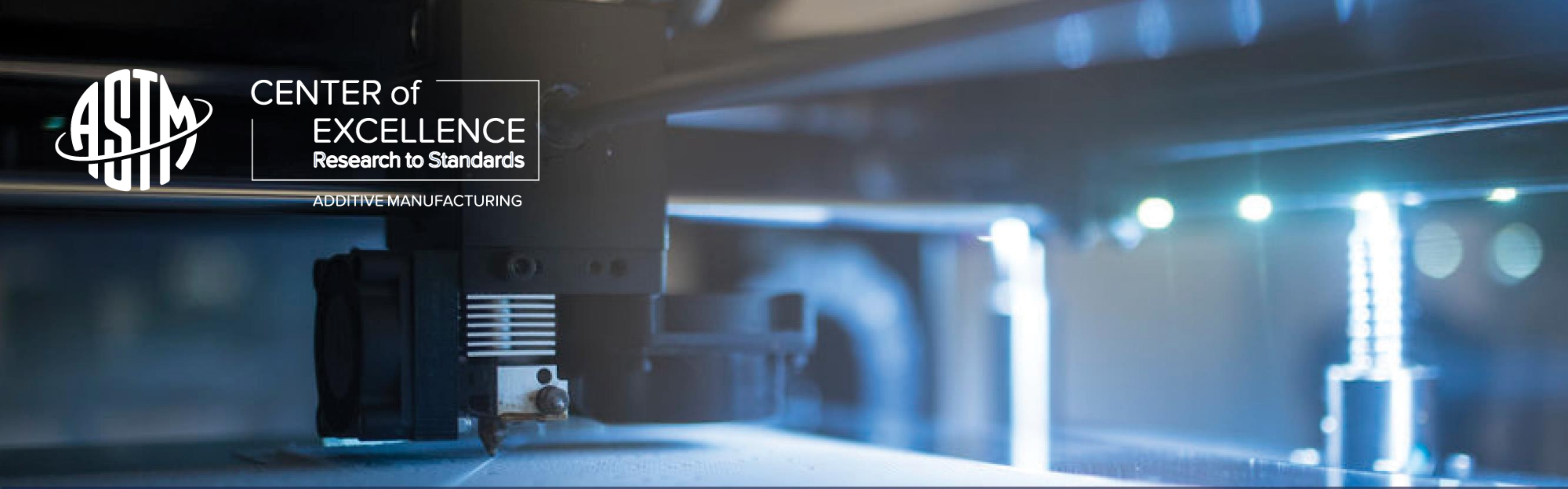
ASTM
CENTER of
EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING



AM Industrialization and Automation

4th ASTM AM CoE Snapshot Workshop (Virtual)

Additive Manufacturing Developments for Rocket Engines: Applications, Advanced Materials and Large Scale Techniques

Paul Gradl, NASA Marshall Space Flight Center

Presenter Bio

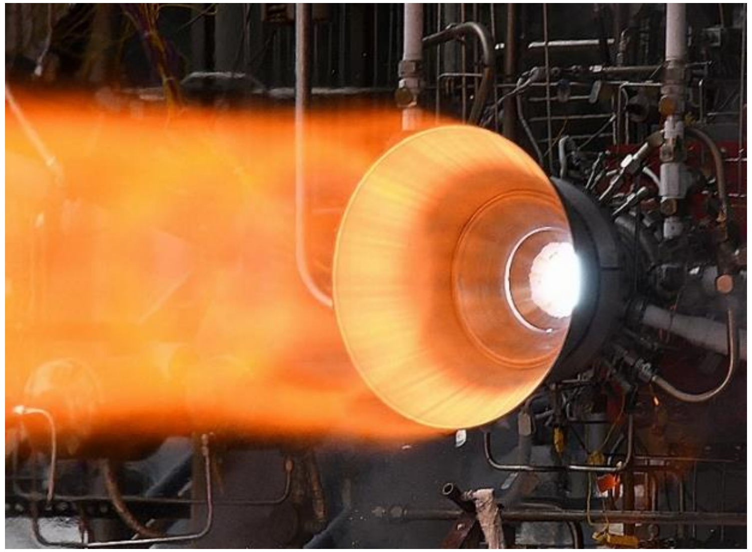
Paul Gradl

- Senior Engineer in Component Technology Development
- NASA Marshall Space Flight Center

Paul Gradl is a Senior Propulsion Engineer at NASA Marshall Space Flight Center (MSFC) in the Propulsion Division, Engine Components Development and Technology Branch. Mr. Gradl serves as principal investigator and leads several projects for additive manufacturing of liquid rocket engine combustion devices and supports a variety of development and flight programs over the last 16 years. He authored and co-authored over 40 conference and professional papers and journal articles; holds four patents in additive; and taught several classes in additive manufacturing for propulsion. Three of his papers were recognized as industry-leading efforts in the field of additive manufacturing for propulsion. Gradl is the recipient of numerous NASA and industry awards including two NASA Exceptional Achievement Medals, NASA Exceptional Service Medal, MSFC Research and Technology, NASA Technology Transfer, Engineering Partnership Award, and NASA Space Flight Honoree to name a few. Mr. Gradl serves on several committees and chairs various sessions at leading conferences on additive manufacturing.

Introduction and Agenda

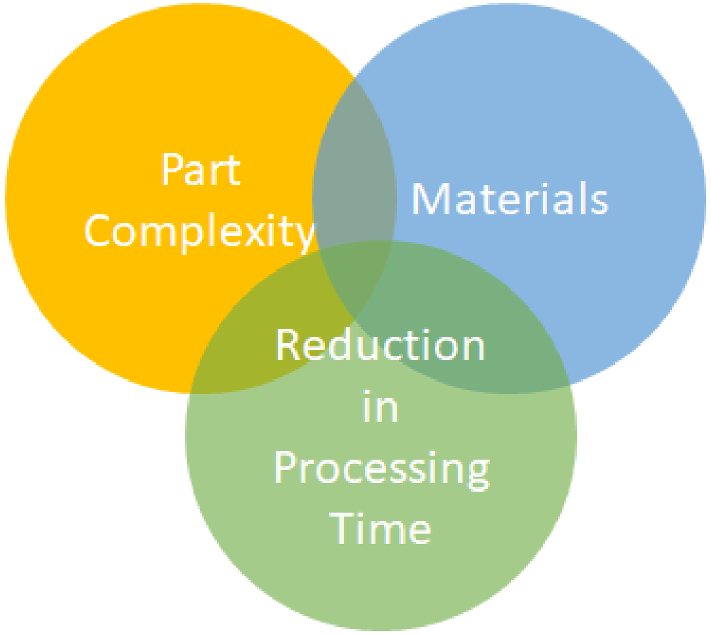
- Motivation for using AM in rocket engines
- Brief Case Study
- Overview of AM Techniques and Trades
- L-PBF and its limitations
- Large scale techniques and examples
- New material developments for AM
- Current focuses in AM for rocket engines



Hot-fire testing of bimetallic additively manufactured combustion chamber

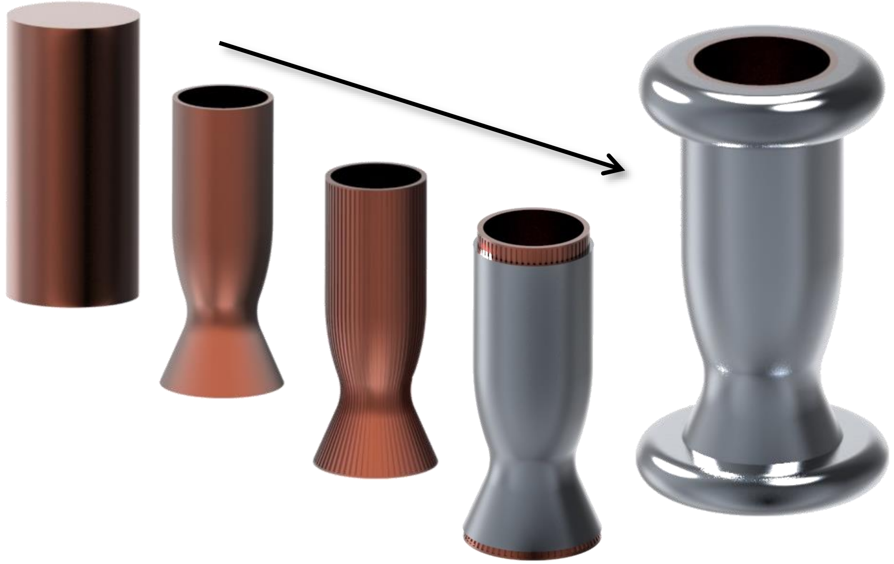
Introduction and Motivation

- Metal Additive Manufacturing provides significant advantages for lead time and cost over traditional manufacturing for rocket engines
  - Lead times reduced by 2-10x and 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



Case Study – Combustion Chambers

Traditional Manufacturing



12-18 mos / $310k*

AM Development

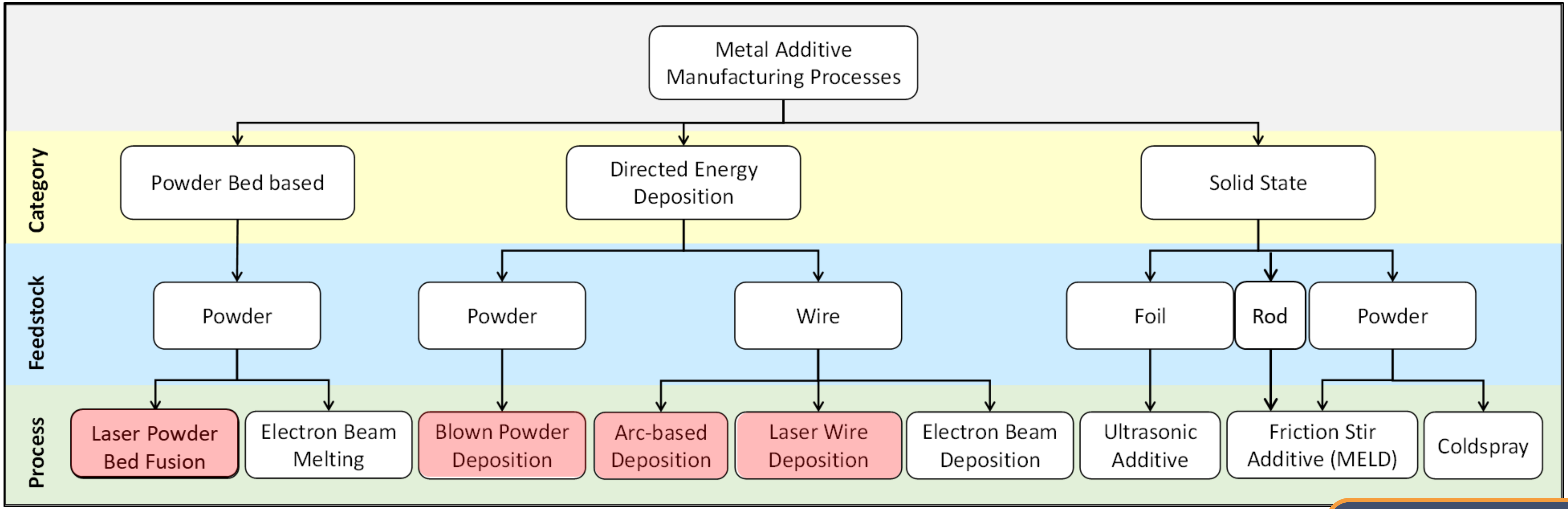
6-8 mos / $200k*

Evolving AM

3-5 mos / $125k**

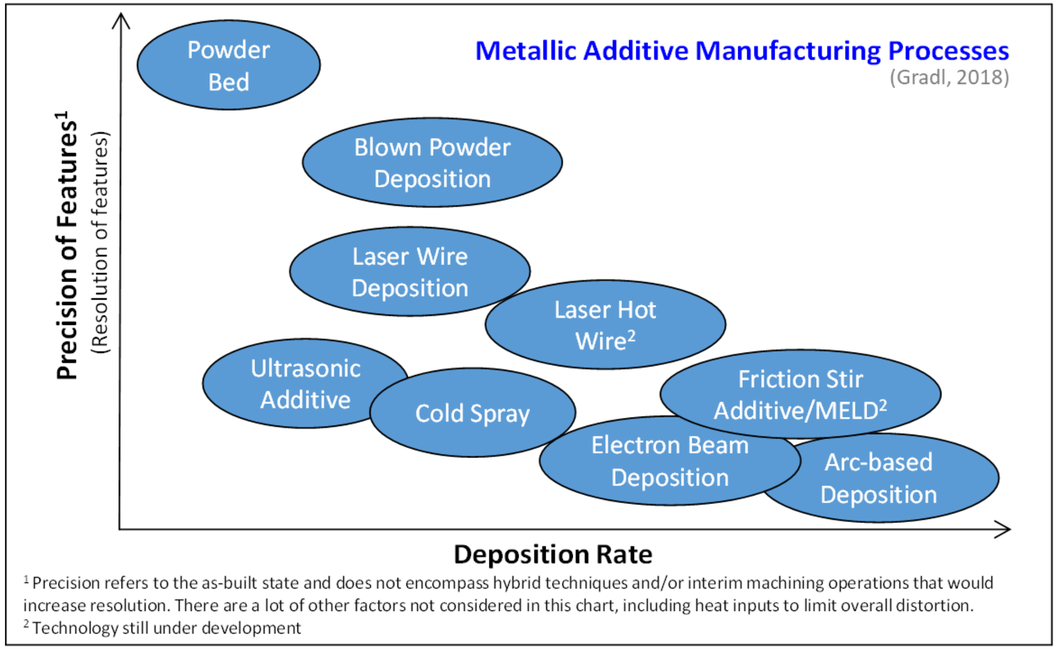
*Dollars in USD **Manifolds not shown, but included in cost

Focus of AM Techniques for Rocket Engines



*Does not include all metal AM processes

Various criteria for selecting AM techniques

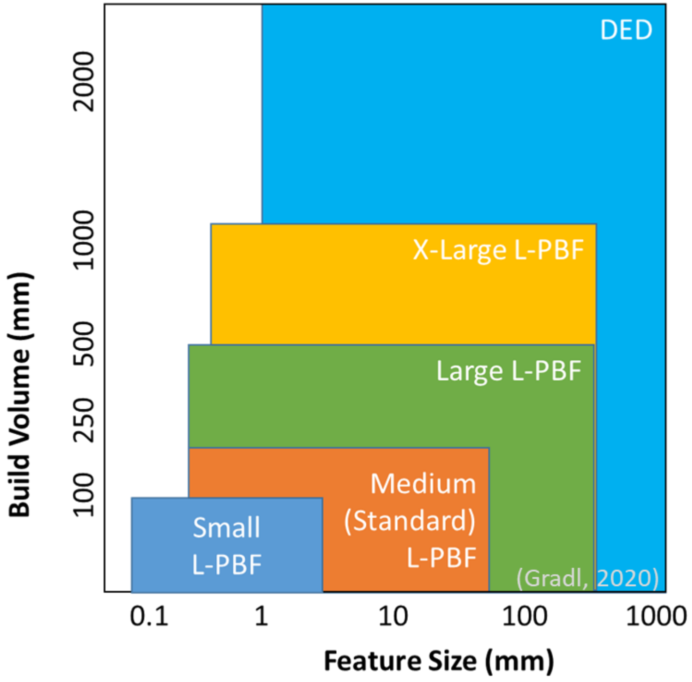


Metallic Additive Manufacturing Processes

(Gradl, 2018)

[1] Precision refers to the as-built state and does not encompass hybrid techniques and/or interim machining operations that would increase resolution. There are a lot of other factors not considered in this chart, including heat inputs to limit overall distortion.

[2] Technology still under development



(Gradl, 2020)

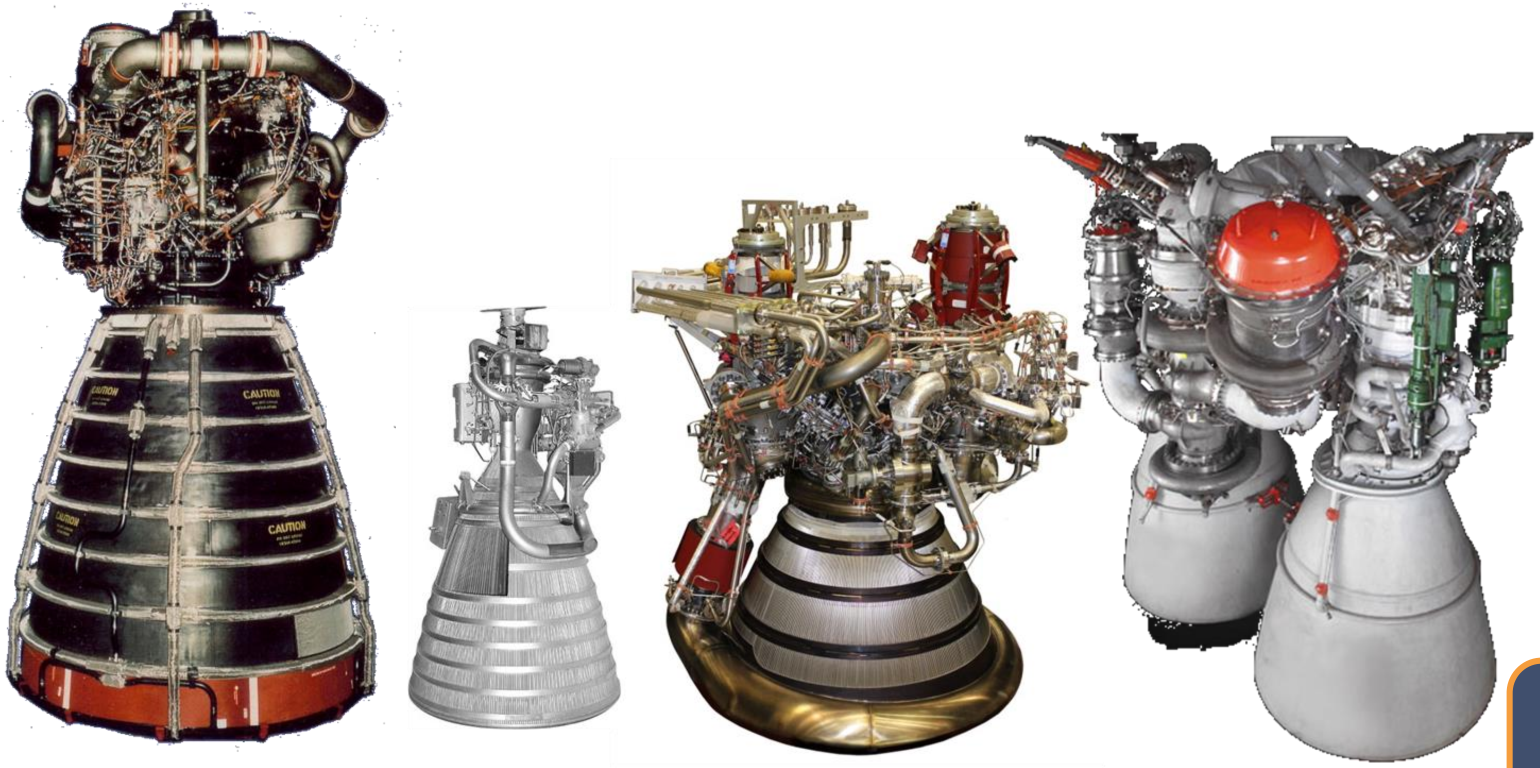
- Complexity of Features
- Scale of Hardware
- Material Physics
- Cost
- Speed of Process
- Material Properties
- Internal Geometry
- Availability

Example of L-PBF for rocket applications

- **Extreme environments, complex shapes, and new materials**
  - Combustion Chambers (regen-cooled)
  - Injectors
  - Cryogenic Fluid Management
  - In-space thrusters
  - Turbomachinery (Fuel and LOX)
    - Pump and turbine ends of rotating
  - Nozzles
  - Ignition systems
  - Valves
  - Lines, ducts

The need for large scale AM

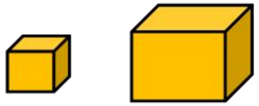
SSME/RS-25 **RL-10A-4** **J-2X, Regen Only** **RD-180**



90″ 46″ 70″ 56″

Nozzle Exit Dia.

L-PBF Build Boxes

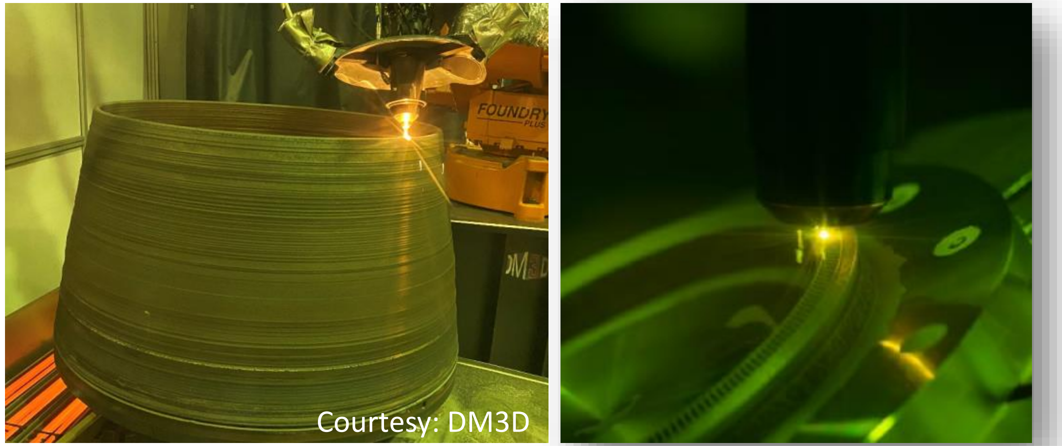


10x10x10 15.5x24x19

(inches)

AM solutions for large scale

Blown Powder DED

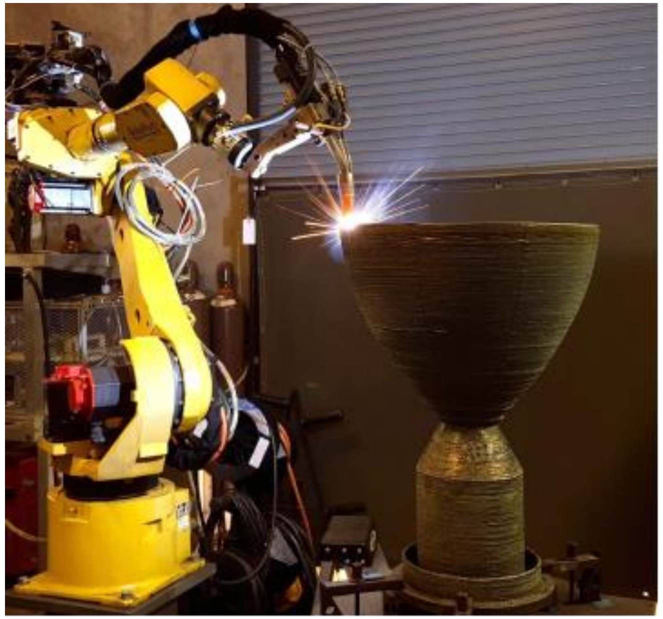


Courtesy: DM3D

Courtesy: RPMI

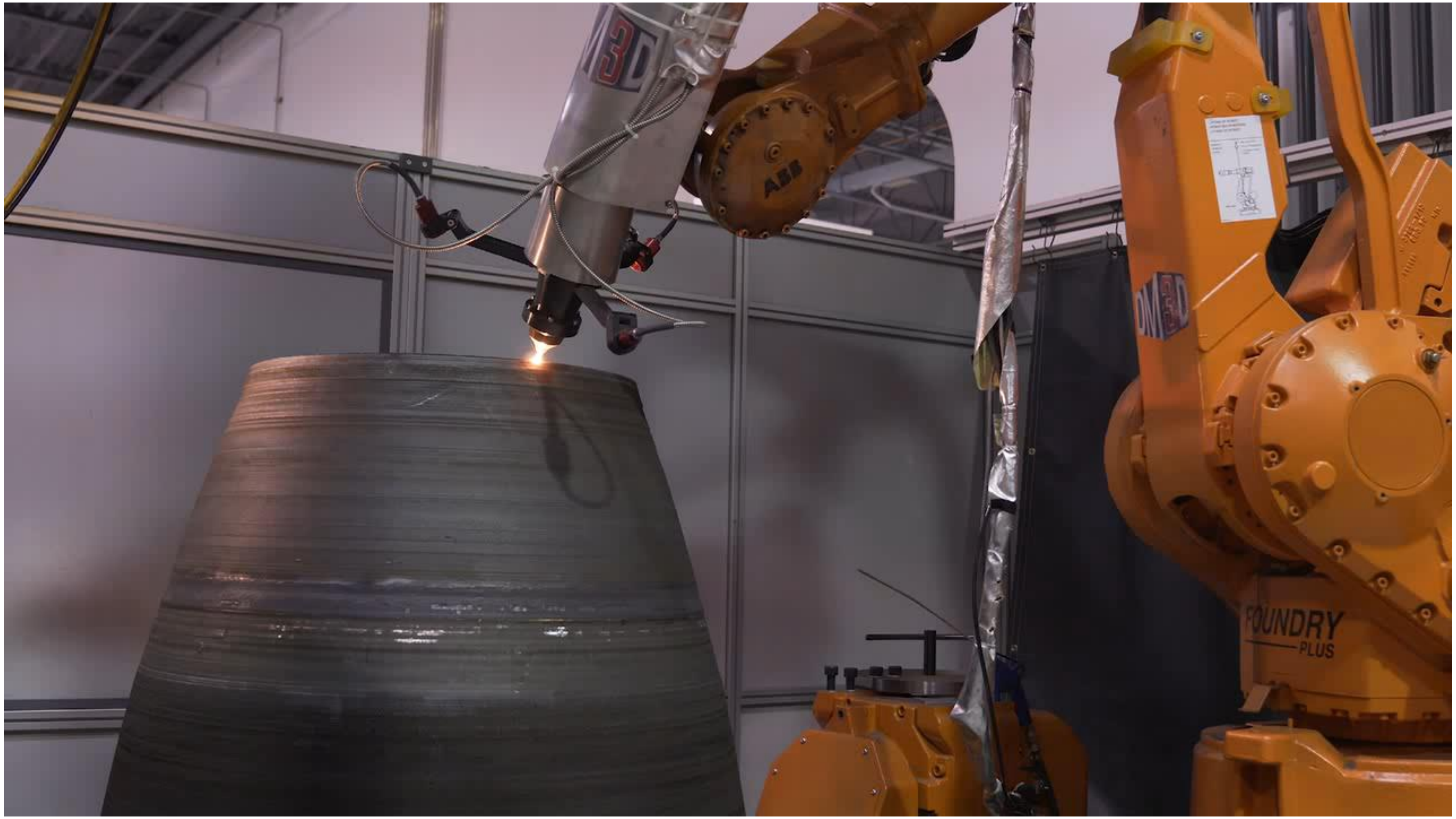
Wire Arc Deposition

Courtesy: Keystone

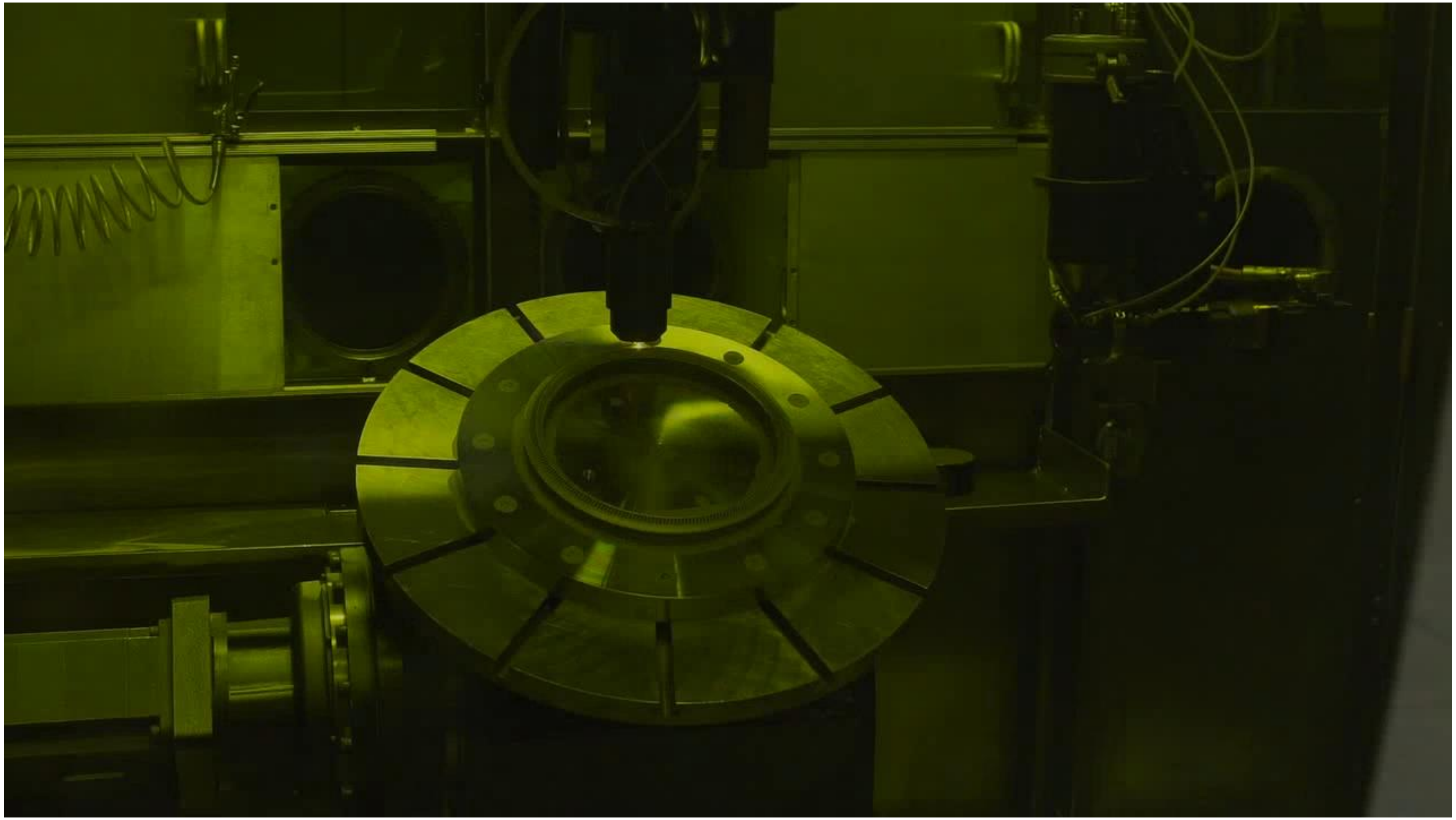


Gradl, P. R., & Protz, C. S. (2020). Technology advancements for channel wall nozzle manufacturing in liquid rocket engines. *Acta Astronautica*. https://doi.org/10.1016/j.actaastro.2020.04.067

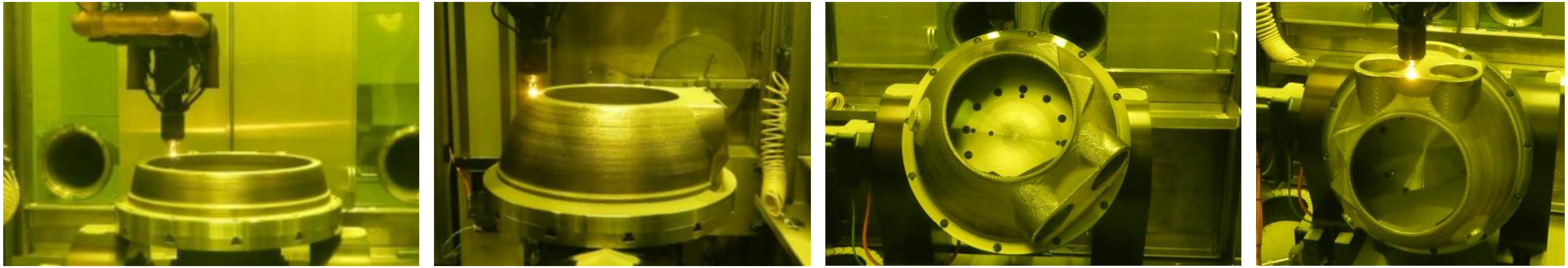
Example of blown powder DED for large-scale nozzles



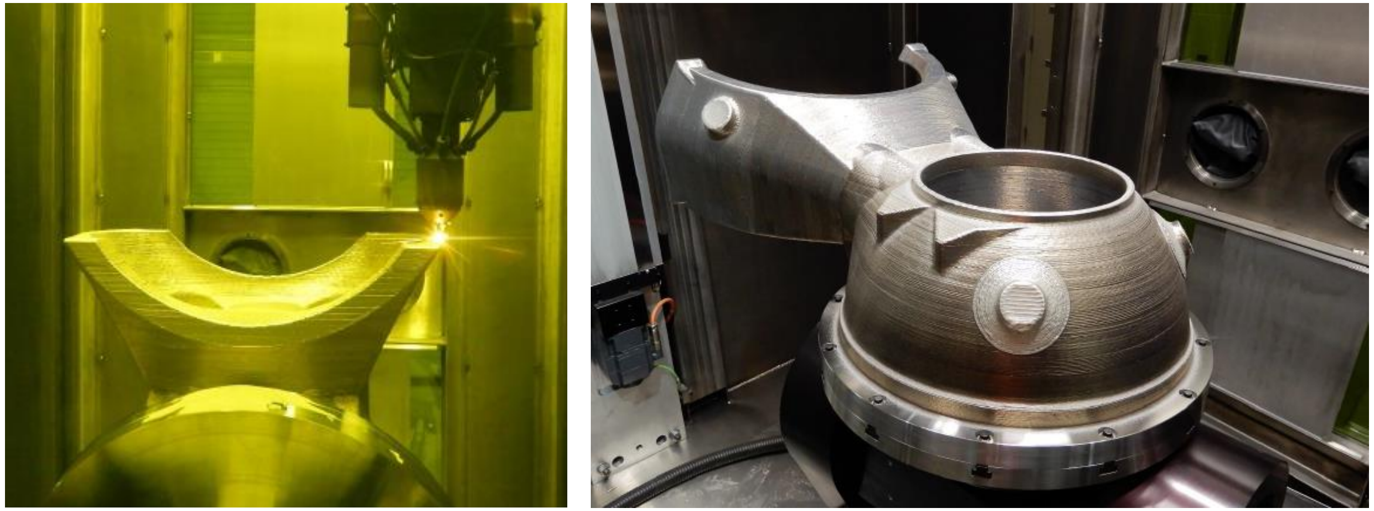
Example of blown powder DED for large-scale nozzles



Example of large scale complex AM



Freedom in design and deposition strategies



RS25 Powerhead demonstrator under NASA SLS Artemis (Courtesy: RPMI)

Material Availability for Rocket Applications

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

As available materials and processes continue to grow, so does complexity of characterization and standardization

Ni-Base

Inconel 625
Inconel 718
Hastelloy-X
Haynes 230
Haynes 282
Haynes 188
Monel K-500
C276
Rene 80
Waspalloy

Fe-Base

SS 17-4PH
SS 15-5 GP1
SS 304
SS 316L
SS 420
Tool Steel
(4140/4340)
Invar 36
SS347
JBK-75
NASA HR-1

Cu-Base

GRCop-84
GRCop-42
C-18150
C-18200
Glidcop
CU110

Al-Base

AlSi10mg
A205
F357
6061 / 4047

Refractory

W
W-25Re
Mo
Mo-41Re
Mo-47.5Re
C-103
Ta

Ti-Base

Ti6Al4V
γ-TiAl
Ti-6-2-4-2

Co-Base

CoCr
Stellite 6,
21, 31

Bimetallic

GRCop-84/IN625
C-18150/IN625

MMC

Al-base
Fe-base
Ni-base

Industry Materials developed for L-PBF, E-PBF, and DED processes *(not fully inclusive)*

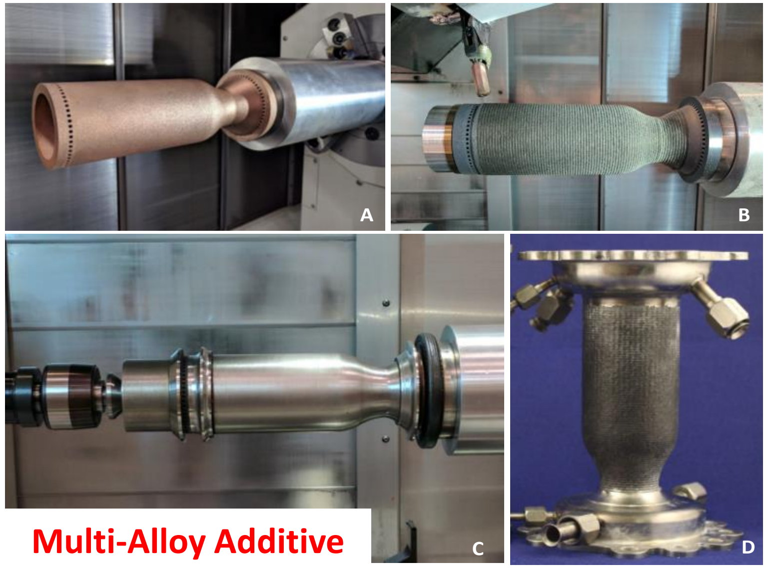
AM Copper alloys for combustion chamber, GRCop-42 and GRCop-84

- Oxidation and blanching resistance during thermal and oxidation-reduction cycling
- A maximum use temperature around 800°C, depending upon strength and creep requirements
- Good mechanical properties at high use temperatures (2x of typical copper)
- NASA and industry partners working to mature the entire supply chain, characterization, properties and component application

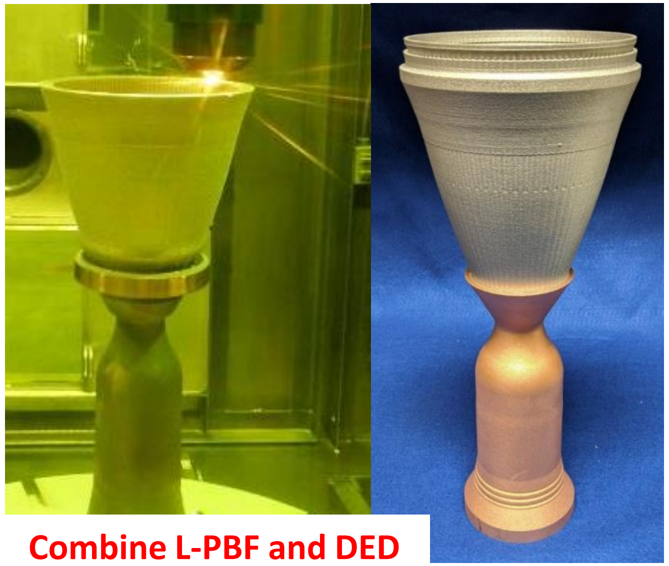
Element	GRCop-42 Wt %	GRCop-84 Wt %
Cr	3.1 – 3.4	6.2 – 6.8
Nb	2.7 – 3.0	5.4 – 6.0
Fe	Target <50 ppm	Target <50 ppm
O	Target <400 ppm	Target <400 ppm
Al	<50 ppm	<50 ppm
Si	<50 ppm	<50 ppm
Cu	Balance	Balance
Cr:Nb Ratio	1.12 – 1.15	1.12 – 1.15

Gradl, P., Protz, C., Ellis, D.C., Greene, S.E. "Progress in Additively Manufactured Copper-Alloy GRCop-84, GRCop-42, and Bimetallic Combustion Chambers for Liquid Rocket Engines." 70th International Astronautical Congress 2019. 21-25 October 2019. Washington, DC. United States. IAC-19.C4.3.5x52514

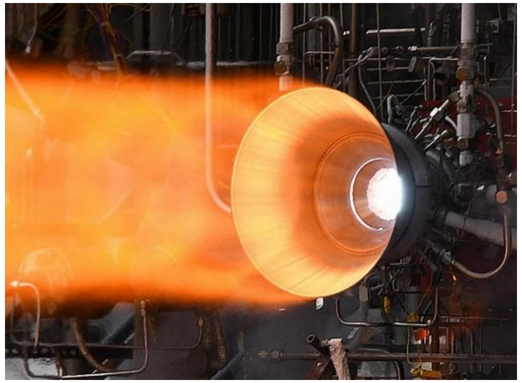
Example of AM GRCop-alloys used in rocket engines

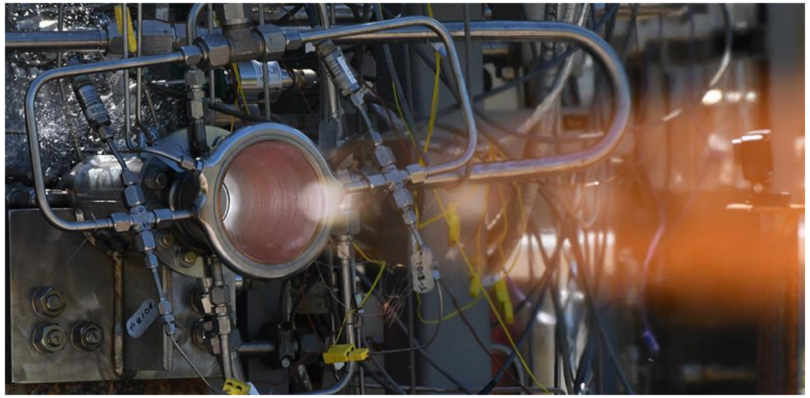


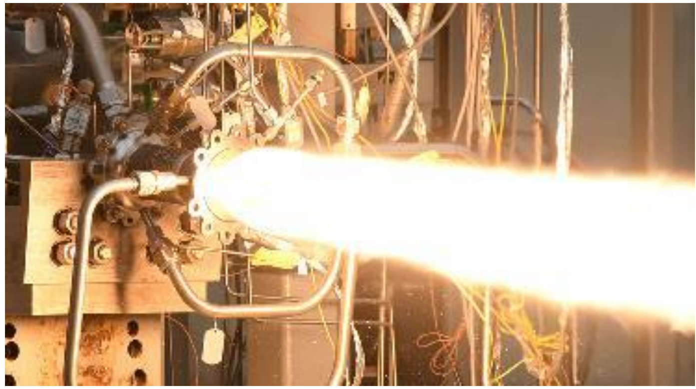
Multi-Alloy Additive



Combine L-PBF and DED

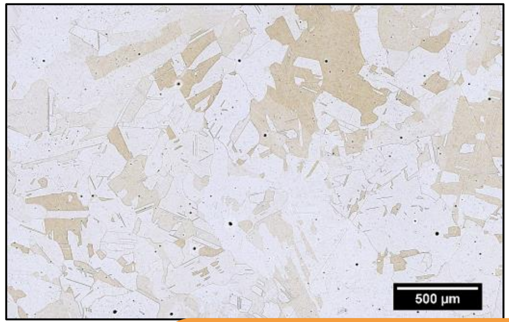






Using AM for NASA HR-1, Hydrogen Resistant Alloy

- NASA HR-1 is a high-strength Fe-Ni-base superalloy that resists high-pressure hydrogen environment embrittlement (HEE), oxidation, and corrosion.
- "HR" stands for **<u>H</u>**ydrogen-**<u>R</u>**esistant (HEE resistant)
- Originally derived from JBK-75, developed at NASA MSFC in mid-1990's
- NASA-HR-1 is a unique alloy that extends the compositional range of existing HEE-resistant Fe-Ni-base superalloys.



Katsarelis, C., Chen, P., Gradl, P.R., Protz, C.S., Jones, Z., Ellis, D.E., Evans, L. "Additive Manufacturing of NASA HR-1 Material for Liquid Rocket Engine Component Applications." Paper presented at 2019 JANNAF 11th Liquid Propulsion Subcommittee (LPS), December 9-13. Tampa, FL. (2019).

Examples of Additive NASA HR-1

40” dia and 38” height nozzle with internal features built in 30 days using BP-DED

Courtesy: RPM Innovations (RPMI)

Continued Developments in AM

- Large scale, small feature resolution DED processes
- Supplemental processing and post-processing
    - Dissolvable supports
    - Surface Enhancement Technology
    - Inspection and in-situ monitoring
- Bimetallic and multi-metallic deposition with a variety of processes
    - Combining additive processes to achieve optimization
- New alloy development and/or with new processes
    - Refractory, Superalloys for specific environments
- Full material characterization and property development
- Standardization of post-processing
- Certification of AM processes for flight applications

Summary

- Rocket engines are a prime use of AM with the appropriate process approach
- Many metal AM processes are available and maturing – select based on component requirements
- New materials are being developed for harsh environments
- Large metal AM provides new opportunities with complex internal features
- Standards and certification of the process in-work
- AM is evolving and there is a lot of work ahead