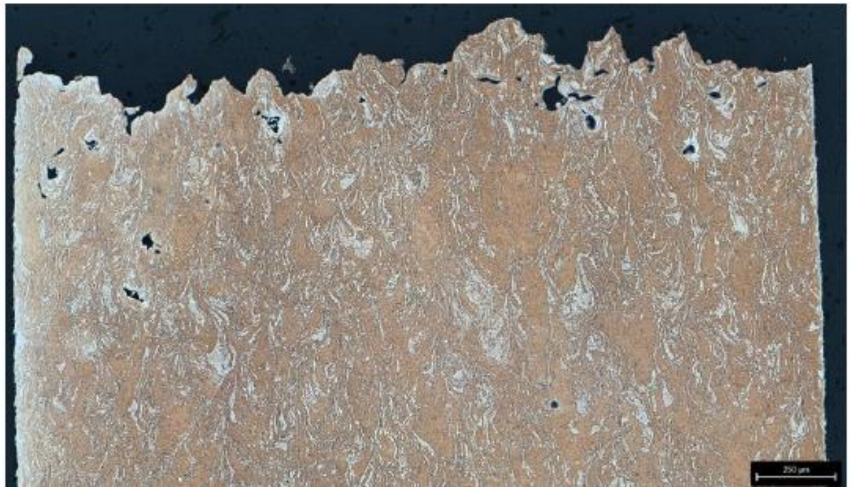
- Granular fracture surface, indicating a brittle fracture
- Irregular shape porosity, indicating lack of fusion



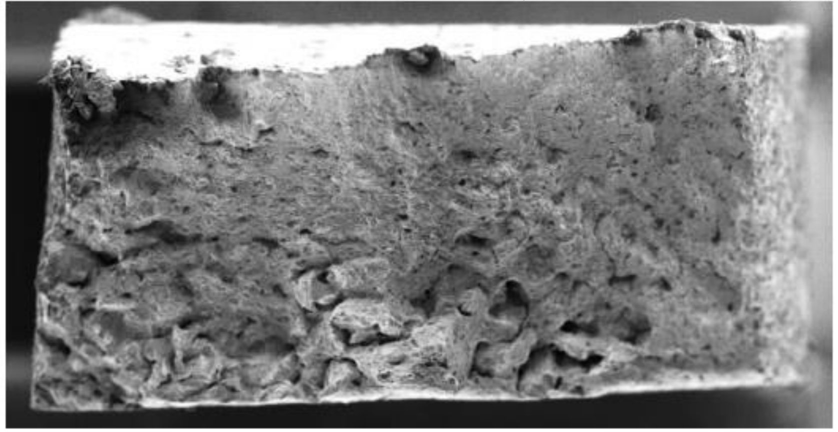
1T2B



- Granular fracture surface, indicating a brittle fracture
- Laser scan pattern clearly visible



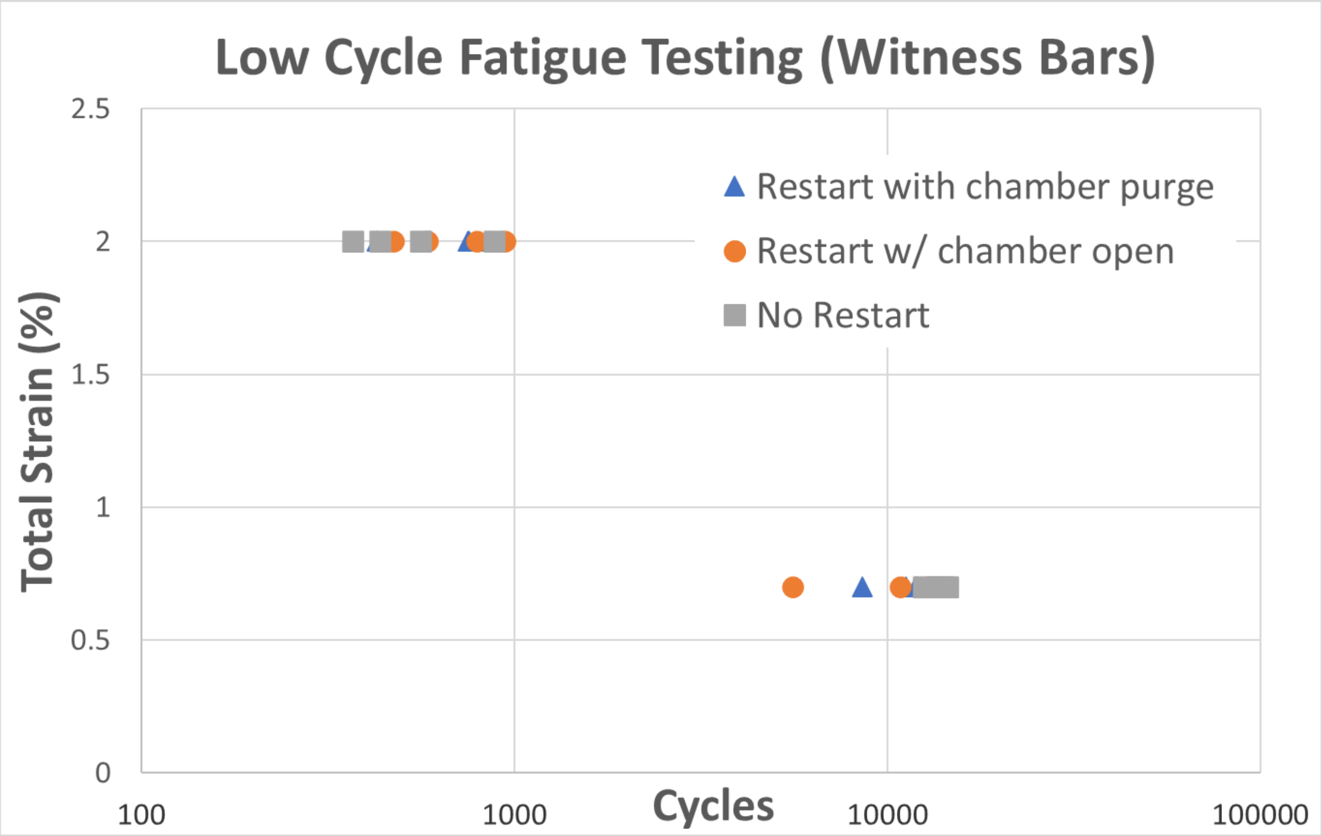
1T3B (Chamber Control)



- Overloaded fracture surface and necking, indicating a more ductile fracture
- Less porosity compared to witness lines

Low Cycle Fatigue of Emulated Build Interruption Samples

- LCF conducted at room temperature, total strain of 0.7% and 2%
- R = -1, triangular



	Restart w/purge	Restart, open	No restart
2%, Avg	785	781	562
St Dev	175	182	228
0.7%, Avg	12171	10677	13669
St Dev	1657	3582	849

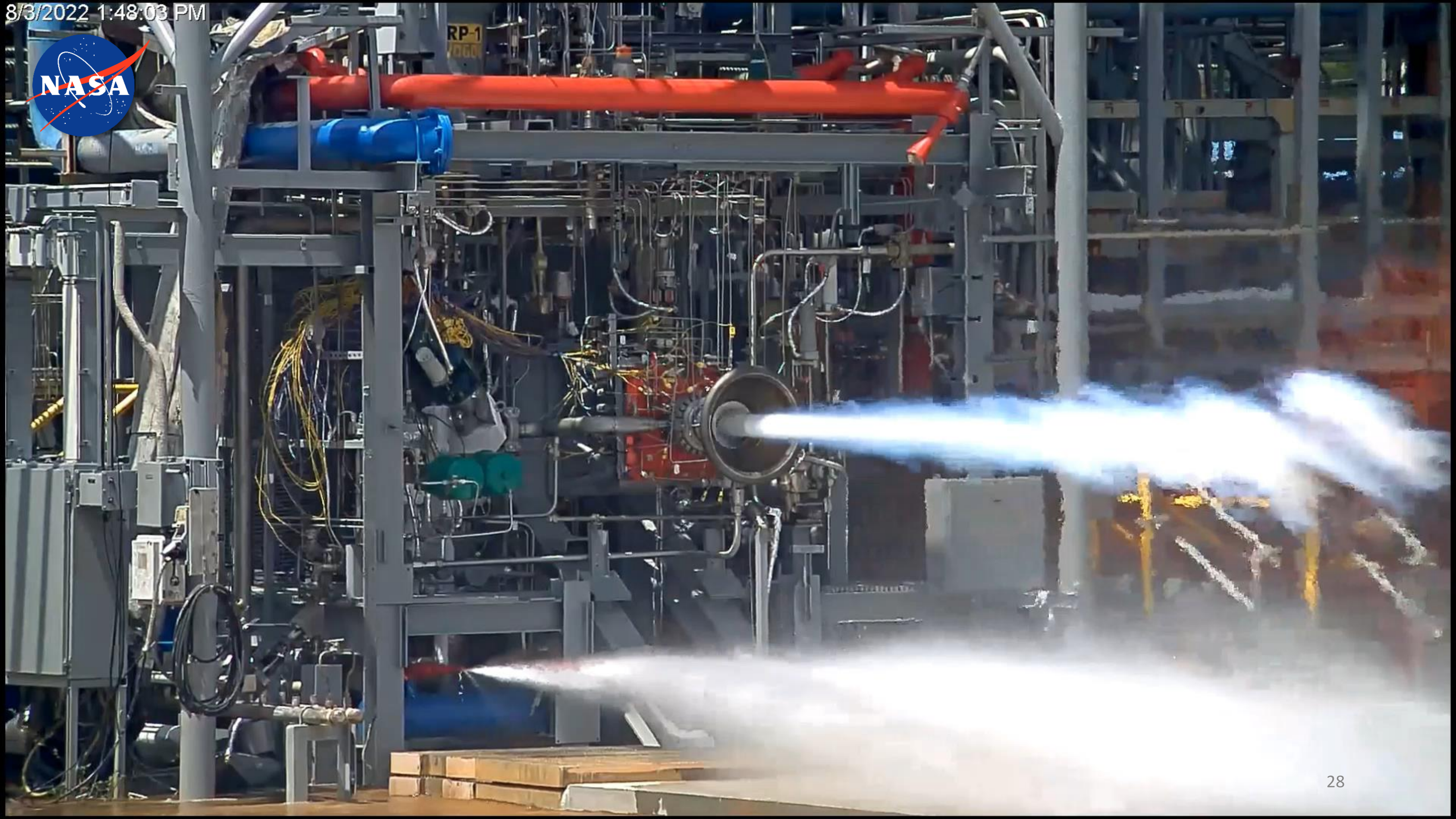
Strain, %	Cycles, Nf
2	924
2	840
2	529
2	846
0.7	9,760
0.7	12,597
0.7	13,531
0.7	12,796
2	668
2	593
2	986
2	878
0.7	5,579
0.7	10,805
0.7	13,426
0.7	12,899
2	369
2	437
2	559
2	882
0.7	14,038
0.7	12,514
0.7	14,499
0.7	13,624

*4 samples per test case

Failure Conclusions and Recommendations

- The L-PBF GRCop-42 chambers built under LLAMA had higher porosity (1-2%) that congregated more at witness lines causing lack of fusion and tensile overload.
  - Granular surfaces, unmelted particles, and irregular pores were observed in microtensile specimens (sectioned) from chambers.
- Demonstrates the <u>process sensitive nature of AM parts</u> and build interruptions need to be properly documented, fully evaluated, and properly dispositioned.
- <u>Build log indicated no issues with parameters, but *an issue*</u> (parameters, lens, etc) caused the porosity and HIP did not fully close these voids.
- Build interruptions in GRCop-42 components do not inherently possess weakened material properties if a restart procedure is properly executed.
- <u>Full height specimens should be built with all components</u> to characterize the material.
- While not subject to NASA-STD-6030, this chamber provides a good case study on why it is important that AM materials used in critical applications adhere to NASA-STD-6030 standards and the need for robust process development, in-depth material evaluation, and process controls.

Separated Chamber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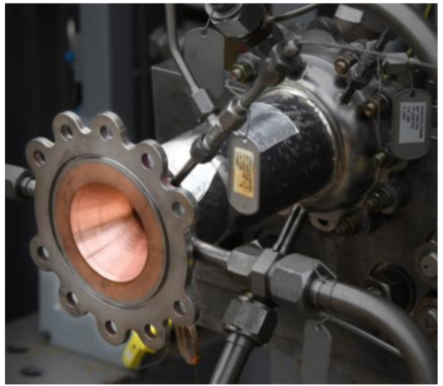
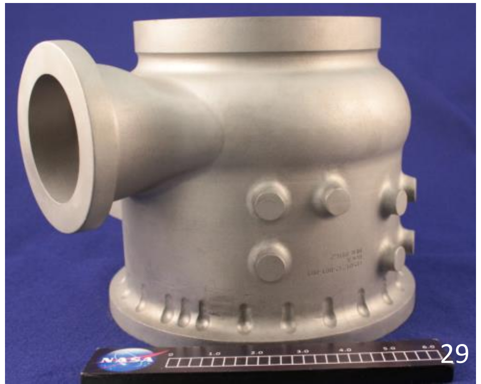
Summary

- 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.





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

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Timothy C. Lieuwen, Editor-in-Chief
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https://arc.aiaa.org/doi/book/10.2514/4.106279

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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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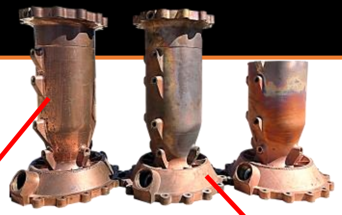
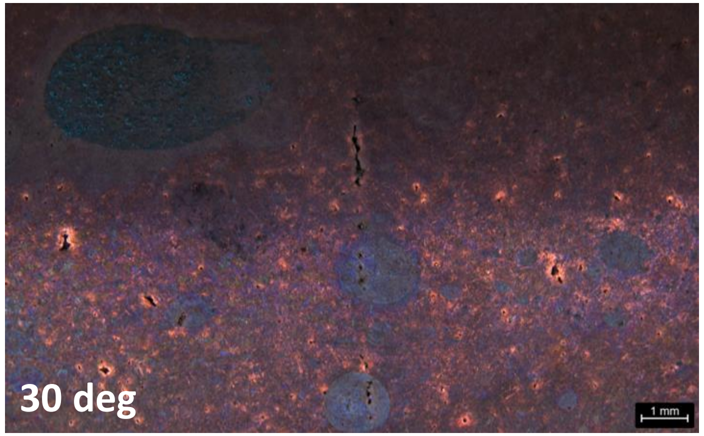
Photo: NASA/Ben Smegelsky

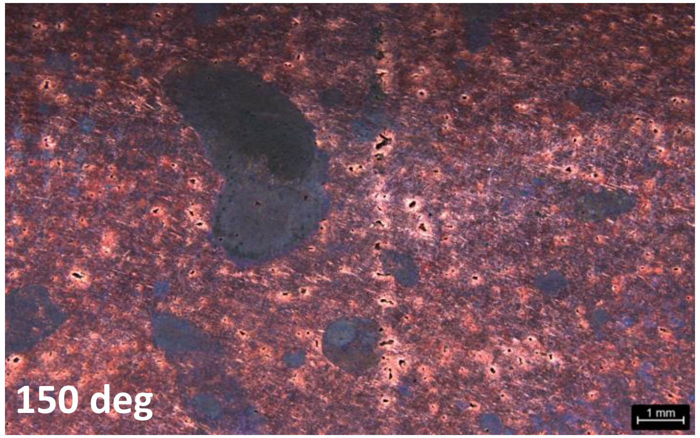
Optical Images of Chambers Post-Test

- Unpolished external surfaces.
- Top (power outage) and bottom (powder overflow) witness lines did not appear to have many detrimental defects.
- Middle witness line on chamber 1, there were some large lack of fusion defects that appeared to line up with the restart line.
- Chamber 3 – no defects visible at the surface beyond the crack that had already developed after test.

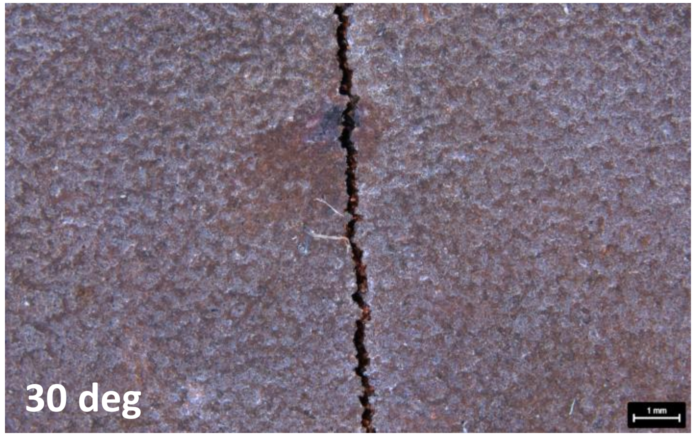


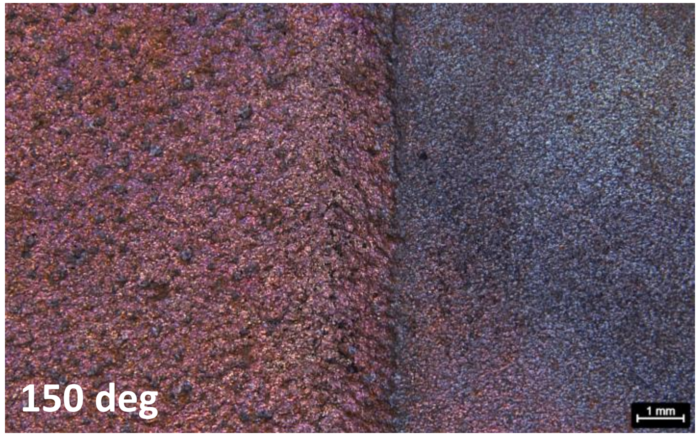
Middle witness line: C1 (untested)
Surface was polished using CMP





Middle witness line: C3 (51 starts)



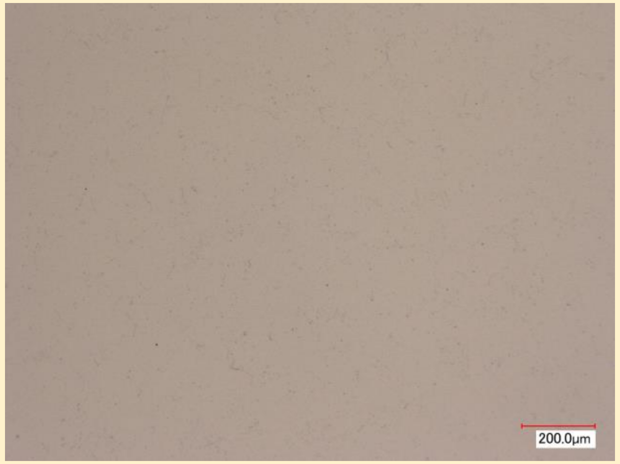


Anomaly Background

- Tested in early 2021
- Location: MSFC Test Stand 115
- L-PBF GRCop-42 chamber
    - 8 starts and 83.3 seconds total before separation.
    - No issues observed in prior chamber test data.
- Carbon-Composite experimental nozzle
    - Untested and possessed a noticeable crack.
    - Deemed an acceptable risk for test.

Optical Images of Section

Witness Bar Control with identical restart



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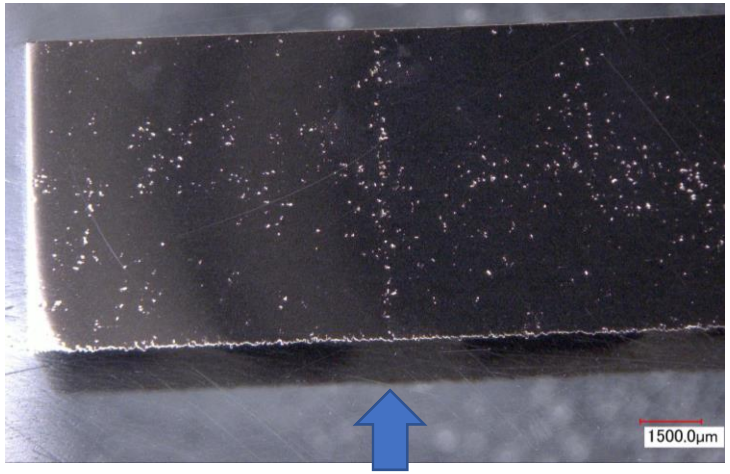
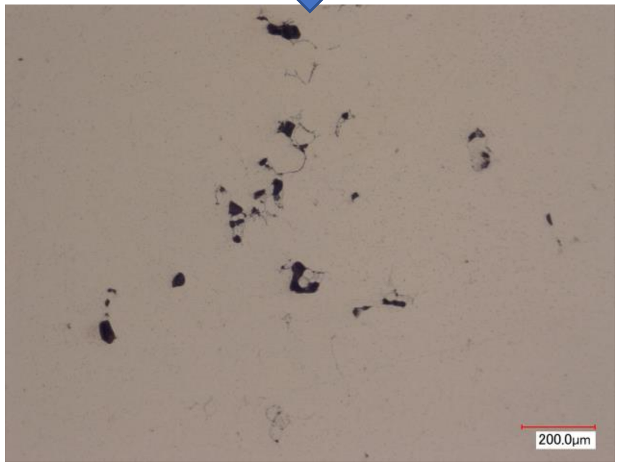
C1 (Leaked), Middle Witness Line





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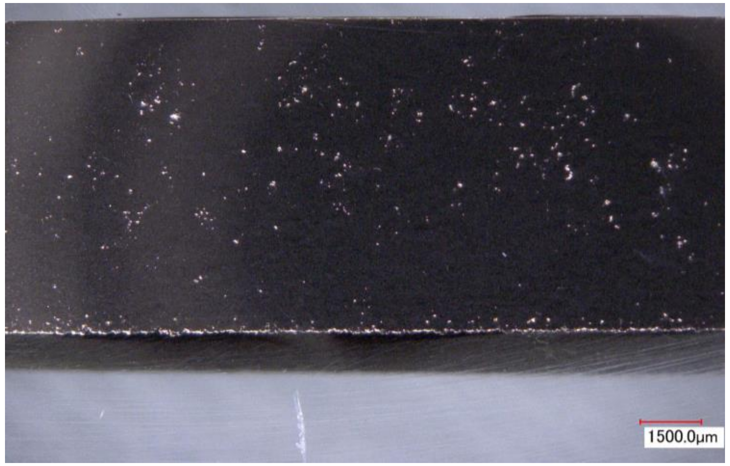
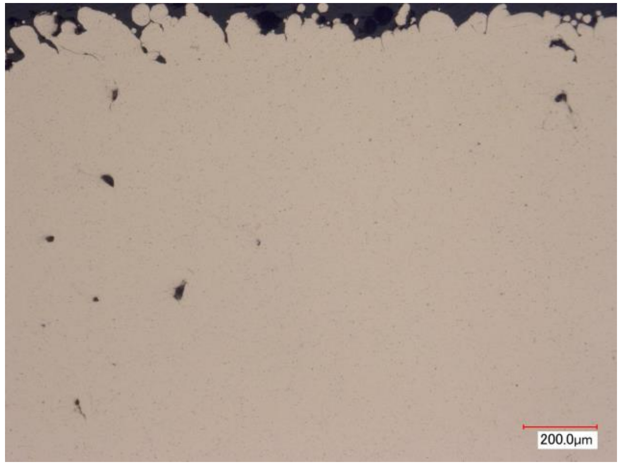
C1 (Leaked), Chamber Control





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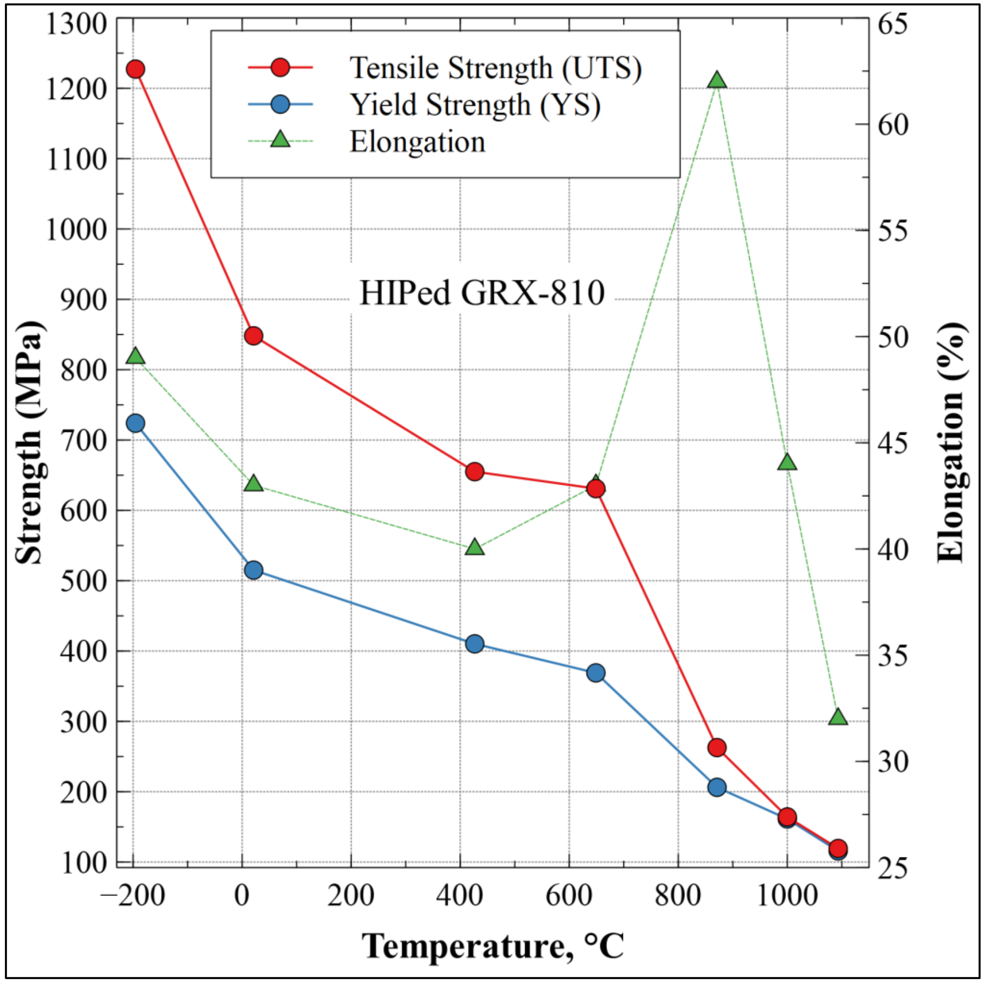
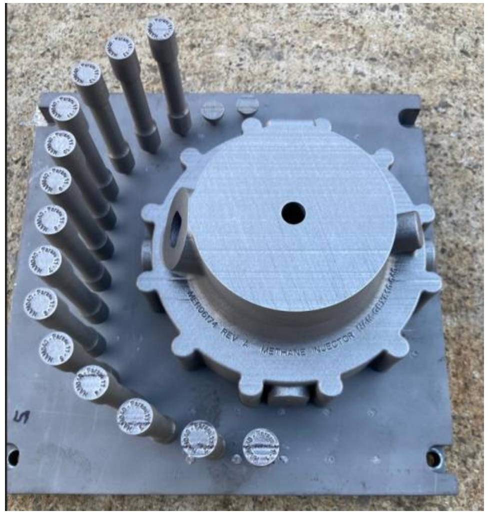
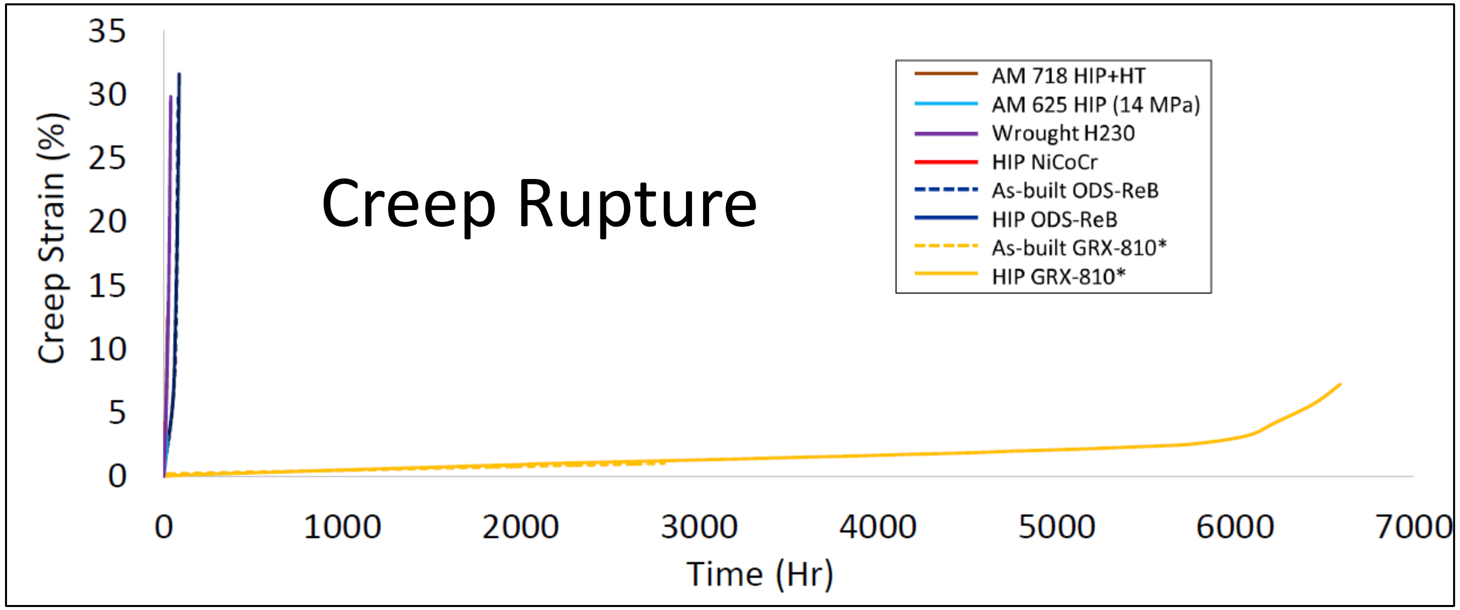
Build Direction ←

GRX-810 Oxide Dispersion Strengthened (ODS) Alloy







Acknowledgements

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- Long Life Additive Manufacturing Assembly (LLAMA) Project
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- Martin Annett
- Lynn Machamer
- RPM Innovations (RPMI)
- Tyler Blumenthal
- DM3D
- GE Research
- Bhaskar Dutta
- REM Surface Engineering
- Powder Alloy Corp
- AP&C
- Formalloy
- Auburn University (NCAME)
- Ben Williams
- Marissa Garcia
- Tim Smith / GRC
  Christopher Kantzos / GRC
- Tal Wammen
- Tom Teasley
- Scott Chartier
- Test Stand 115 crew
- Kevin Baker
- Matt Medders
- Adam Willis
- Nunley Strong
- Zach Taylor
- Matt Marsh
- Darren Tinker
- Dwight Goodman
- Will Brandsmeier
- Jonathan Nelson
- Bob Witbrodt
- Shawn Skinner
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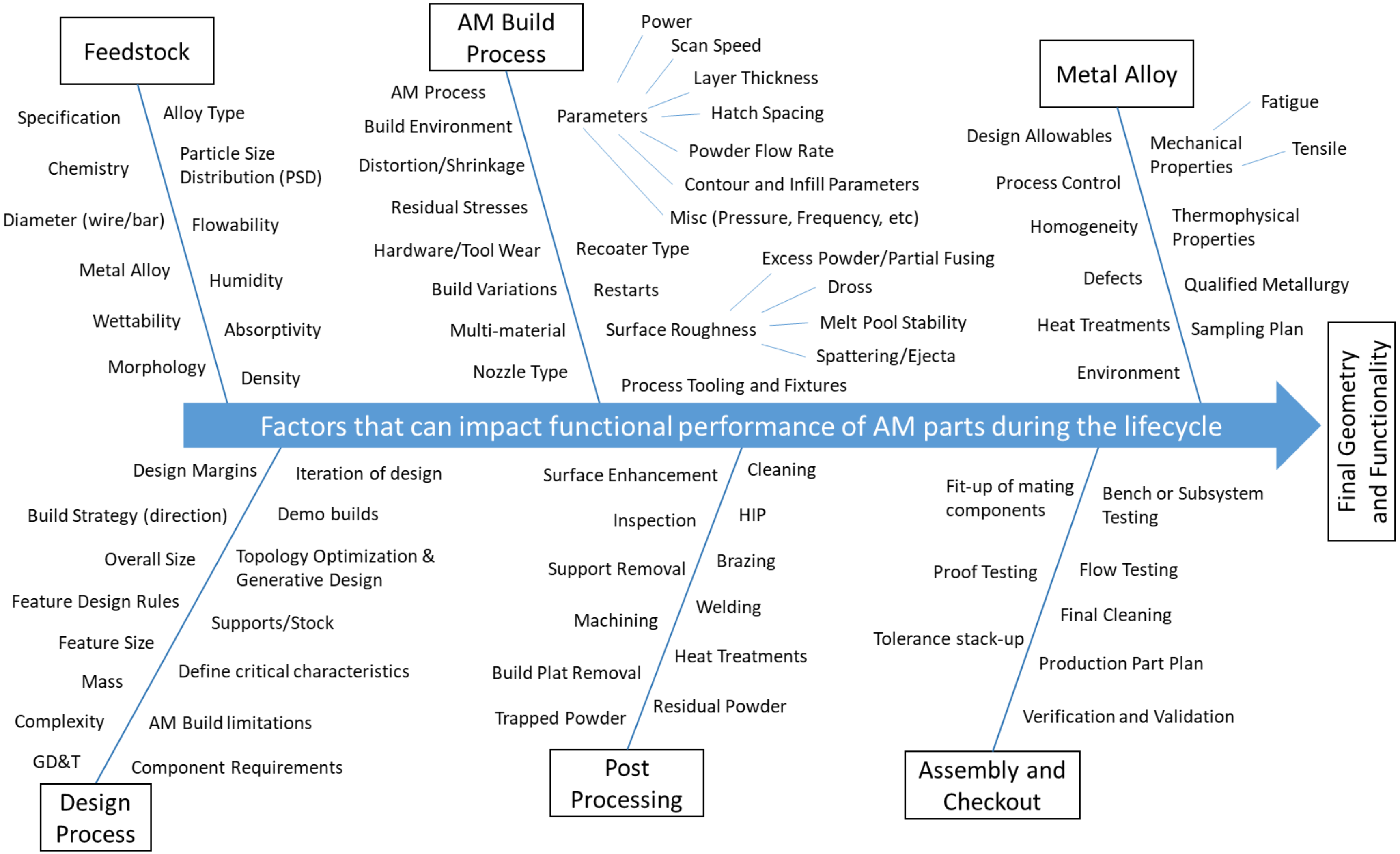
- Johnny Heflin
- Mike Shadoan
  Keegan Jackson
- Many others in Industry, commercial space and academia

The Challenges with AM Processes



Feedstock
- Specification
- Alloy Type
- Chemistry
- Particle Size Distribution (PSD)
- Diameter (wire/bar)
- Flowability
- Metal Alloy
- Humidity
- Wettability
- Absorptivity
- Morphology
- Density

AM Build Process
- AM Process
- Build Environment
- Distortion/Shrinkage
- Residual Stresses
- Hardware/Tool Wear
- Build Variations
- Multi-material
- Nozzle Type
- Parameters
  - Power
  - Scan Speed
  - Layer Thickness
  - Hatch Spacing
  - Powder Flow Rate
  - Contour and Infill Parameters
  - Misc (Pressure, Frequency, etc)
- Recoater Type
- Restarts
- Surface Roughness
  - Excess Powder/Partial Fusing
  - Dross
  - Melt Pool Stability
  - Spattering/Ejecta
- Process Tooling and Fixtures

Metal Alloy
- Design Allowables
- Mechanical Properties
  - Fatigue
  - Tensile
- Process Control
- Homogeneity
- Thermophysical Properties
- Defects
- Qualified Metallurgy
- Heat Treatments
- Sampling Plan
- Environment

Factors that can impact functional performance of AM parts during the lifecycle

Final Geometry and Funcionality

Design Process
- Design Margins
- Iteration of design
- Build Strategy (direction)
- Demo builds
- Overall Size
- Topology Optimization & Generative Design
- Feature Design Rules
- Supports/Stock
- Feature Size
- Define critical characteristics
- Mass
- Complexity
- AM Build limitations
- GD&T
- Component Requirements

Post Processing
- Surface Enhancement
- Cleaning
- Inspection
- HIP
- Support Removal
- Brazing
- Machining
- Welding
- Heat Treatments
- Build Plat Removal
- Residual Powder
- Trapped Powder

Assembly and Checkout
- Fit-up of mating components
- Bench or Subsystem Testing
- Proof Testing
- Flow Testing
- Final Cleaning
- Tolerance stack-up
- Production Part Plan
- Verification and Validation

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

Methodical AM Process Selection

AM Process Selection for Aerospace

Alloy Selection

Overall Part Size

Part Complexity

Feature Resolution

Feedstock

Parameters

Single or Multi-Alloy

Process Economics

Process Availability

Industrial Maturity

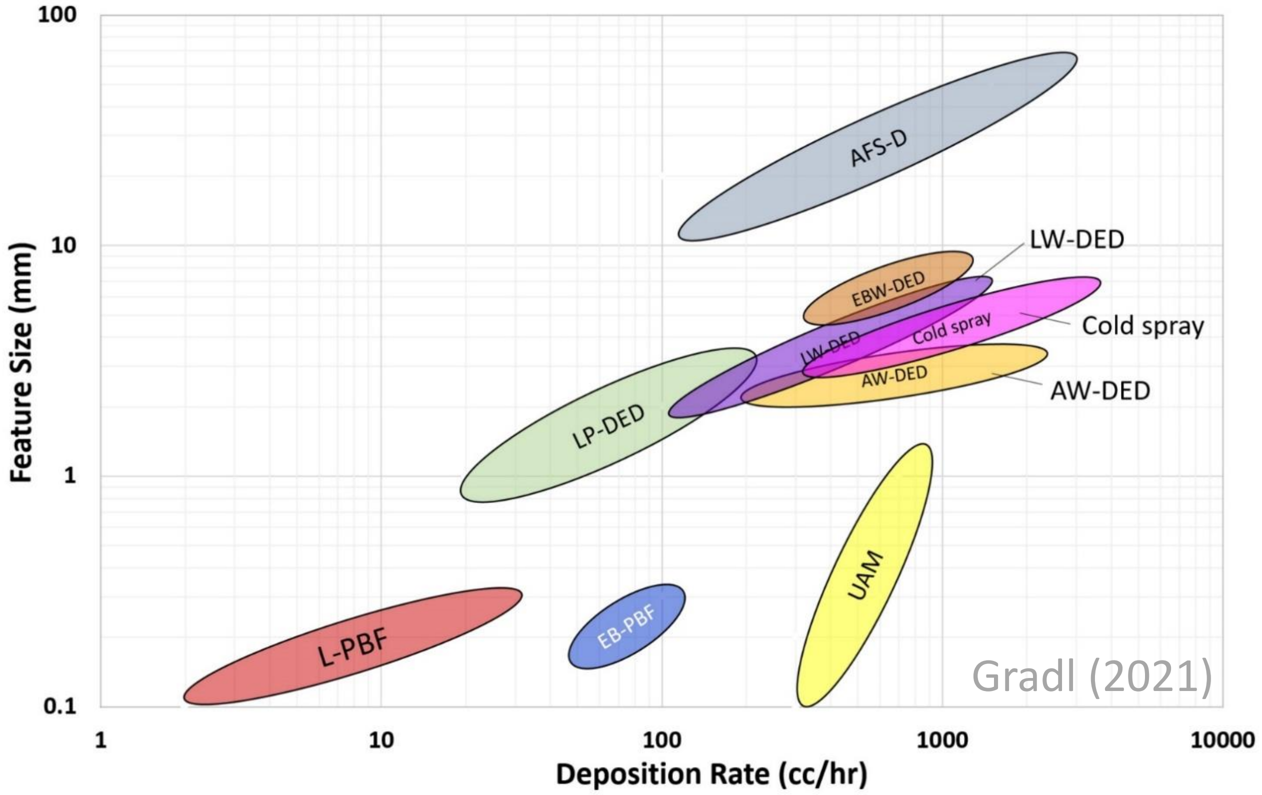
Post-Processing

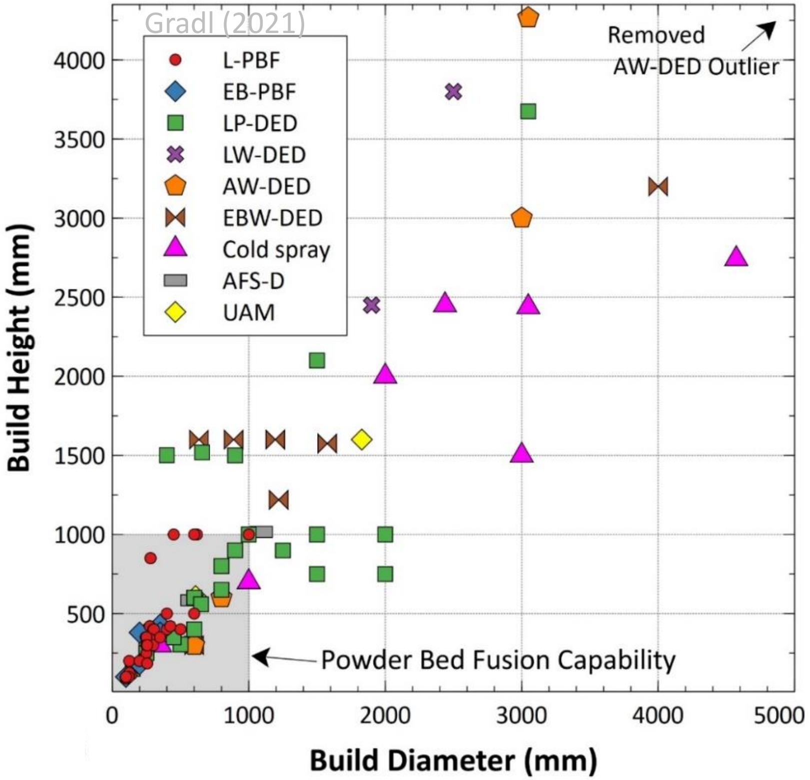
Metallurgical Characteristics and Properties

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

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

Various criteria for selecting AM techniques





Complexity of Features

Scale of Hardware

Material Physics

Cost

Material Efficiency

Speed of Process

Material Properties

Internal Geometry

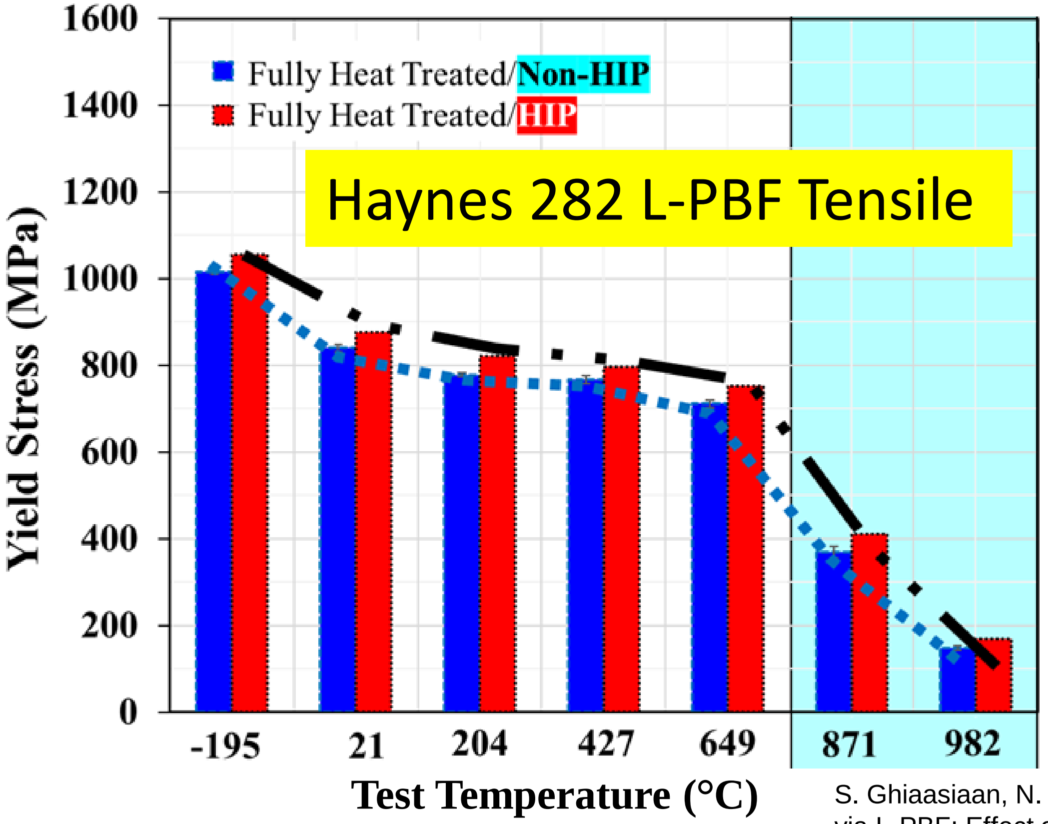
Availability

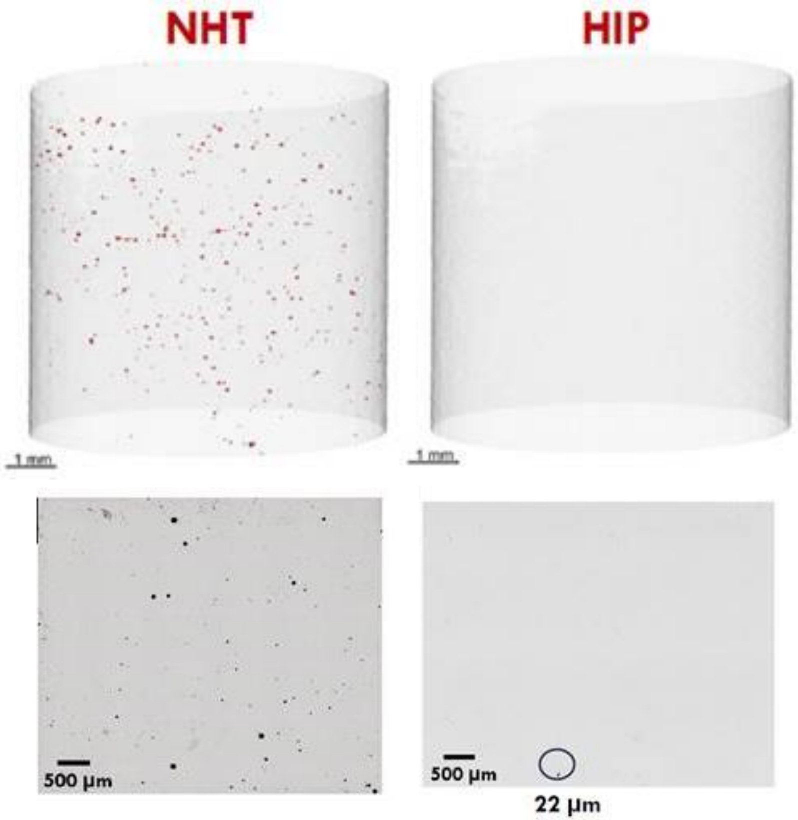
Post Processing

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)

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

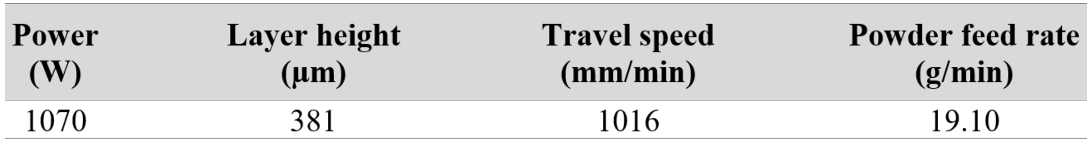
Material	Process
Haynes 282	L-PBF
Haynes 282	LP-DED
Hastelloy X	L-PBF
Hastelloy X	LP-DED
Inconel 625	L-PBF
Inconel 625	LP-DED
Inconel 625	LW-DED
Inconel 625	AW-DED
Inconel 718	L-PBF
Inconel 718	LP-DED
Inconel 718	AW-DED
Inconel 939	L-PBF
Haynes 230	L-PBF
Haynes 230	LP-DED
Haynes 214	L-PBF
Haynes 233	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

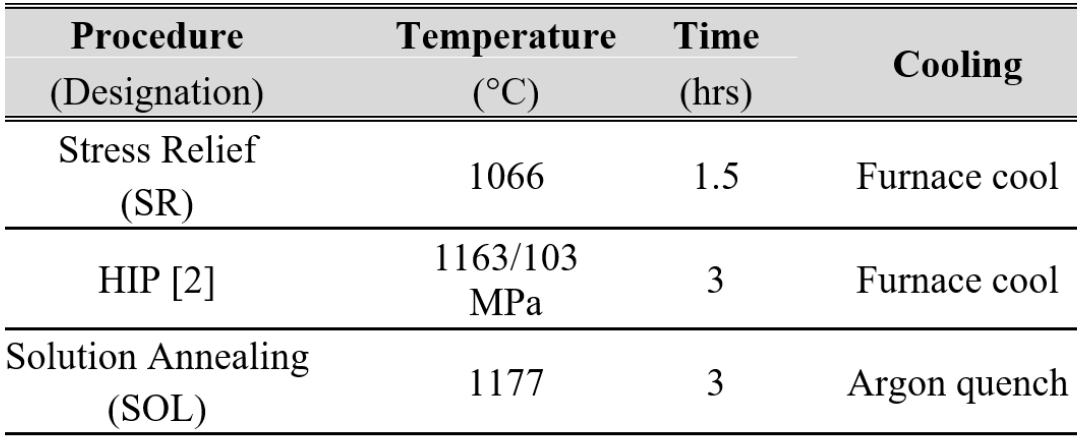
Material	Process
Monel K500	LP-DED
Monel K500	L-PBF
GRCop-42	L-PBF
GRCop-42	LP-DED
GRCop-84	L-PBF
C-18150	L-PBF
Ti6Al-4V	L-PBF
Ti6Al-4V	LP-DED
Ti6Al-4V	LW-DED
Ti6Al-4V	EBW-DED
Ti6242	L-PBF
Ti6242	LP-DED
GRX-810	L-PBF
GRX-810	LP-DED
Haynes 214-ODS	L-PBF
C-103	LP-DED

55+ Alloys in characterization

Data example of Haynes 230 LP-DED



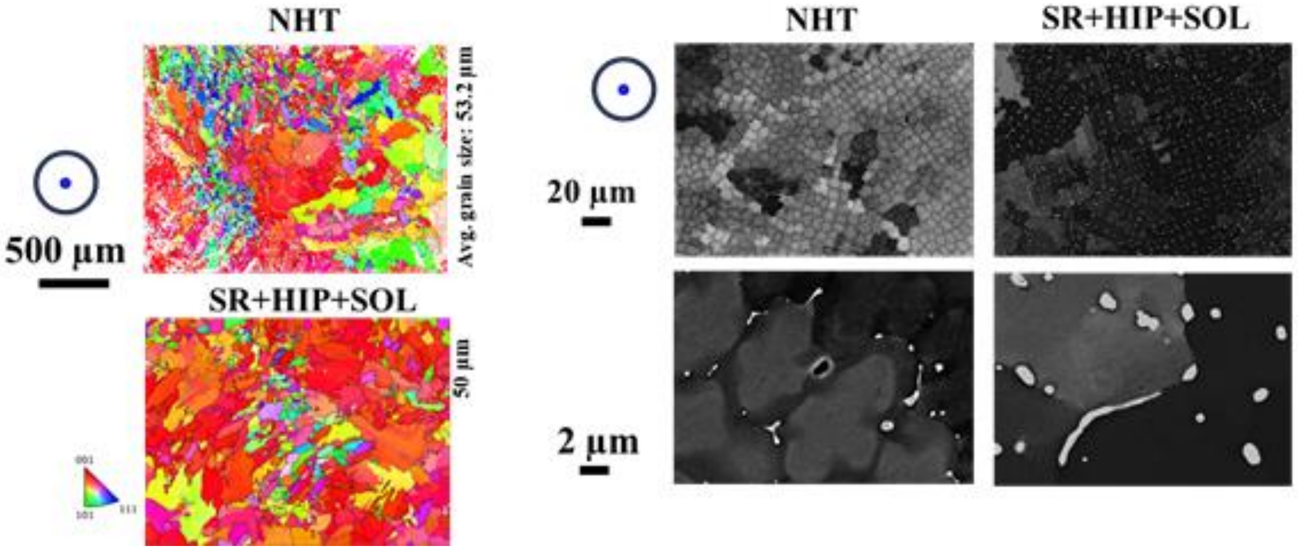
Power (W)	Layer height (µm)	Travel speed (mm/min)	Powder feed rate (g/min)
1070	381	1016	19.10



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

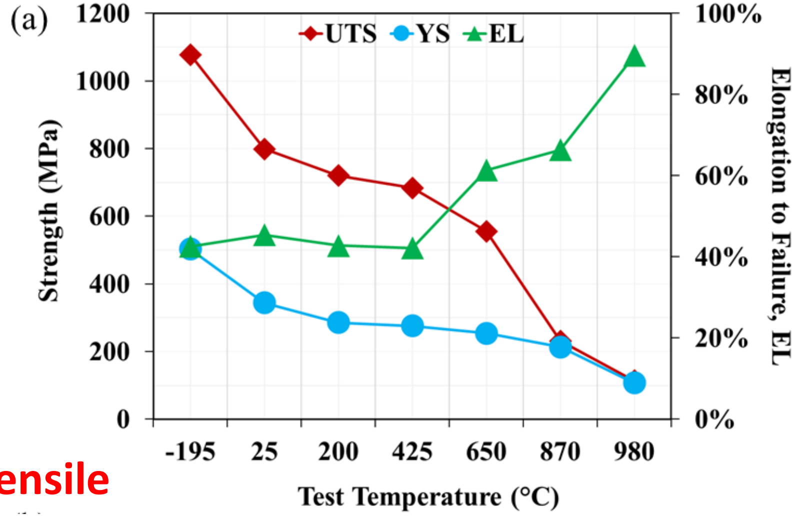
As-Built

Full Heat Treated

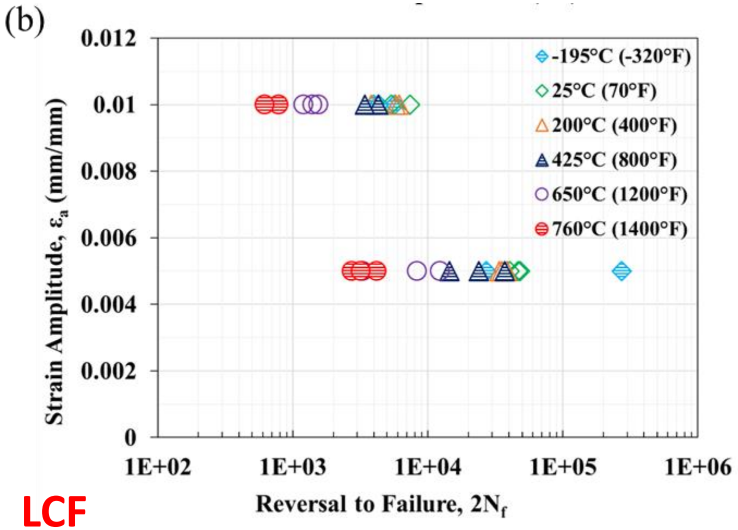


[2] HIP per ASTM F3301

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



Tensile



LCF

ICP & IGF Chemical Analysis

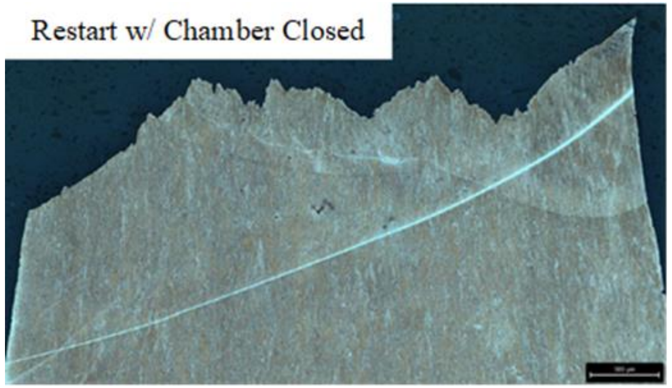
- 7 pieces from entire length of chamber C1
- Observations:
  - Composition did not vary throughout length of chamber
  - Al, Si higher than expected – crucible fluxing potentially
  - Ni, Co, Fe within detection limits
  - O notably high – can reduce conductivity and produce Al-Nb-O particles that create fatigue cracking
- Cr/Nb ratio is strong indicator of GRCop's effectiveness (precipitates for dispersion strengthening)
  - High ratio in chamber pieces
  - Results in excess chromium precipitates
  - Reduces high temp strength and creep resistance
- Important for AM GRCop parts to have consistent compositions

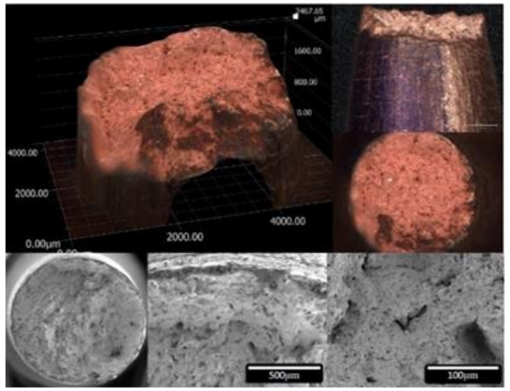
Element	Chamber Avg.	Spec Target	PC Results
Copper	93.88	-	-
Chromium	3.37	3.27	3.10
Niobium	2.57	2.92	2.70
Oxygen	0.06	0.025	0.033
Iron	0.02	0.005	0.007
Aluminum	0.05	0.04	-
Silicon	0.02	0.01	-
Nickel	0.02	-	-
Cobalt	0.01	-	-
Phosphorus	0.01	-	-
Silver	0.01	-	-

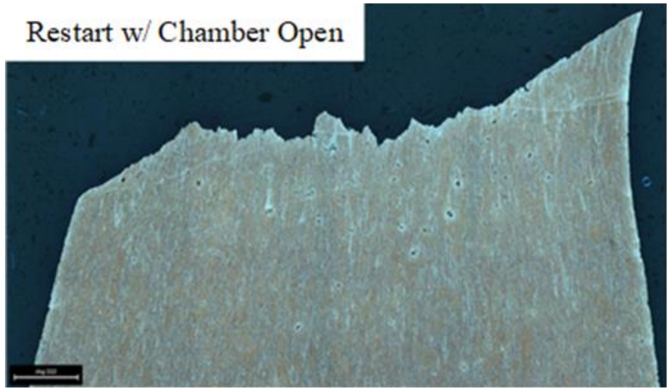
Documentation	Cr/NB Ratio
Chamber Average	1.31
Specification Target	1.13 - 1.18
PC Results	1.15

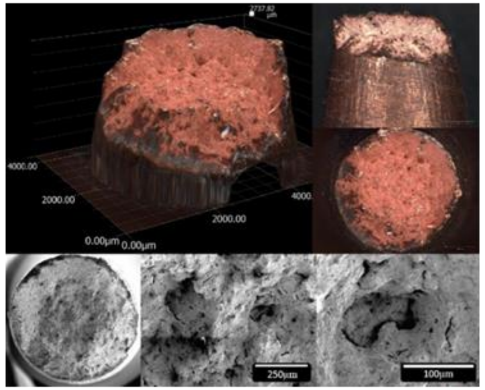
Fractography – Tensile Fracture

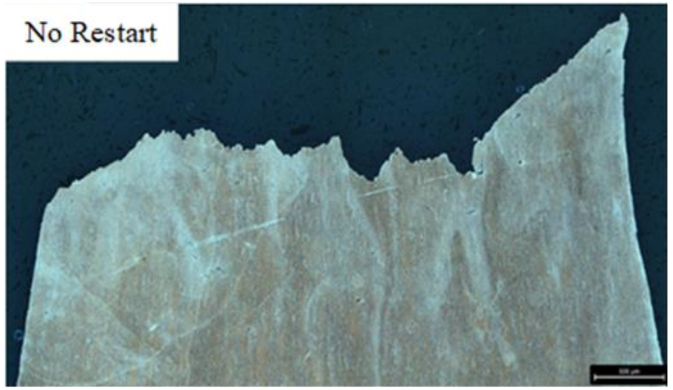
- 3 witness test bars from tensile simulating build stoppages
- Observations:
  - No major differences between fractures
  - Typical cup-cone fracture surfaces common for ductile metals
  - Fracture surfaces had elongated grains
- Conclusions:
  - Similar fractures track with similar properties observed in bars previously

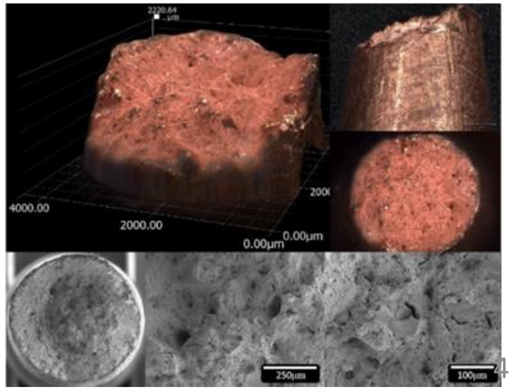

Restart w/ Chamber Closed




Restart w/ Chamber Open




No Restart



Fractography – LCF Fracture

- 3 test bars from LCF
  - Fracture surfaces smeared b/c LCF had fully reversible cycles
  - Closed chamber restart bar never fully fractured
- Observations:
  - Open restart: flat surface before overload failure transition, secondary crack below primary crack
  - No restart: three separate cracks jogged together