National Aeronautics and Space Administration

# Space Exploration using Additive Manufacturing

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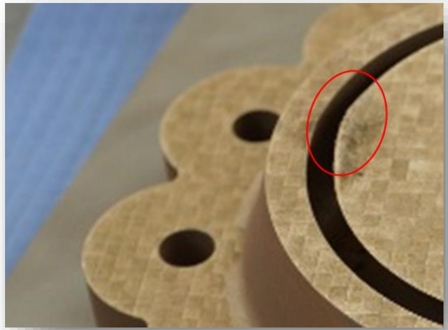
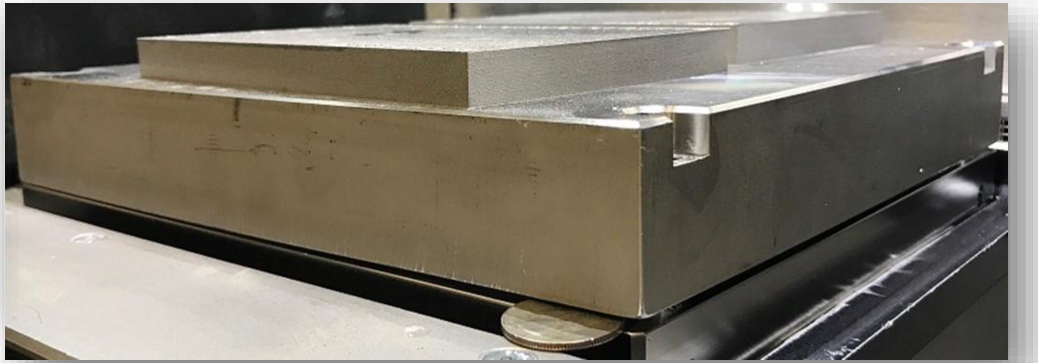
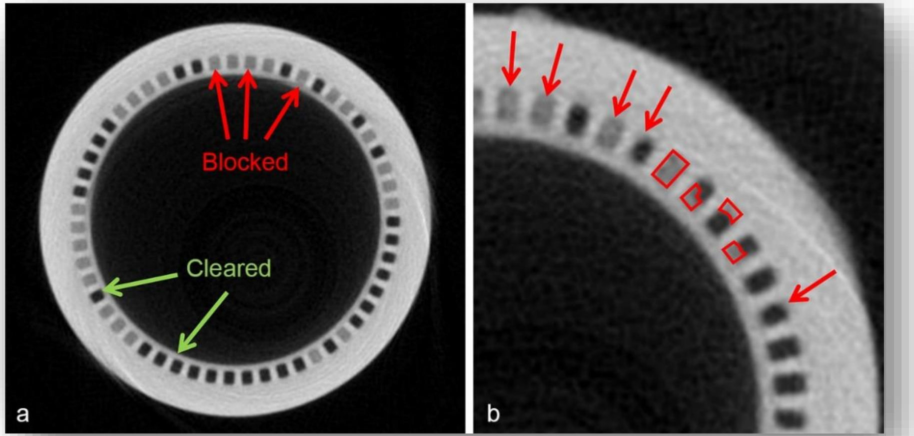
NASA Marshall Space Flight Center

7 February 2024

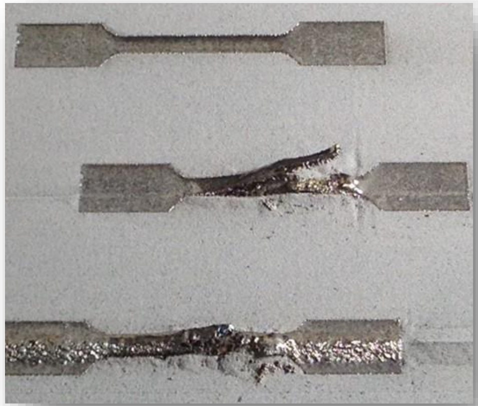
# AM Lifecycle Failures

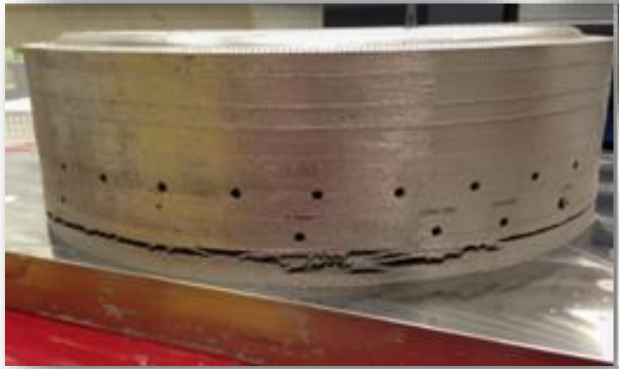


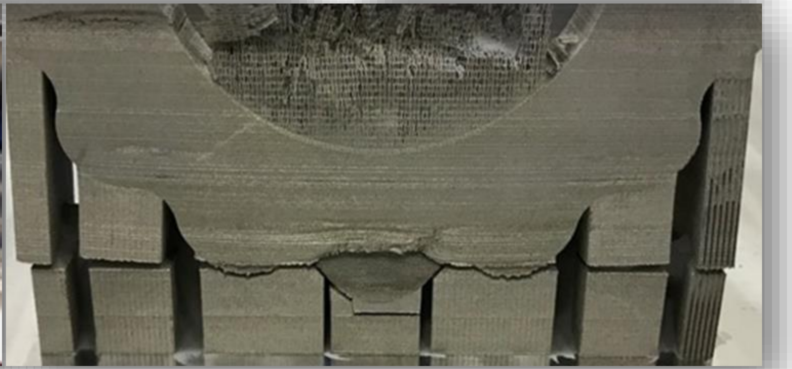


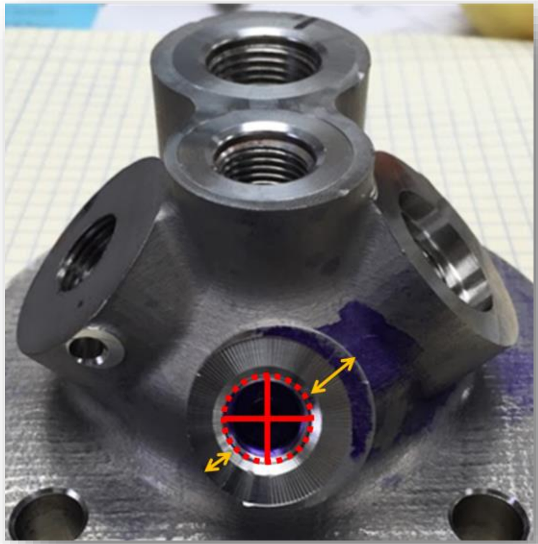


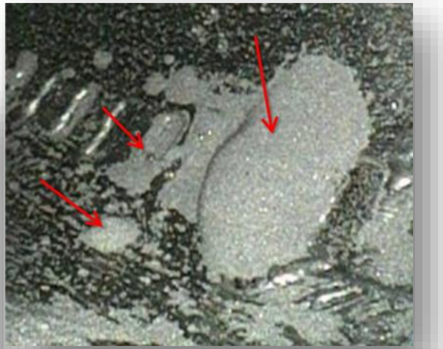

## Design induced process failures



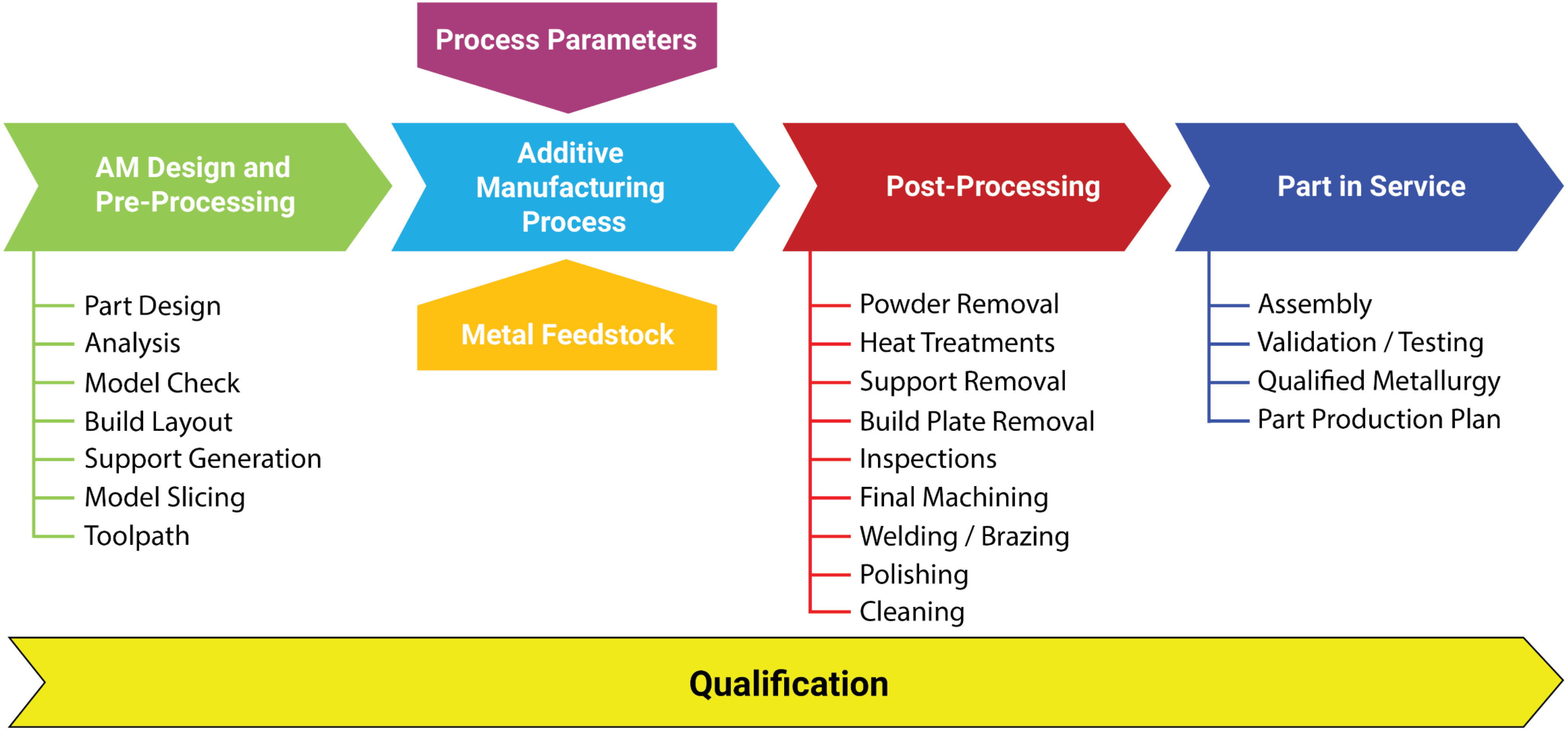








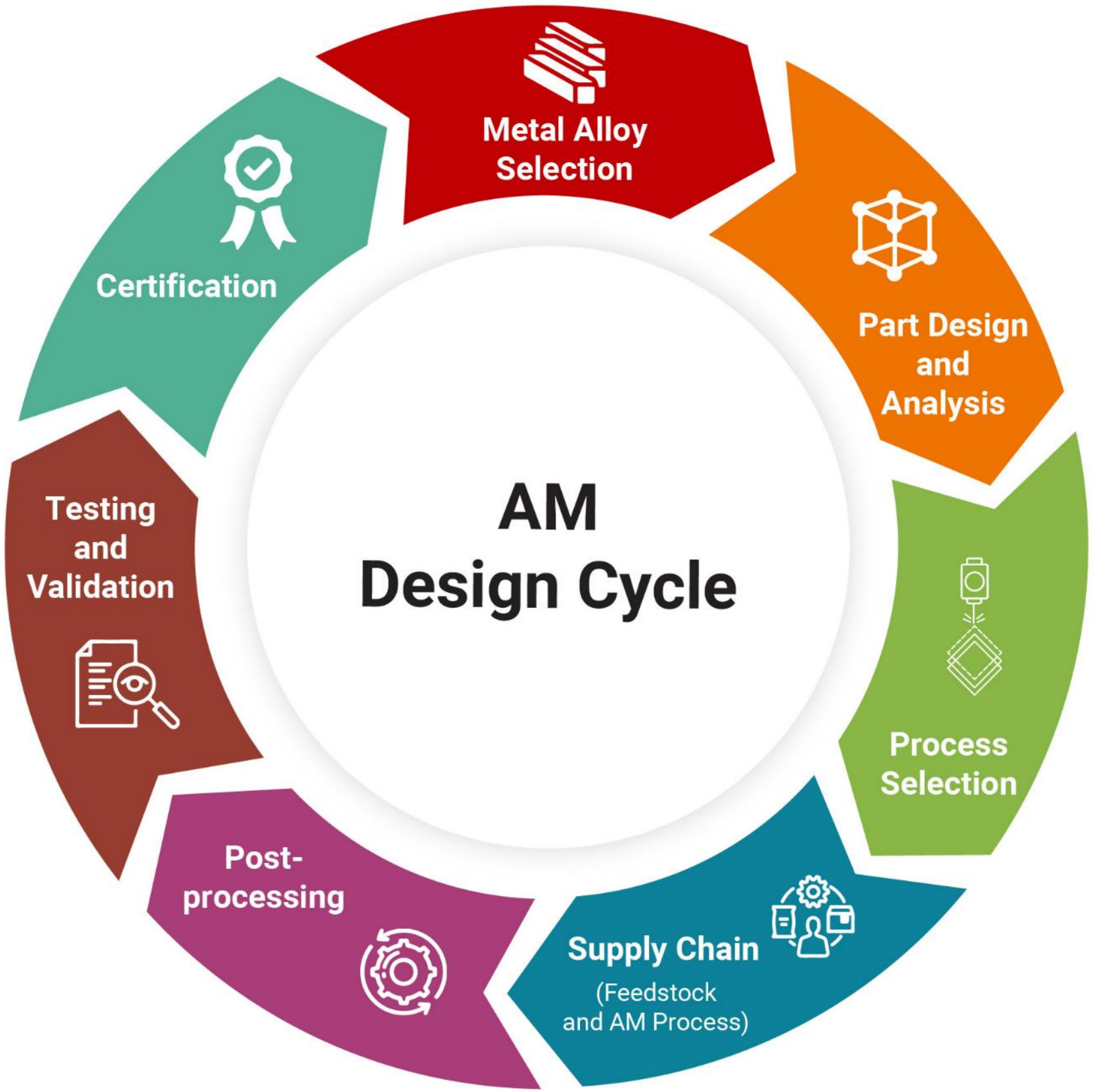
# Typical Additive Manufacturing Lifecycle

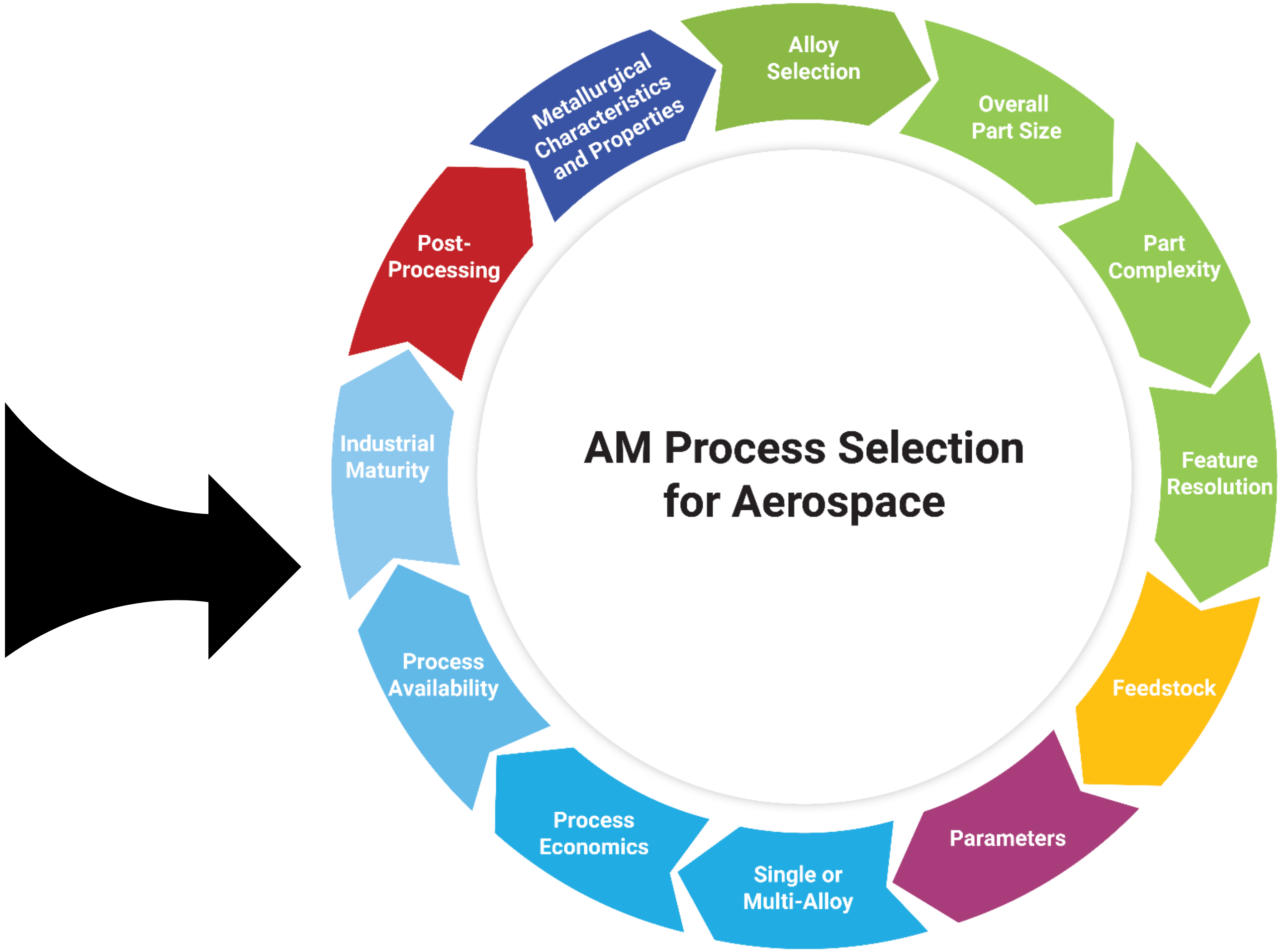



**Proper AM process selection requires an integrated evaluation of all process lifecycle steps**

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

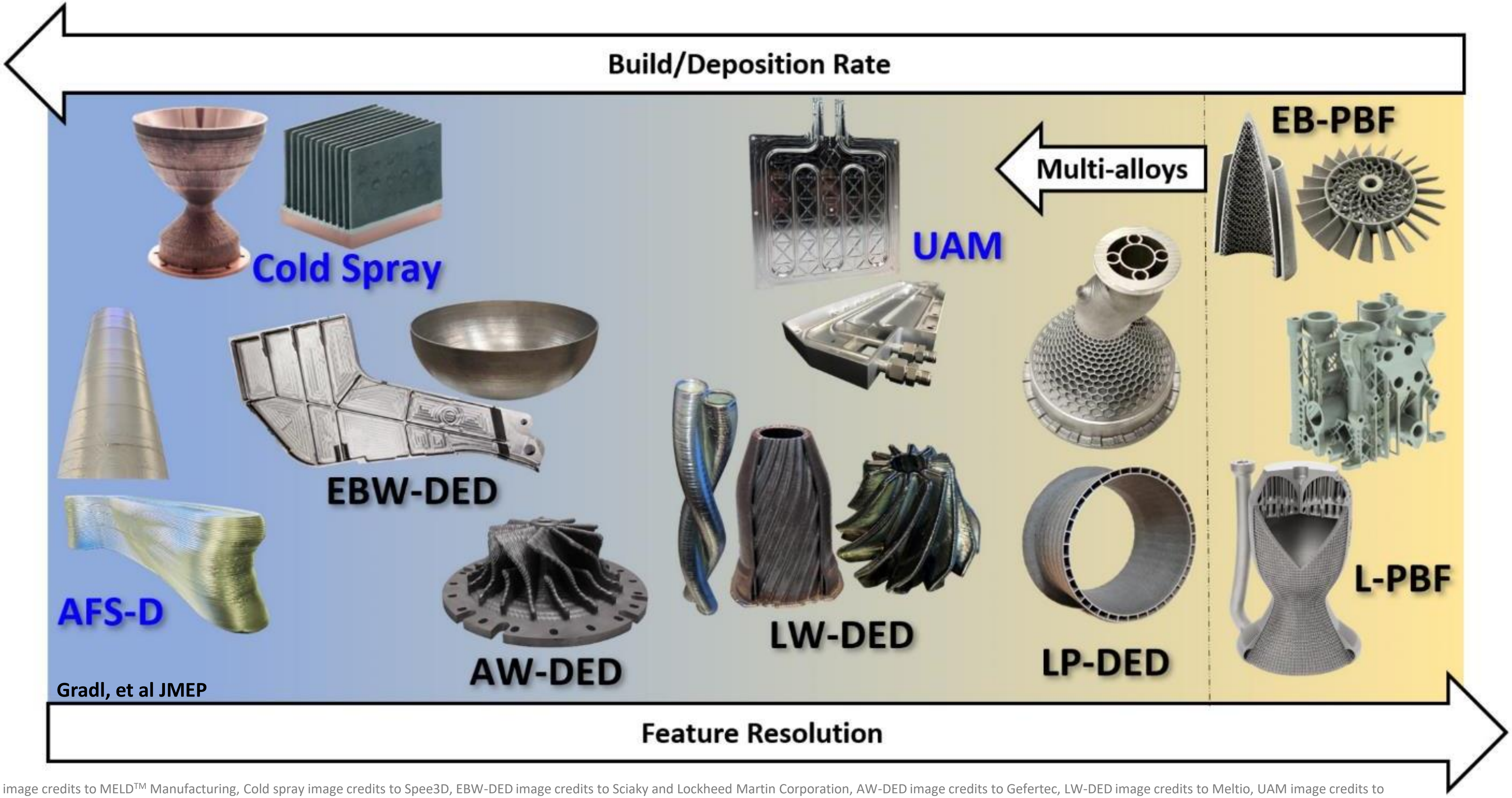
# AM Design Cycle




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

# AM Process Selection Really Matters!




**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.

# Maturity of Metal AM for NASA Applications

# Appropriate Material Definition: Process →Performance

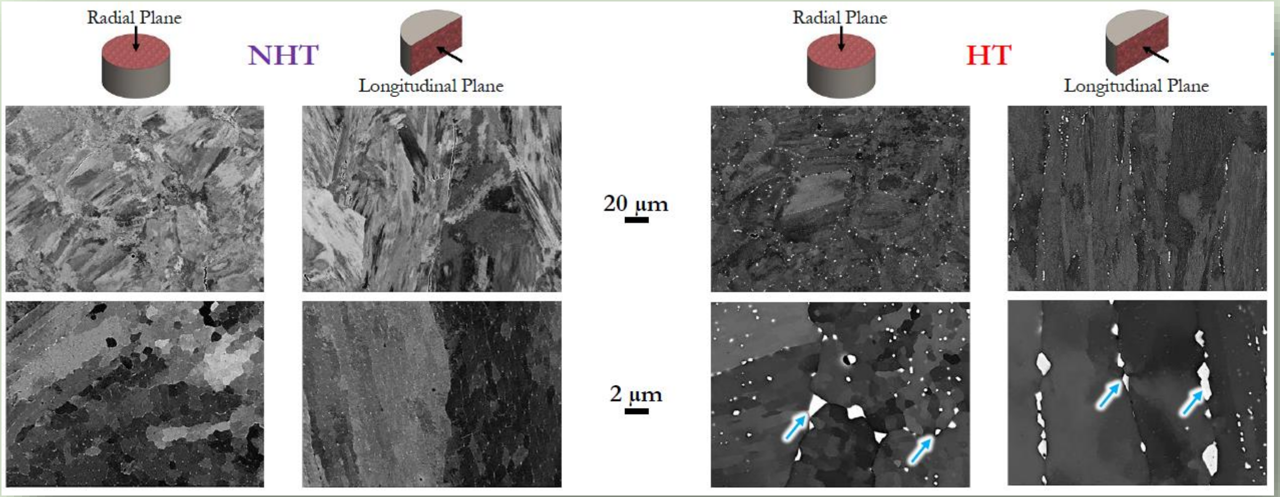
Data from Gradl, Mireles, Protz, Garcia. "Metal Additive Manufacturing for Propulsion Applications", AIAA Progress Series. (2022). Appendix A.

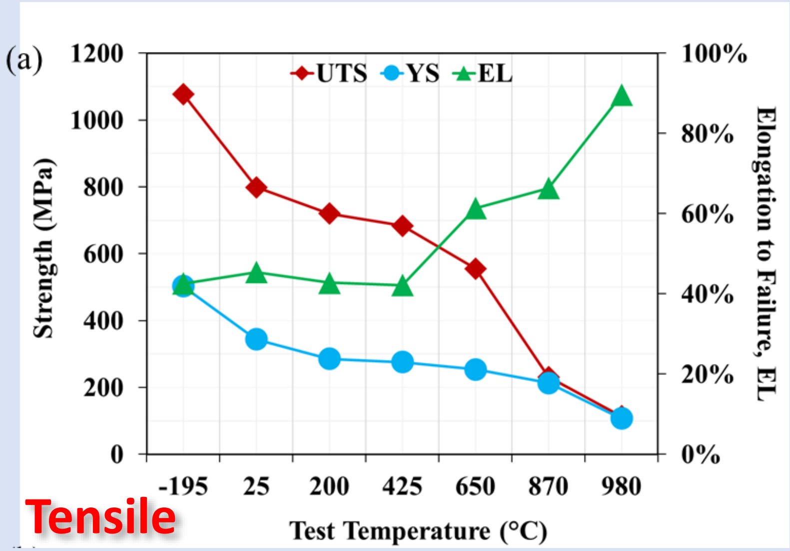
## LP-DED Haynes 230

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

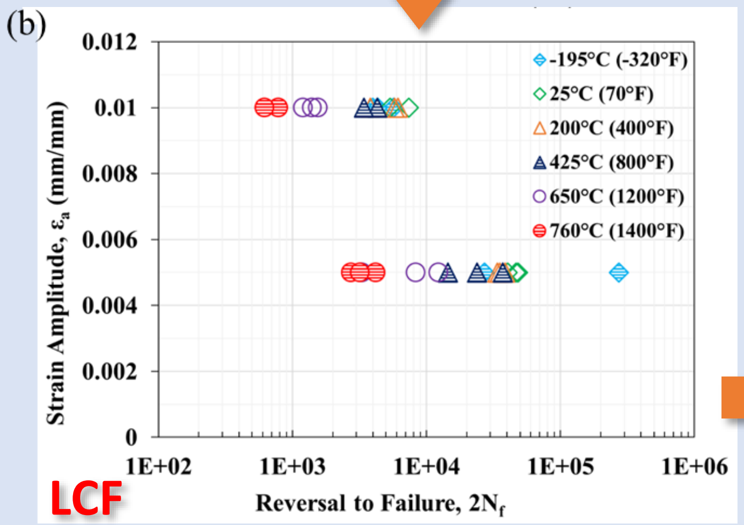
| Procedure (Designation) | Temperature (°C) | Time (hrs) | Cooling |
|---|---|---|---|
| Stress Relief (SR) | 1066 | 1.5 | Furnace cool |
| HIP [2] | 1163/103 MPa | 3 | Furnace cool |
| Solution Annealing (SOL) | 1177 | 3 | Argon quench |

[2] HIP per ASTM F3301

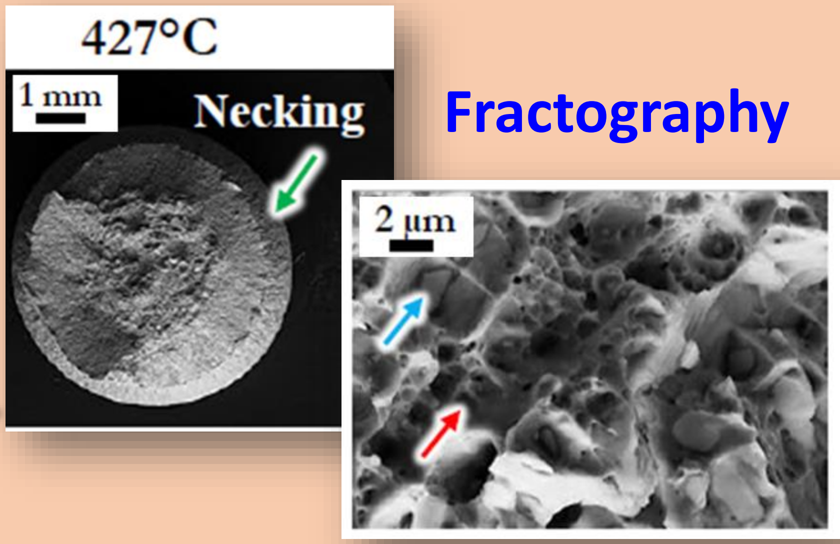



Tensile

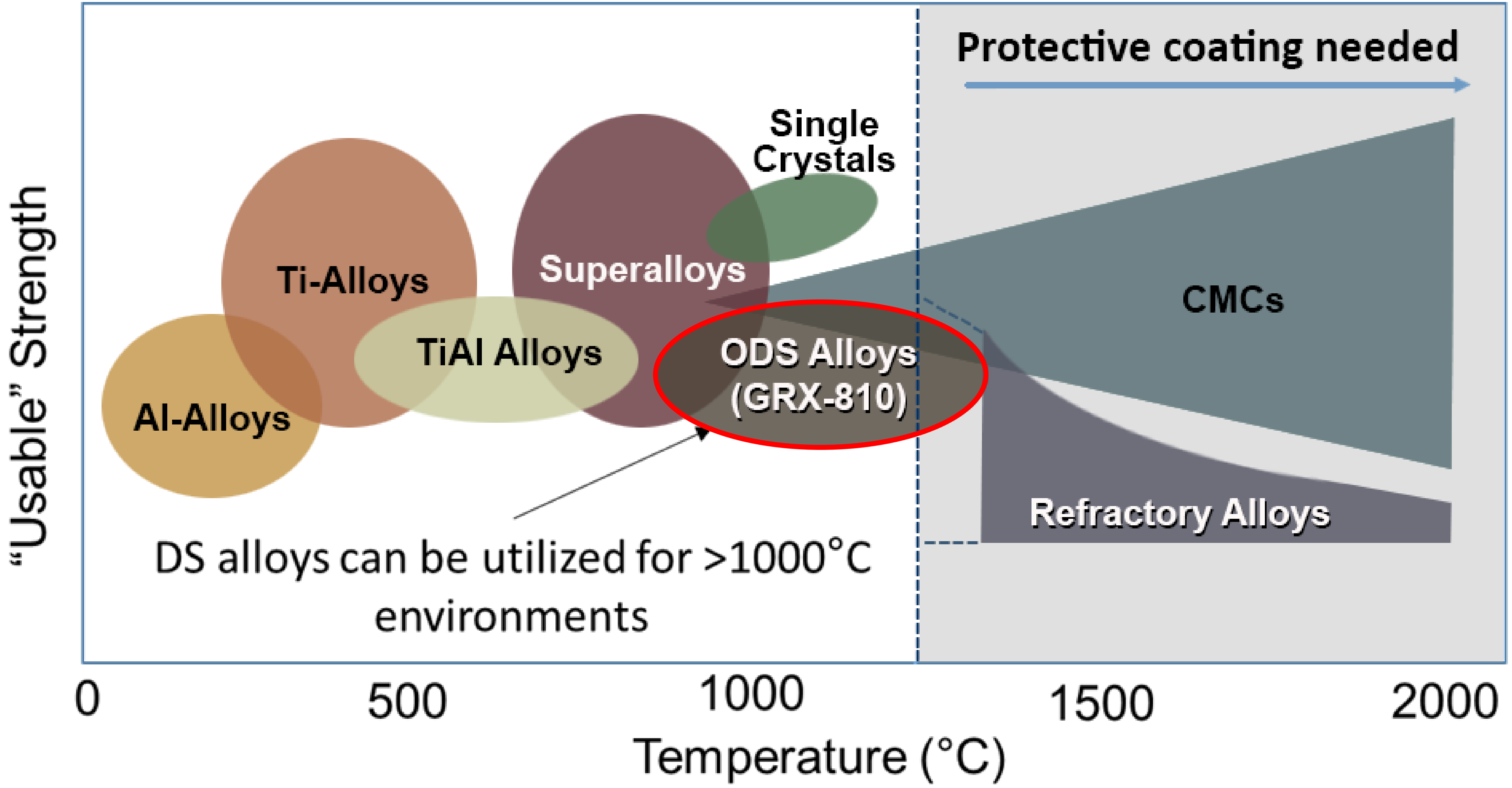



LCF



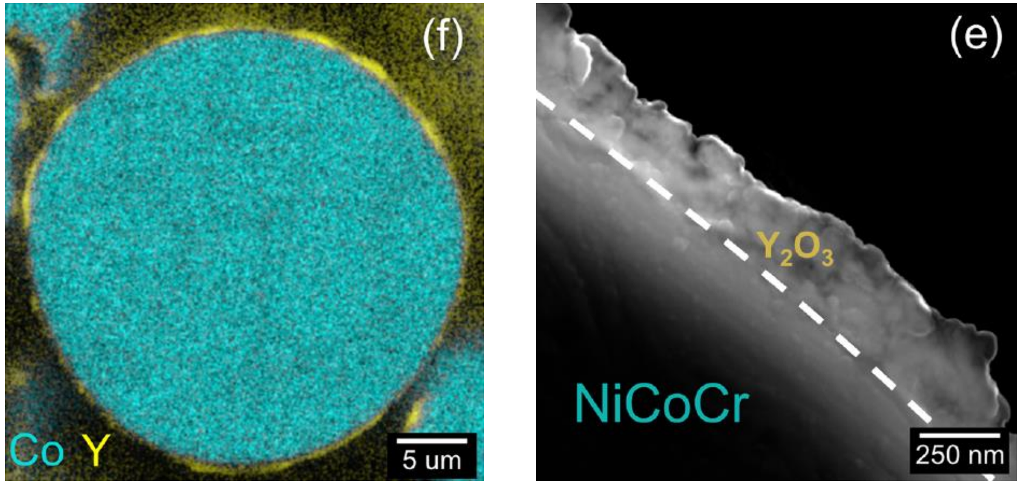

Fractography

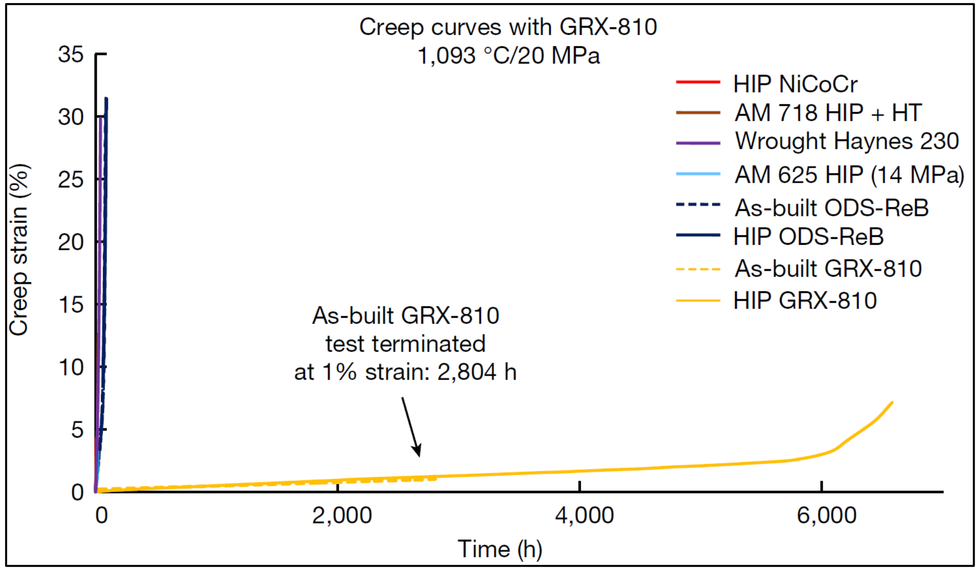
# Landscape of Aerospace Materials and GRX-810

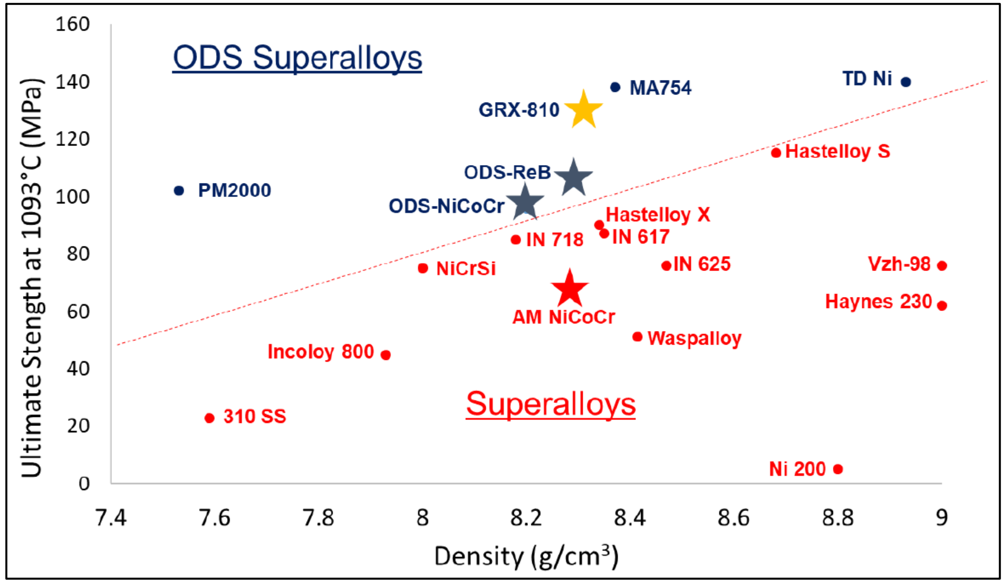


# New AM Alloy Advancements – GRX-810

- **G**lenn **R**esearch Center e**X**treme temperature alloy (GRX-810) was developed using ICME
- Ni-Co-Cr medium entropy alloy with nano-scale $Y_2O_3$ coating.
- Significantly improved properties:
    - 2x strength at elevated temperatures (1100°C)
    - 1,000x better creep rupture
    - 2x better resistance to oxidation




Smith, T.M., Thompson, A.C., Gabb, T.P., Bowman, C.L., Kantzos, C.A., 2020. Efficient production of a high-performance dispersion strengthened, multi-principal element alloy. Scientific Reports 2020 10:1 10, 1–9. https://doi.org/10.1038/s41598-020-66436-5

# AM Maturation Through Rigorous Testing

- **GRX-810** Injector achieved 84 starts and 2,228 sec (Liquid Oxygen/Methane)
- Similar injectors with Inconel 718/625 would see erosion after 8-10 starts
- **GRX-810** nozzle achieved 91 starts and 2,309 sec
- Average temperatures in excess of 1500°F for sustained durations

# Multi-Metallic / Multi-Process AM

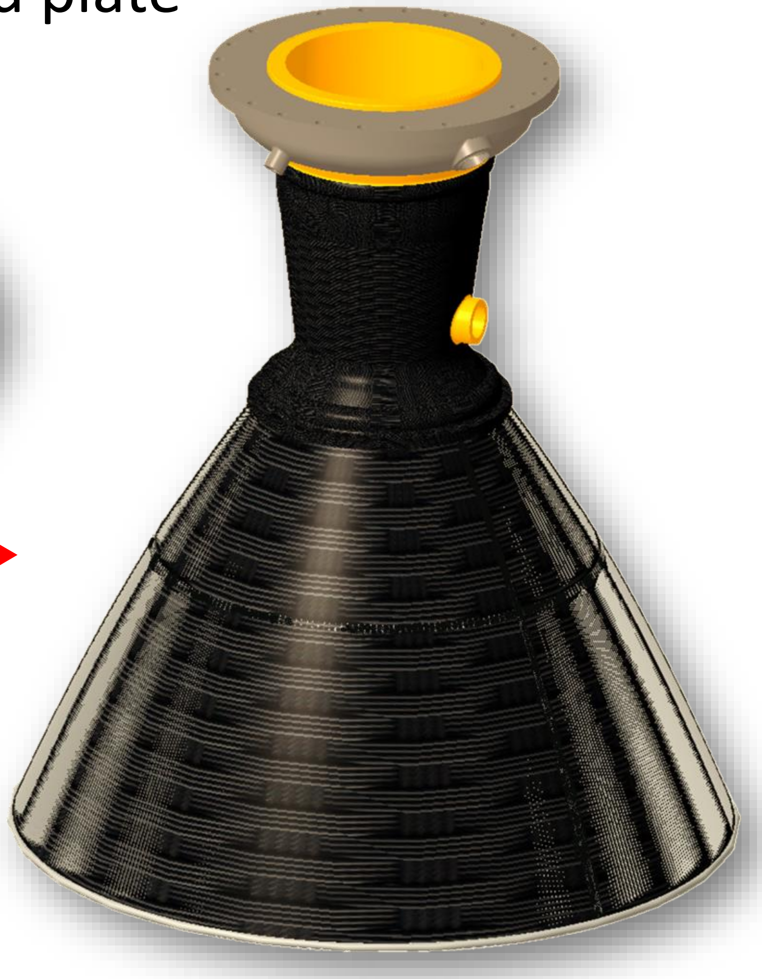
**Combining key technologies into an integrated thrust chamber assembly using:**

1. GRCop-42 L-PBF chamber as central component and "build plate"
2. Large scale laser powder directed energy deposition
3. Bimetallic and multi-alloys for joints
4. Composite overwrap jacket

L-PBF GRCop-42 Chamber Liner

Manifolds applied using bimetallic AM DED

Laser Powder DED of Regen-nozzle directly on chamber



Composite Overwrap of TCA

# RAMPT Multi-alloy Radial and Axial Hardware

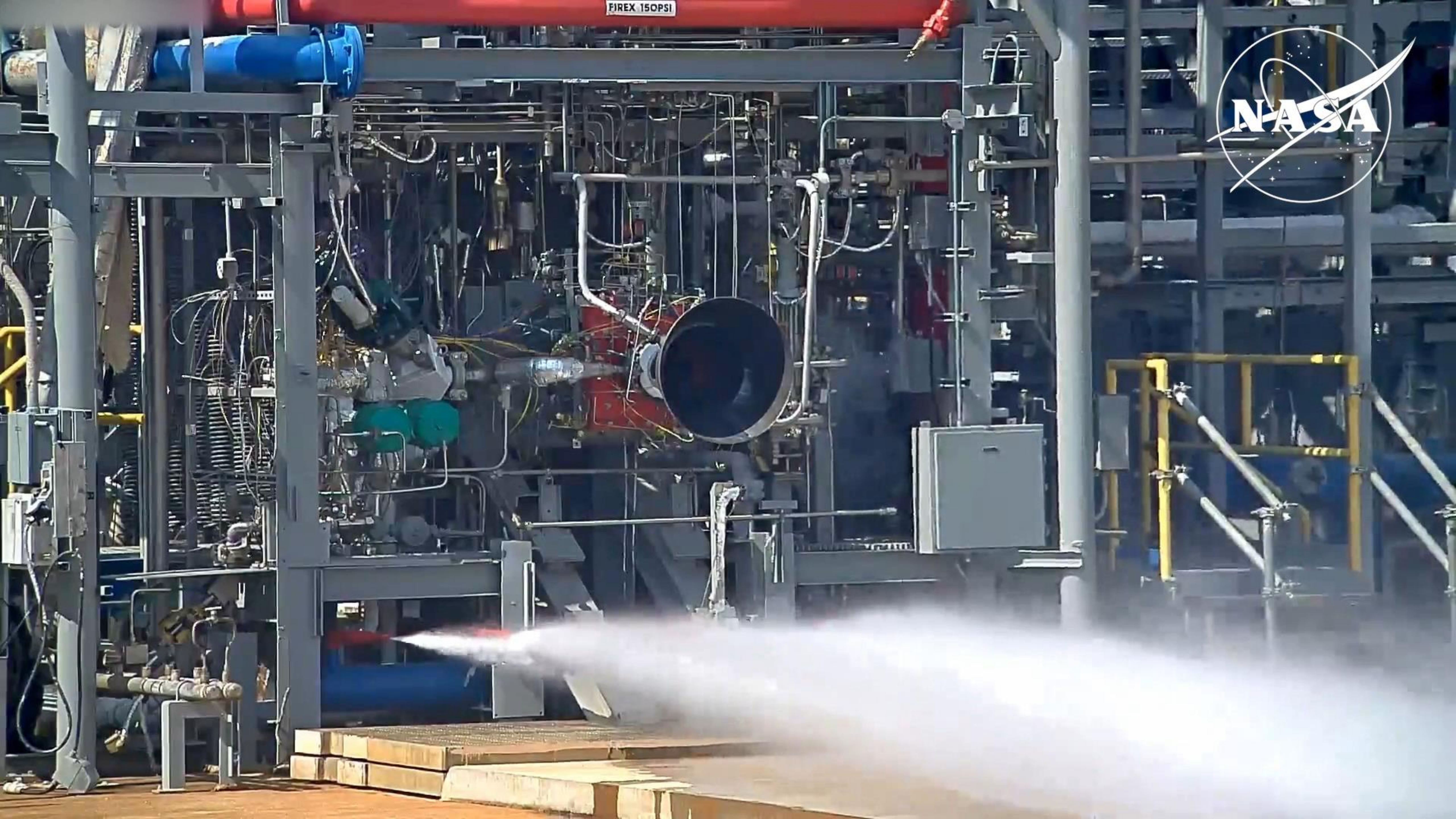
L-PBF Chamber

Manifold Prep LP-DED Setup

Radial LP-DED

Axial LP-DED Nozzle

Final Machining


FIREX 150PSI
NASA

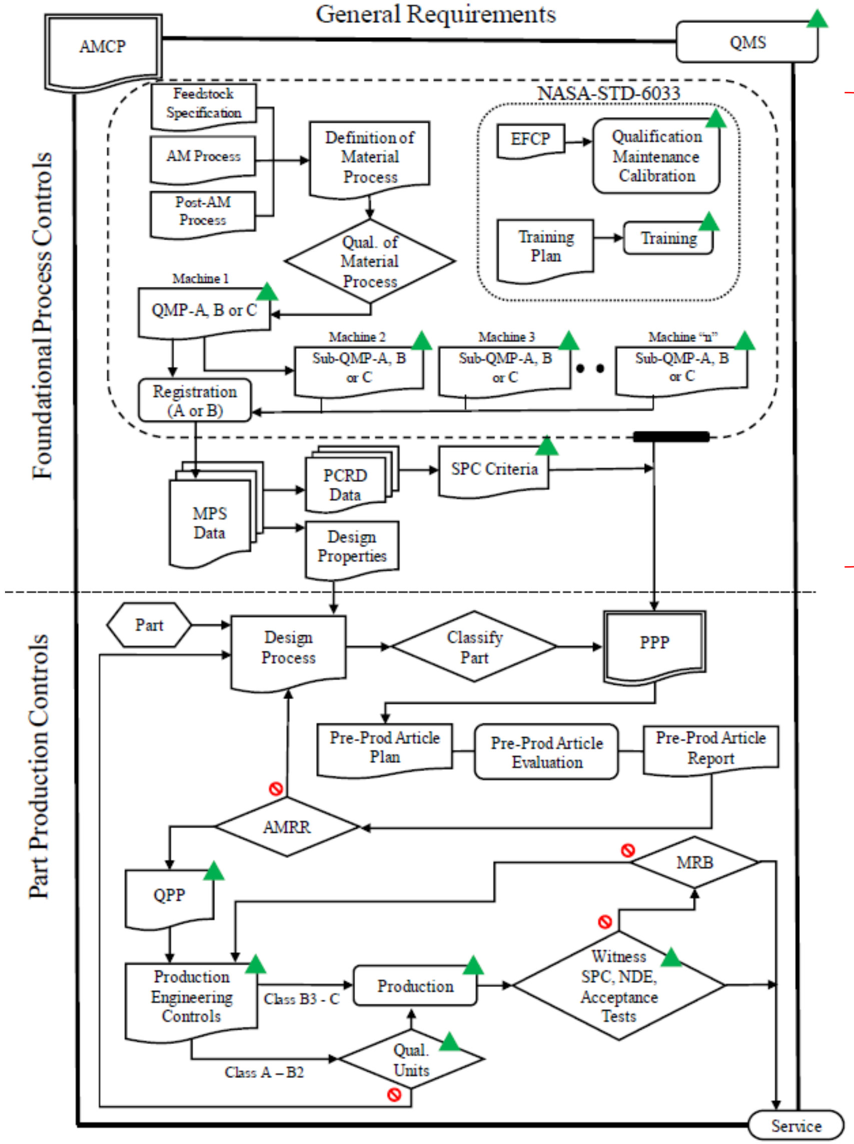
# Proper Processing Requires Guidelines

**What should I worry about?**

**How should I define and control them?**

**Who and When should work them?**

**How Customer/NASA should be aware and approve of them?**



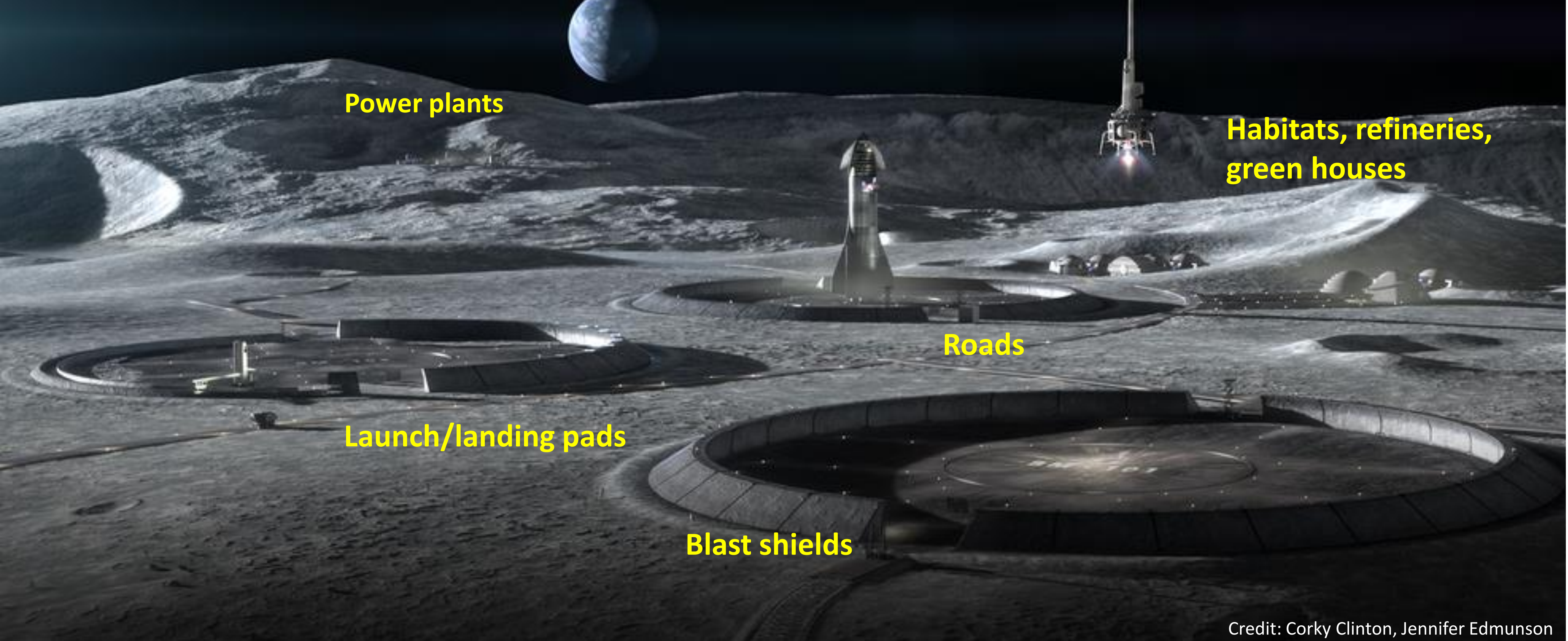

115 "shall" requirement statements in 6030; 31 "shall" statements in 6033

**Foundational Control**

**Part Production Control**

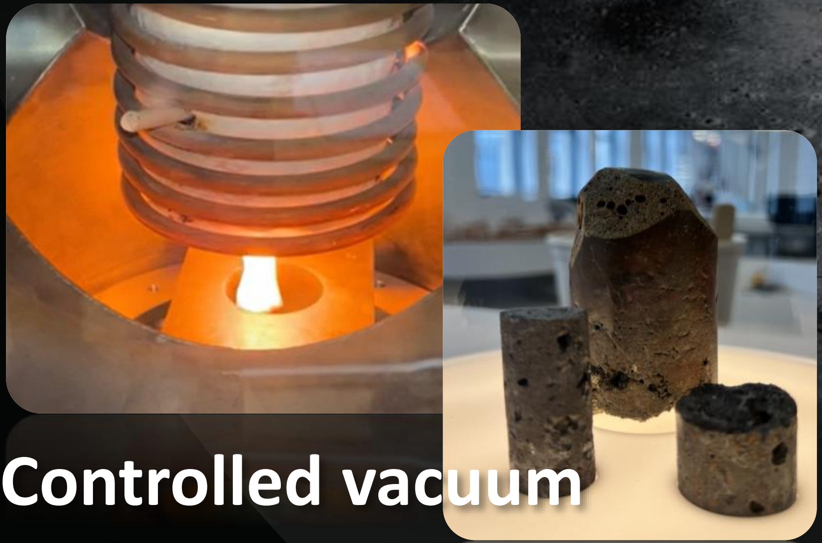
# What is the future of AM and in-space manufacturing?

## Building the infrastructure for a sustainable presence on the moon…




Credit: Corky Clinton, Jennifer Edmunson

# Early Process Development



**Controlled vacuum molten regolith extrusion**

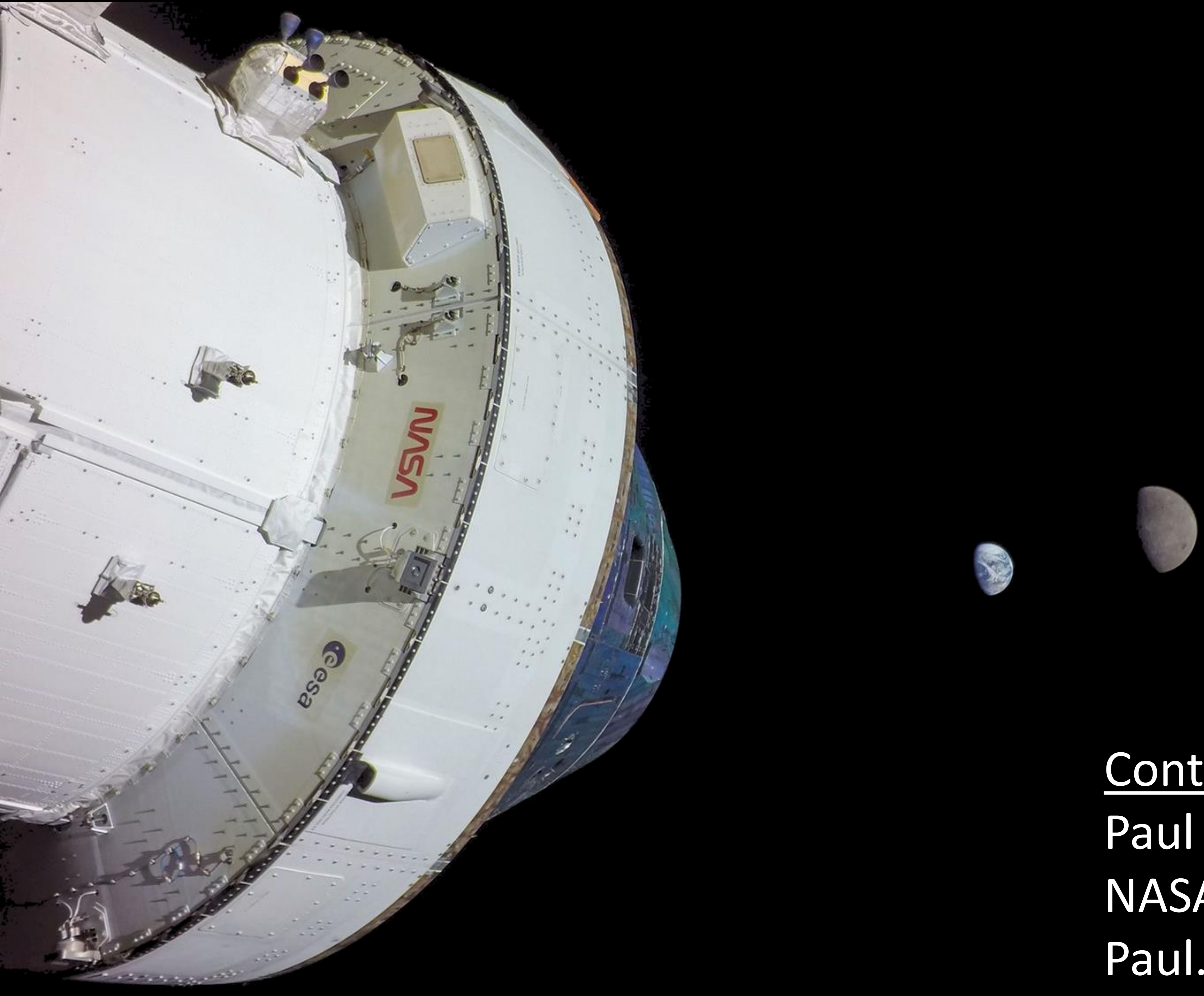
**Directed energy deposition of simulated regolith**

**High vacuum microwave sintering**

Credit: Corky Clinton, Jennifer Edmunson

# Moving Forward

- A thorough understanding of the processes and each of the steps/disciplines involved and interactions between each.
- You must start your planning in the initial stage and include the conversation on qualification early.
- Meticulously planned steps in the correct order; understanding upstream and downstream implications.
- We need to continue conversations across the industry.
- It is going to take lots of practice!

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# Acknowledgements


- Optimized and Repeatable Components using Additive (ORCA) Project
- Transformational Tools and Technology (TTT)
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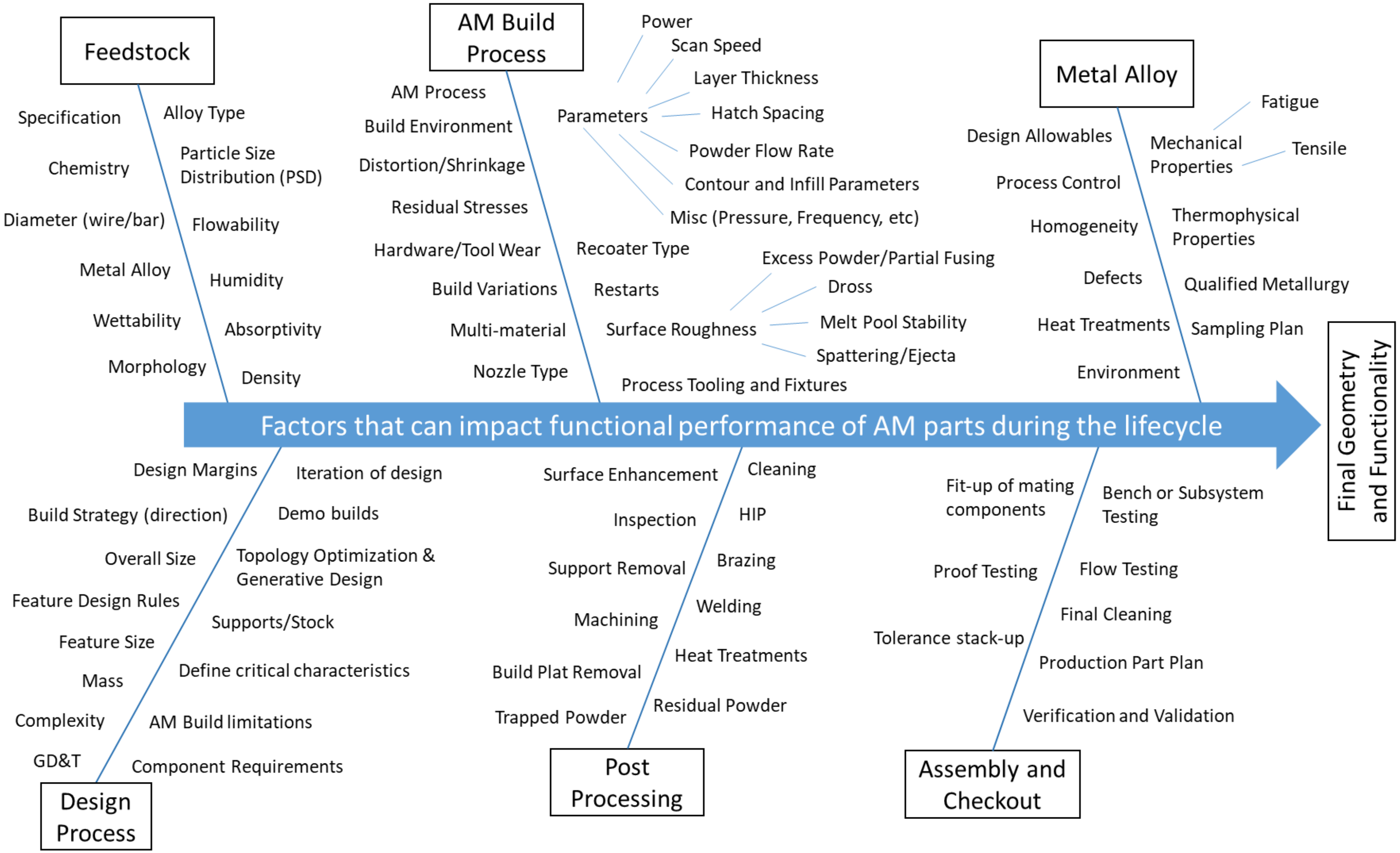
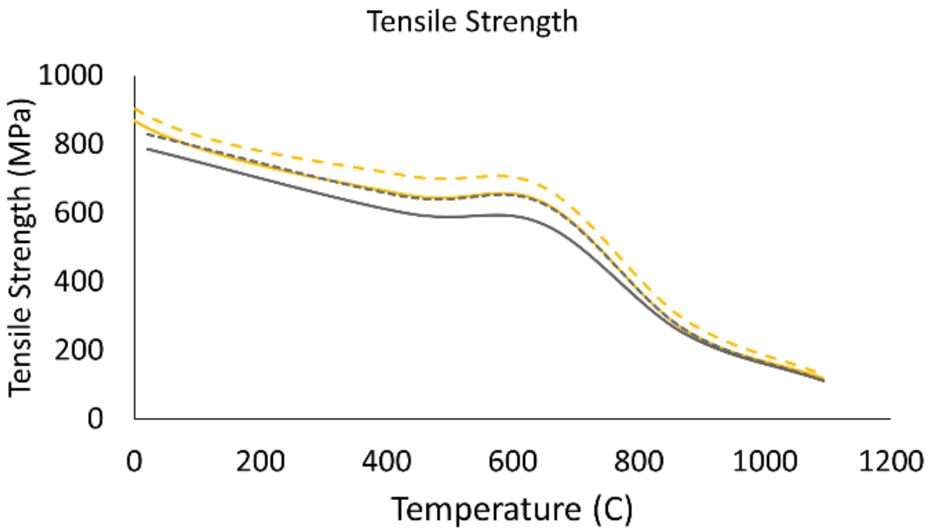
- PAC
- RPM Innovations
- TS115 test crew
- Auburn University
- Nima Shamsaei
- Shuai Shao
- Omar Mireles / LANL
- And many others involved

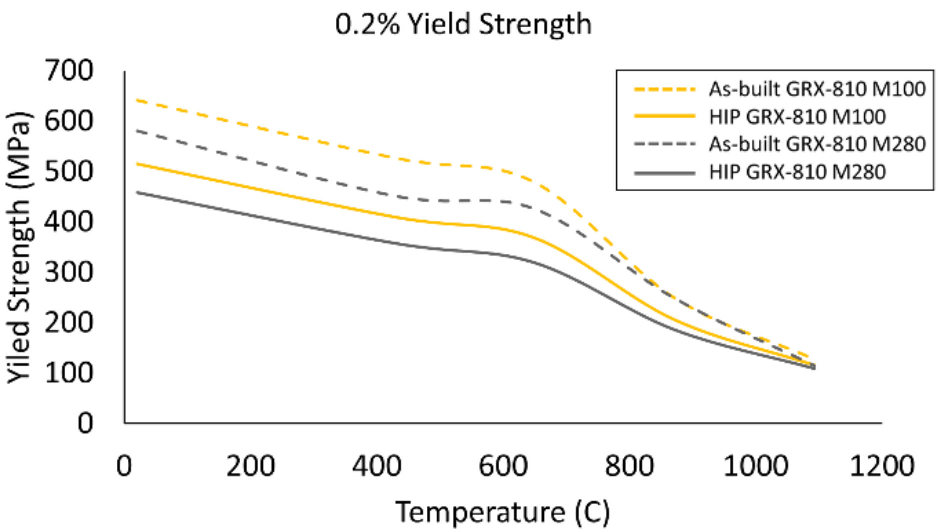
# The Challenges with AM Processes



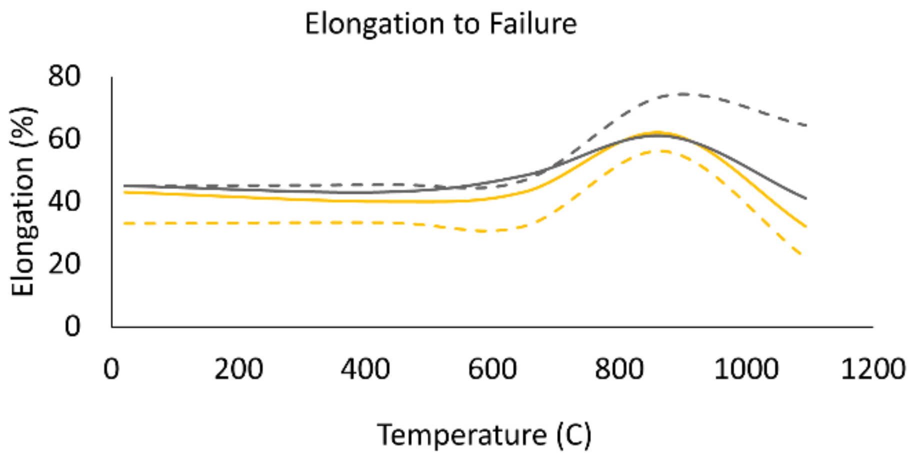

**There are a lot of inputs and steps in the AM lifecycle that must go right to meet the expected geometry**

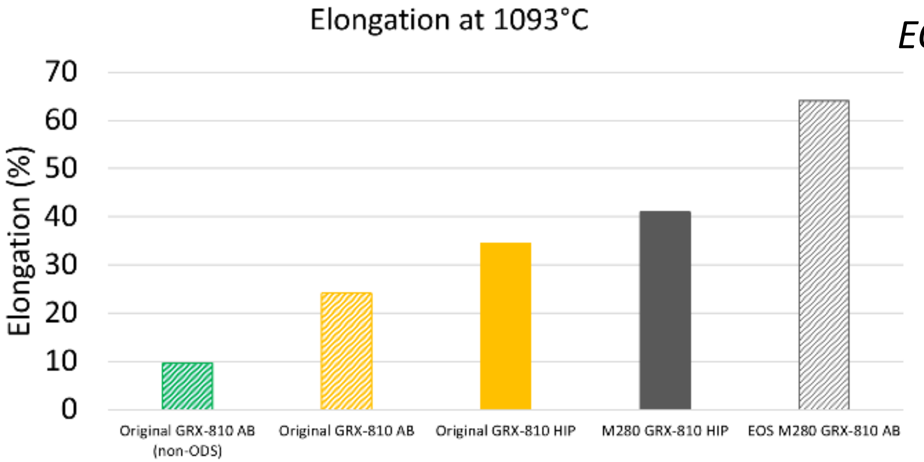
# GRX-810 Mechanical Properties




*EOS M100 (40 μm focus)*
*EOS M280 (100 μm focus)*

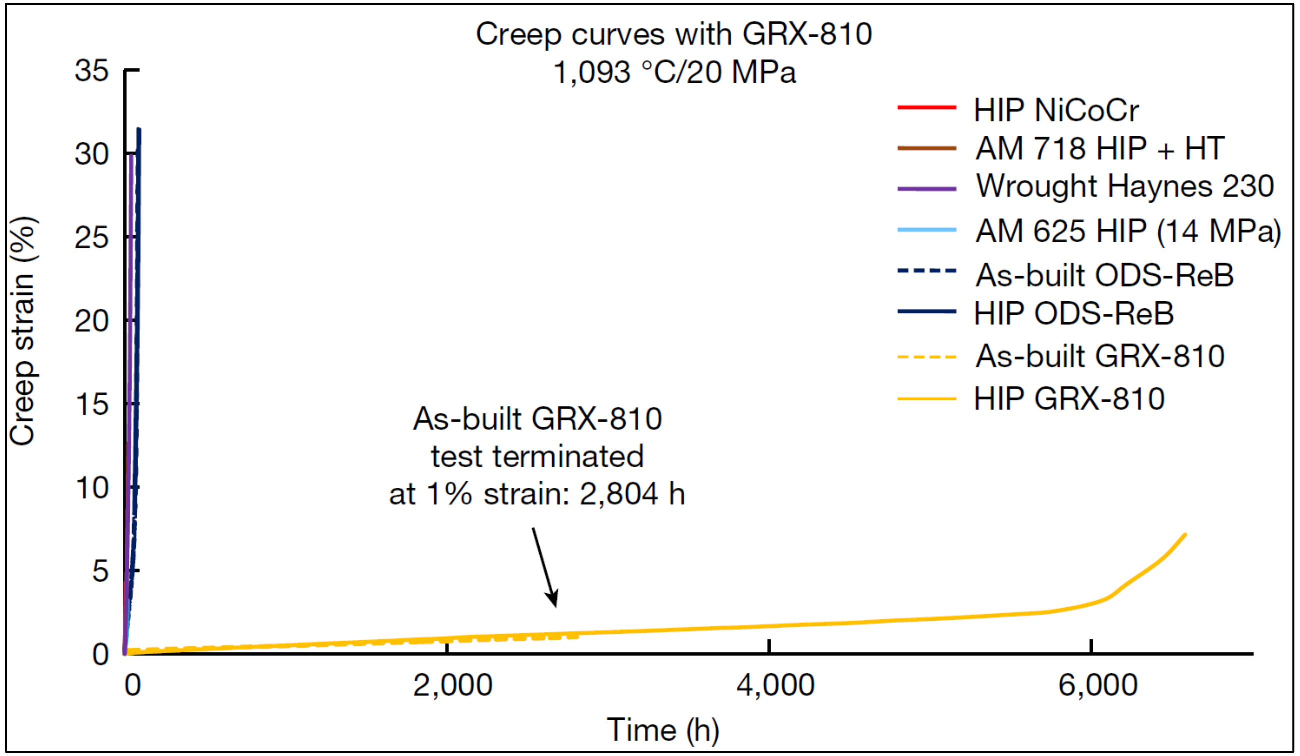



**Tensile properties of GRX-810 produced using an EOS M100 and using an EOS M280. Notable differences in room temperature strength and high temperature elongation were observed between the different lots.**

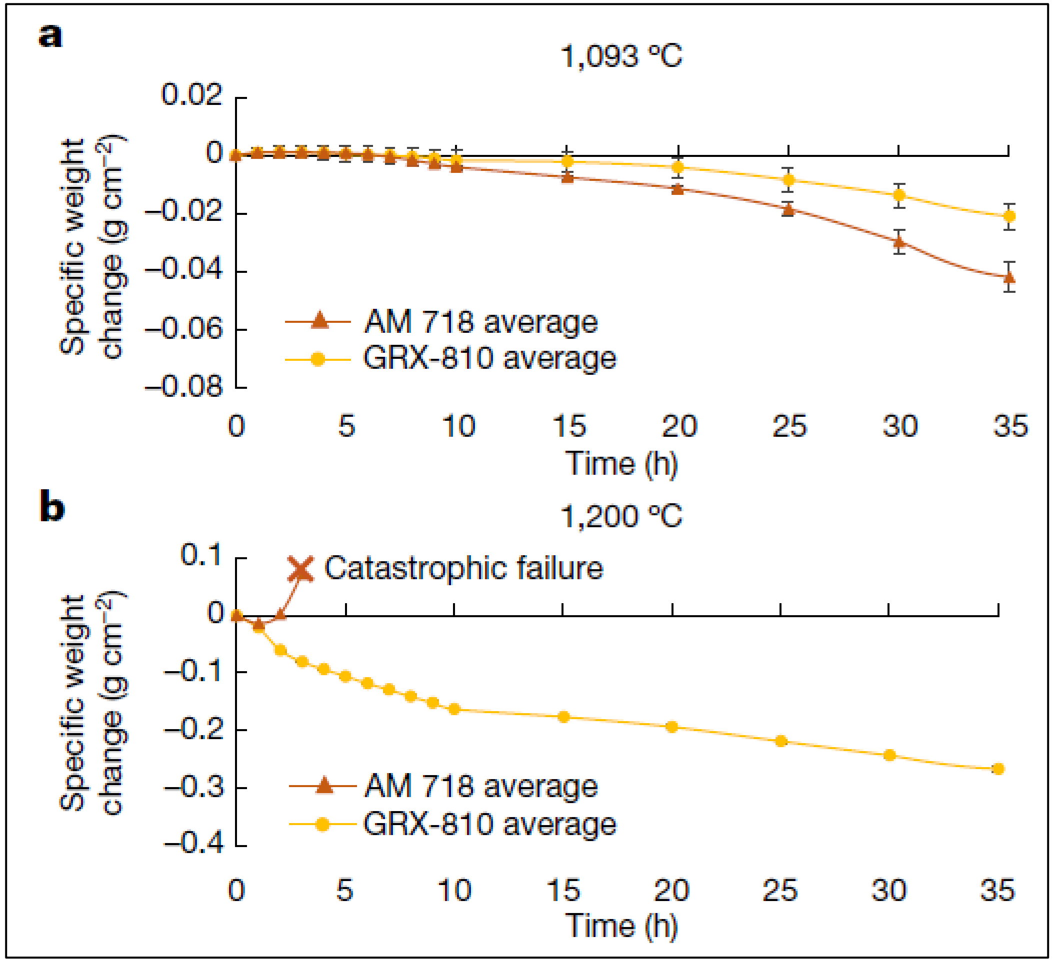
# GRX-810 Stress Rupture and Oxidation

## Stress rupture shows 1,000x improvement over typical Ni-based superalloys




Creep results from M100 and M280 showing similar trends, although M280 performing better

## Cyclic oxidation at 1093°C and 1200°C





Smith, T.M., Kantzos, C.A., Zarkevich, N.A., Harder, B.J., Heczko, M., Gradl, P.R., Thompson, A.C., Mills, M.J., Gabb, T.P., Lawson, J.W., 2023. A 3D printable alloy designed for extreme environments. Nature. https://doi.org/10.1038/s41586-023-05893-0

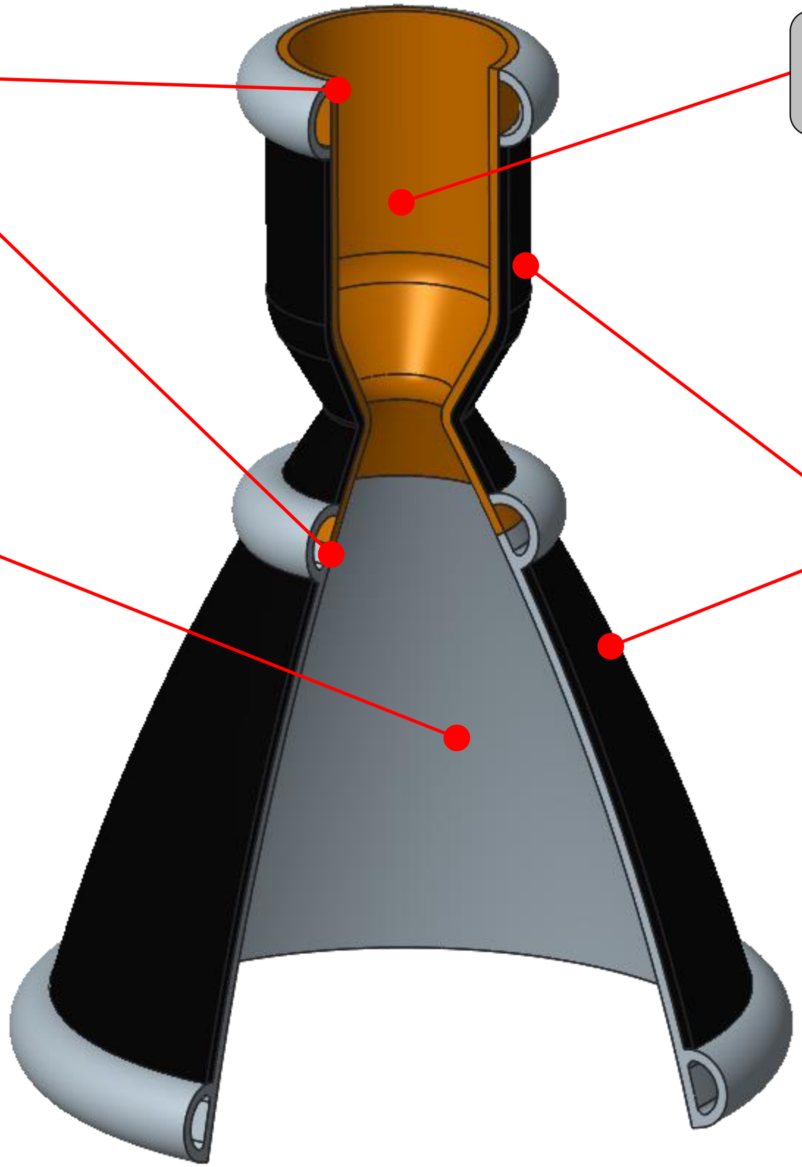
# Multi-metallic Additive Manufacturing under RAMPT Project

**Bimetallic Deposited Manifolds**
**and Nozzle Interface**

- Develops commercial supply chain
- Optimizes weight based on selective material deposition
- Reduces costs
- Evaluating DED and solid-state AM processes

**Integrated Large Scale DED**
**Freeform Manufacturing Deposition**
**Regen-Cooled Nozzle**

- Selected Laser Powder Directed Energy Deposition (LP-DED)
- Demonstrate integral channels using DED process
- Demonstrate coupled chamber and nozzle configuration to reduce weight
- Reduces complexity
- Significantly increases scale for AM processes for regen-cooled components



**L-PBF AM Copper**
**Chamber**

- Based on prior LCUSP development
- Proven Technology for GRCop alloys
- Expand to GRCop-42
- Advances and expands commercial supply chain

**Composite Overwrap**

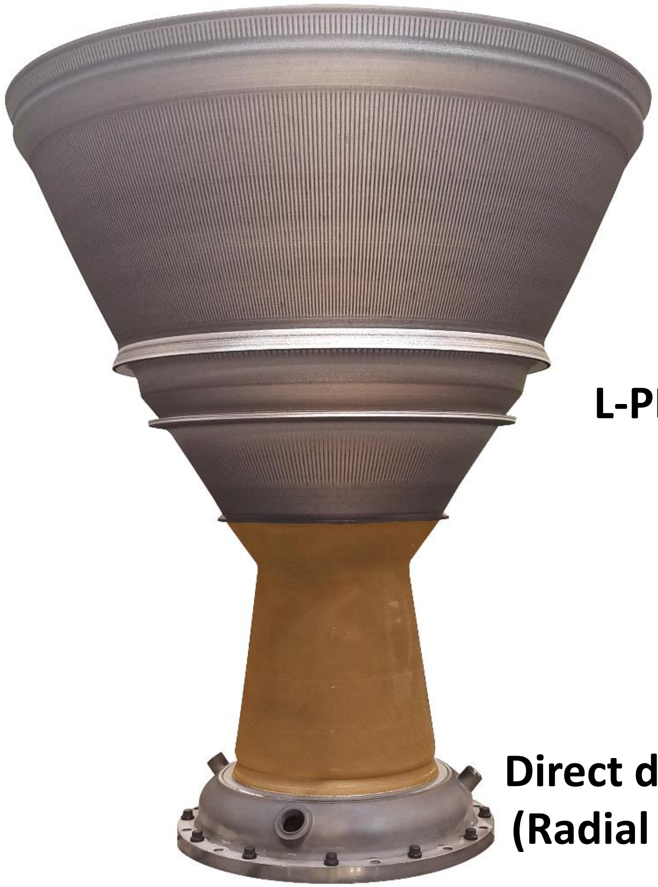
- Significantly reduces weight for high chamber pressure TCA's
- Reduces distortions caused by bimetallic cladding
- Reduces overall cost and fabrication schedules
- Builds upon prior composite overwrap pressure vessel (COPV) technology

# Multi-metallic and multi-process hardware development

Credit: RPMI

L-PBF Liner / LP-DED Jacket

L-PBF Liner / Coldspray Jacket



Direct deposit LP-DED nozzle
(Radial and Axial Bimetallic)

L-PBF Liner / EBW-DED Jacket

L-PBF GRCop-42 to Inco 625