Large Scale and Multi-Alloy Rocket Engine Component Development using Various Metal Additive Manufacturing Techniques

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National Aeronautics and Space Administration (NASA)

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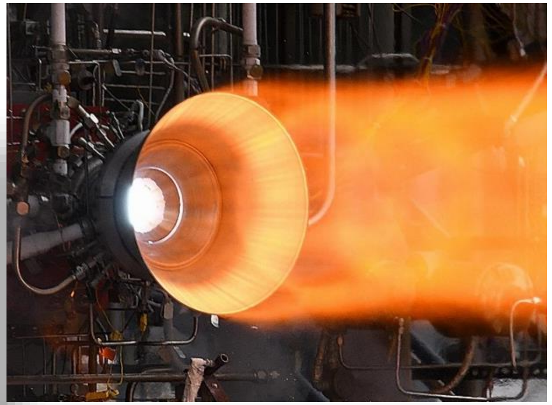
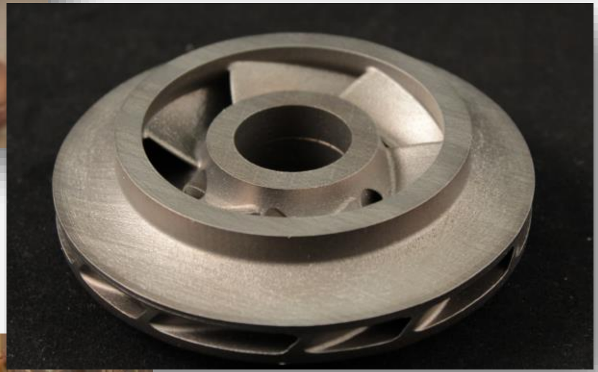
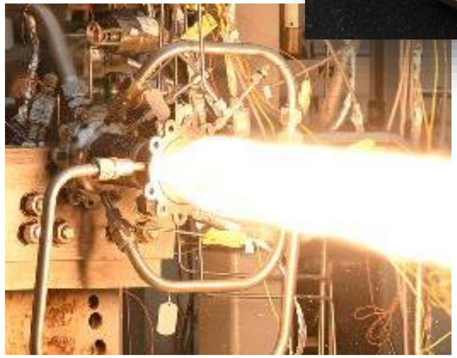
2020 JANNAF LPS AMP Additive Manufacturing Technical Interchange Meeting (TIM)

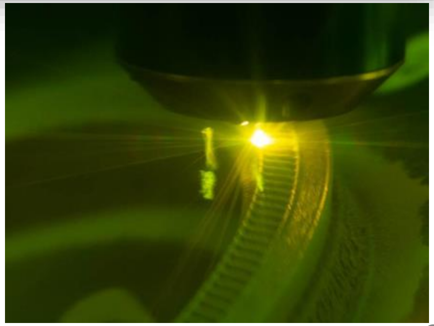
Overview of Additive Manufacturing (AM) at NASA for Rocket Engines

- Background and Goals at NASA with Metal AM
- Focus of Techniques for AM
  - Laser Powder Bed Fusion (L-PBF)
  - Blown Powder Directed Energy Deposition (DED)
  - Wire Arc Additive Manufacturing (WAAM)
- Large scale AM component examples
- AM Materials for Liquid Rocket Engines
- Summary and new developments



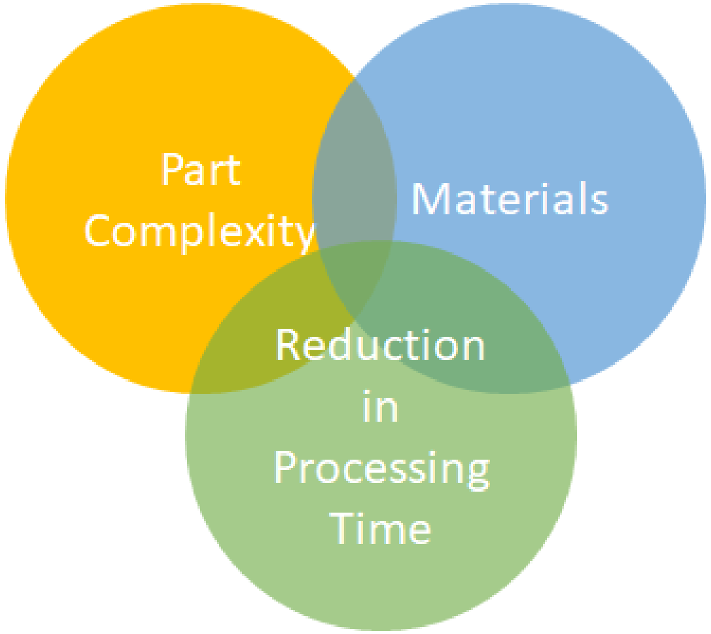




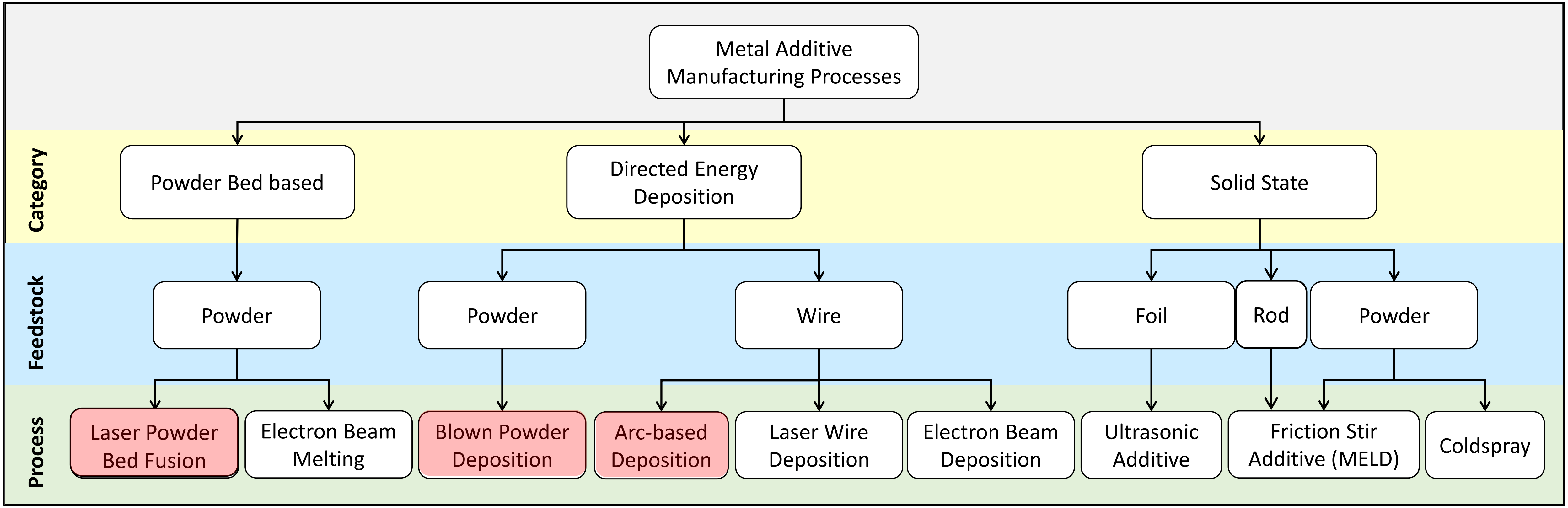


Motivation and Overview

- Additive Manufacturing (AM) has provided new opportunities for liquid rocket engine components to reduce cost, reduce lead time and improve performance
- NASA and commercial industry have demonstrated AM on various development and flight programs as a feasible technology
- Current AM technology using Laser Powder Bed Fusion (L-PBF) has limitations of volume that can be built
- There is a need to develop large scale additive manufacturing techniques for engine components such as regeneratively-cooled combustion devices and further improve performance through weight reduction
- Opportunities to develop new alloys and combining techniques to optimize component applications



Presentation focus of Metal AM Technologies



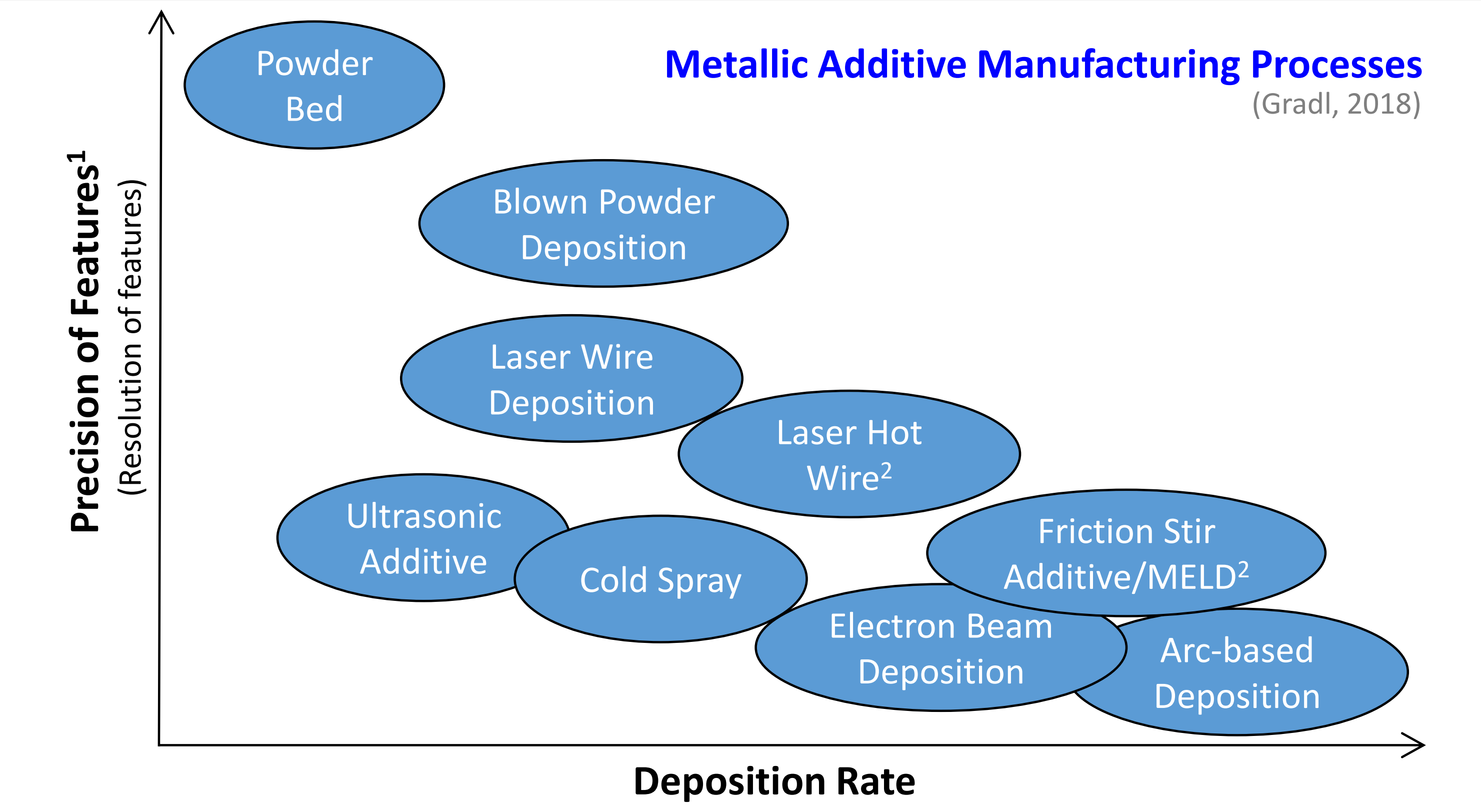
*Does not include all metal AM processes

NASA has developed and tested components in sizes from 100 - 35,000 lbf thrust using a variety of these metal AM techniques and many of these pieces have been hot-fire tested.

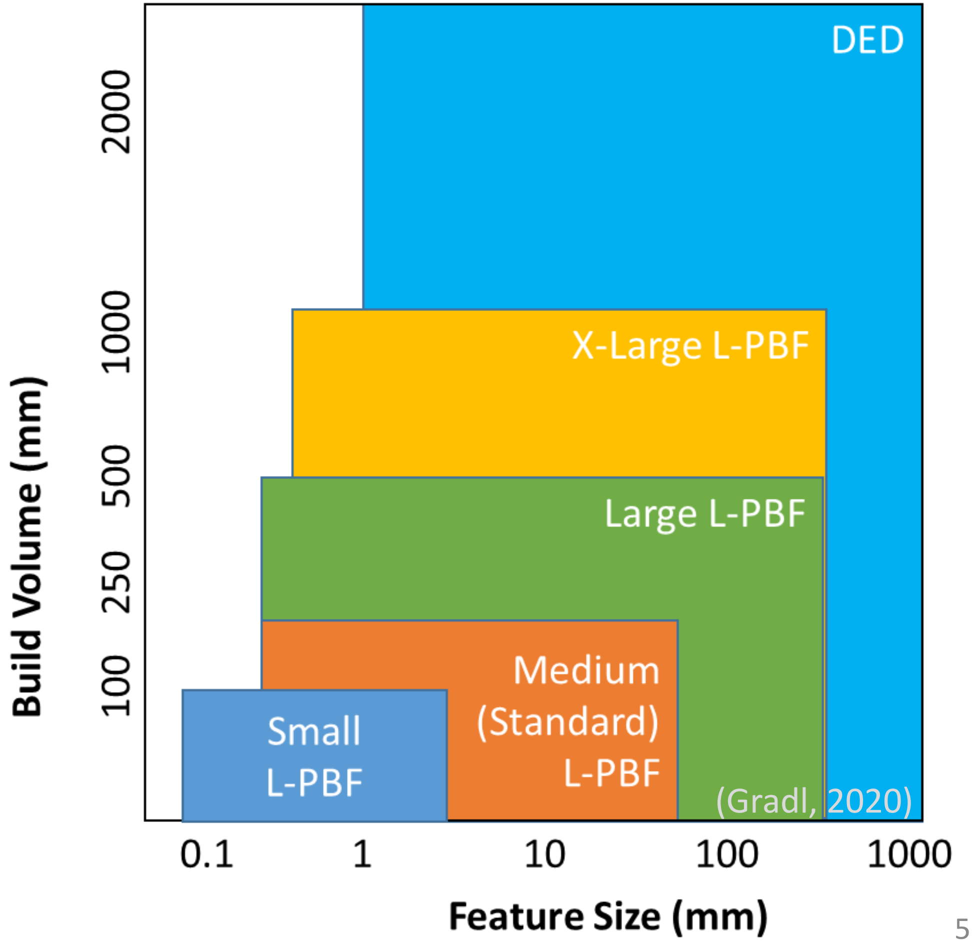
Trades and Selection of Metal AM Technologies

Complexity of Features | Scale of Hardware | Material Physics | Speed of Process

Cost | Material Properties | Internal Geometry | Availability



[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



Materials for Liquid Rocket Engines

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

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

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

Al-Base
AlSi10mg
A205
F357
6061 / 4047

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

Ti-Base
Ti6Al4V
γ-TiAl
Ti-6-2-4-2

Co-Base
CoCr
Stellite 6, 21, 31

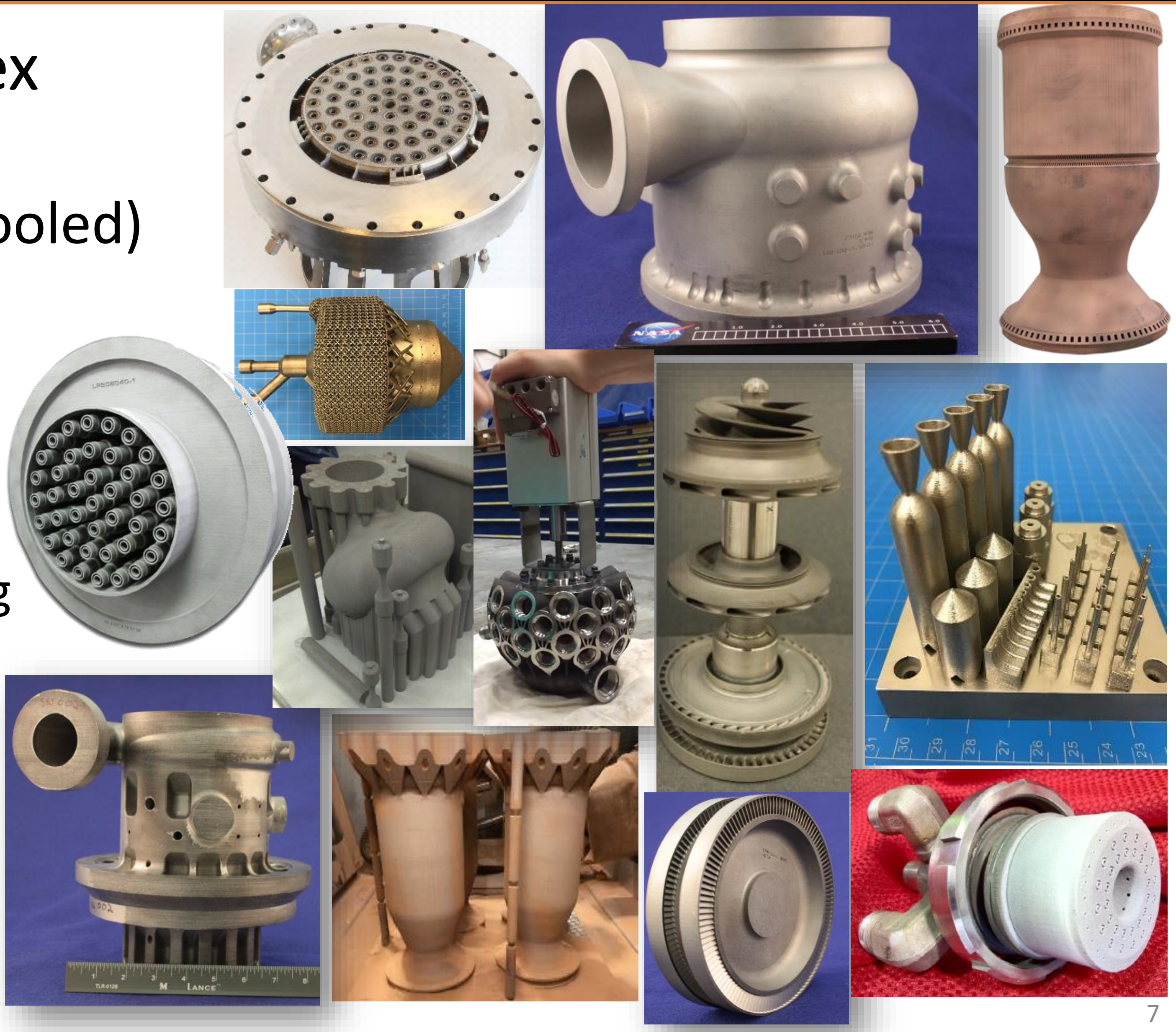
Refractory
W
W-25Re
Mo
Mo-41Re
Mo-47.5Re
C-103
Ta

Bimetallic
GRCop-84/IN625
C-18150/IN625

MMC
Al-base
Fe-base
Ni-base

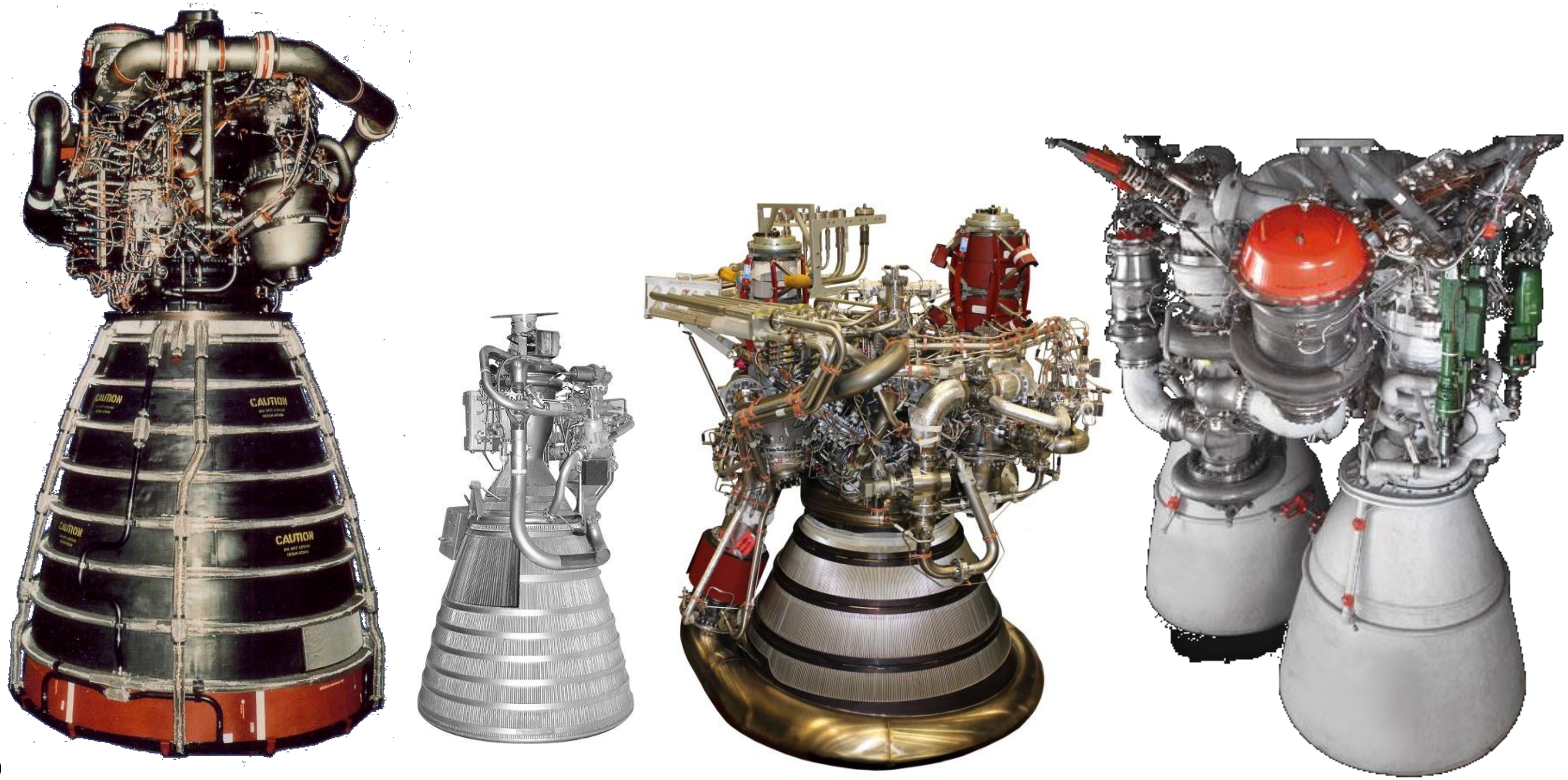
Focus of L-PBF and Examples

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

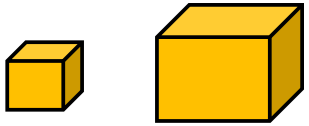


Need for Large Scale AM Technologies

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



L-PBF Build Boxes



10x10x10 15.5x24x19

(inches)

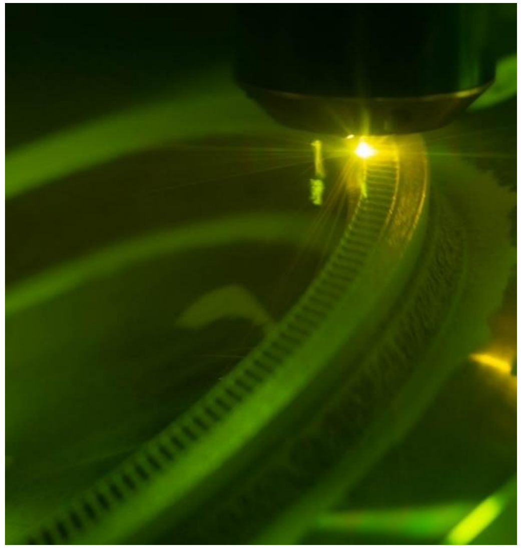
90″ 46″ 70″ 56″

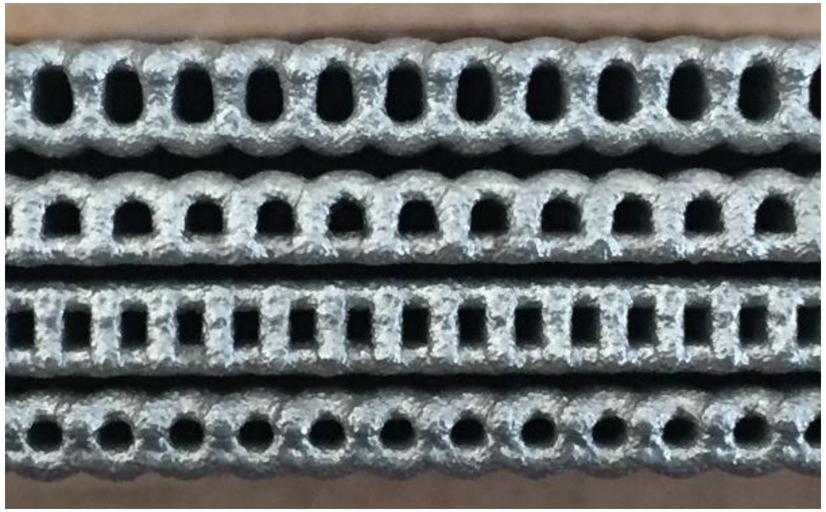
Nozzle Exit Dia.

Gradl, P., Greene, S., Protz, C., Bullard, B., Buzzell, J., Garcia, C., Wood, J., Osborne, R., Hulka, J. Cooper, K. Additive Manufacturing of Liquid Rocket Engine Combustion Devices: A Summary of Process Developments and Hot-Fire Testing Results. 54th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4625). July 9-12, 2018. Cincinnati, OH.

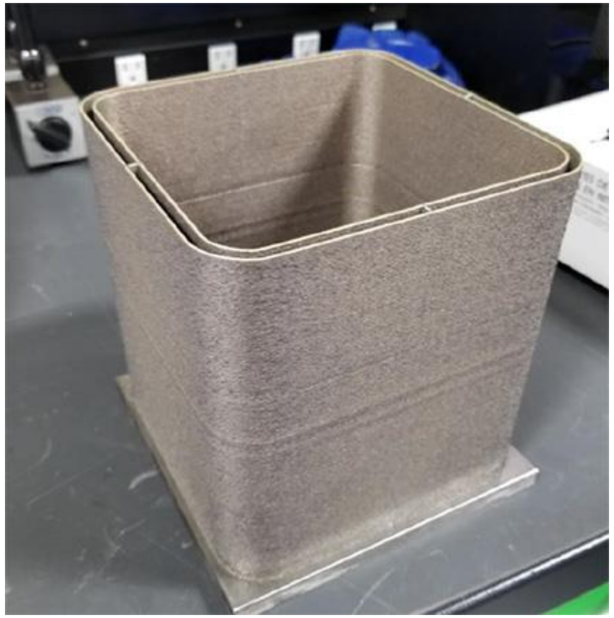
Large Scale Blown Powder Directed Energy Deposition (DED) for Regeneratively-cooled Nozzles

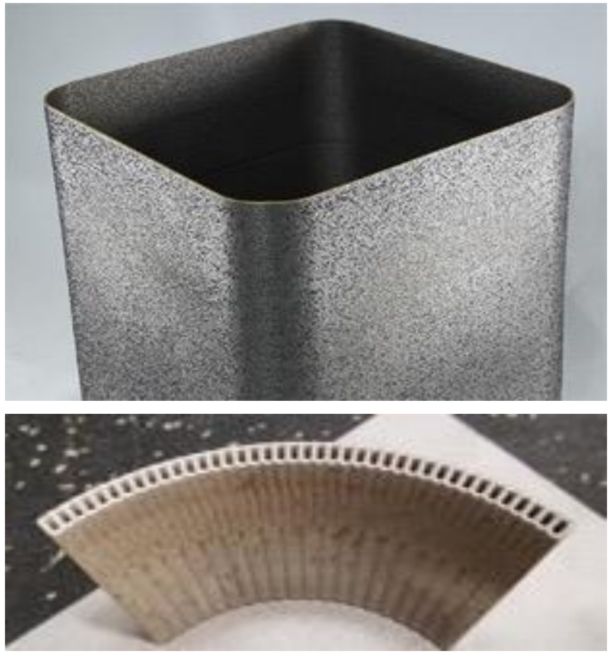
- Blown powder DED (BP-DED) was selected for the integral channel large-scale integrated nozzle providing significant scale options
  - Process being developed with industry partners
- Prior publications detailed early process and hardware development work on the BP-DED and successful subscale hot-fire testing
- Process selected as it provided a good trade of deposition rates along with feature resolution needed for integral channels
- Channels have been demonstrated in various configurations, providing new design options



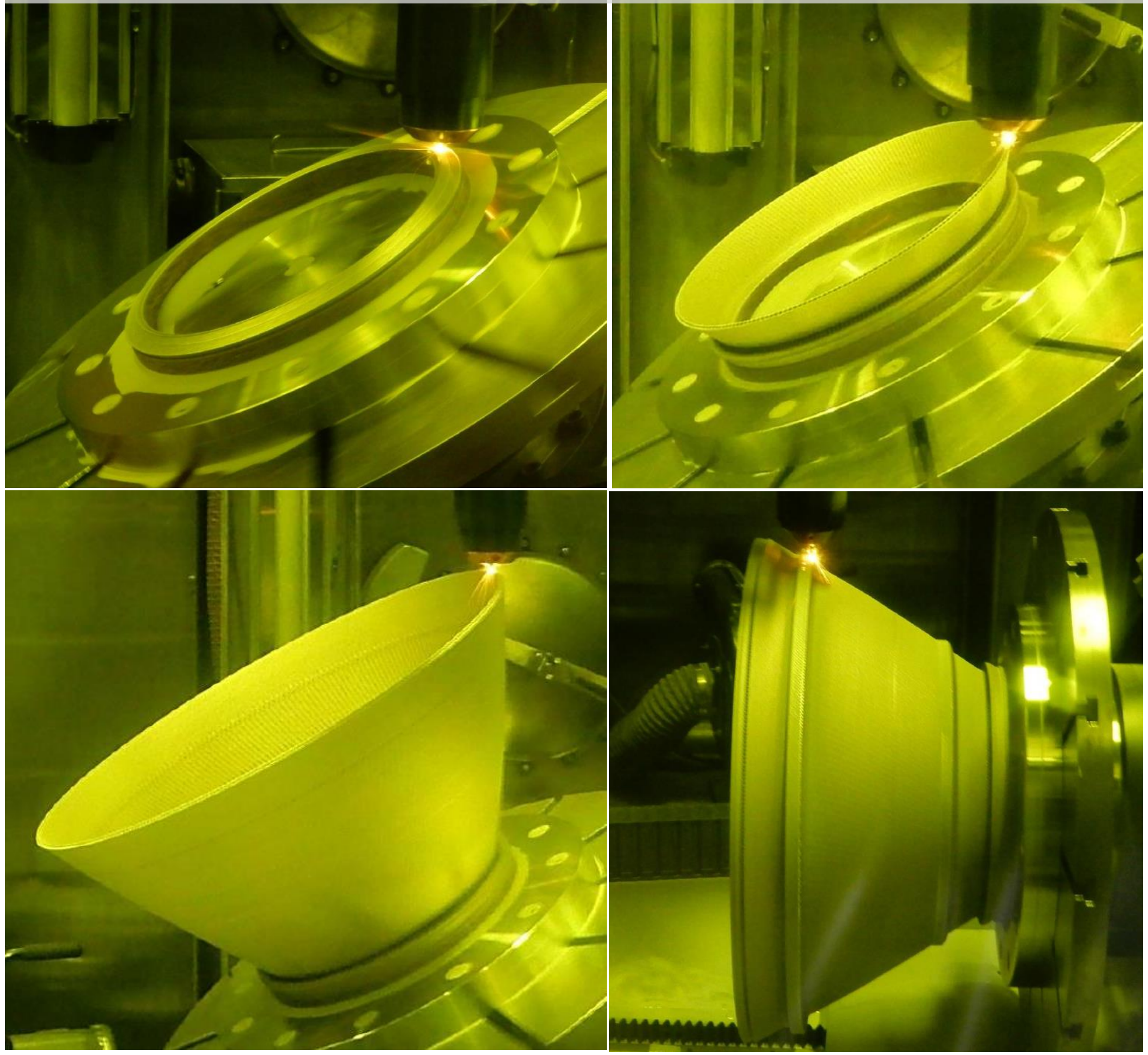


Large-Scale Thin Wall Deposition Channel Wall Nozzles





Process Development for DED of nozzles

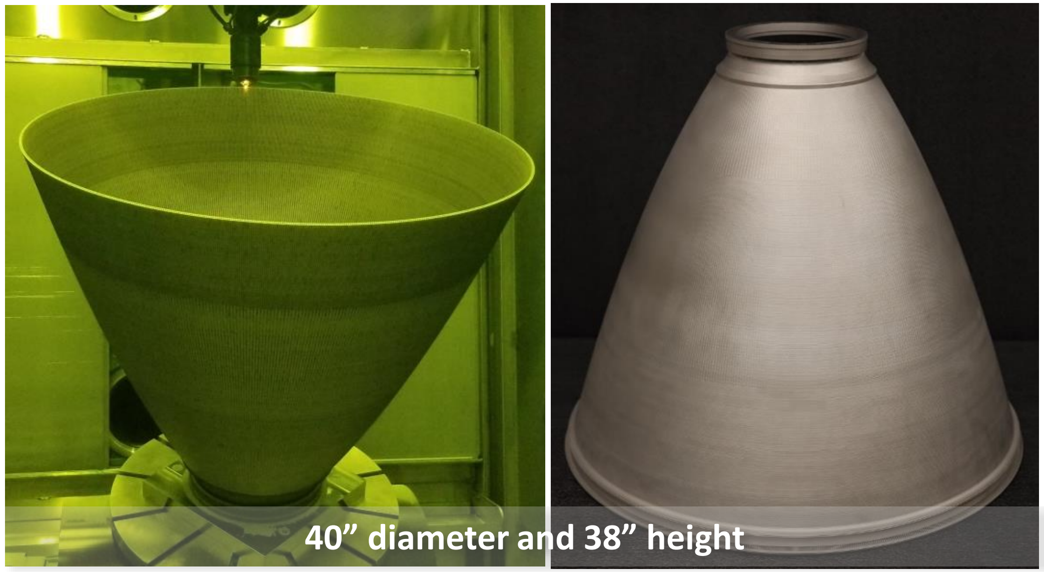


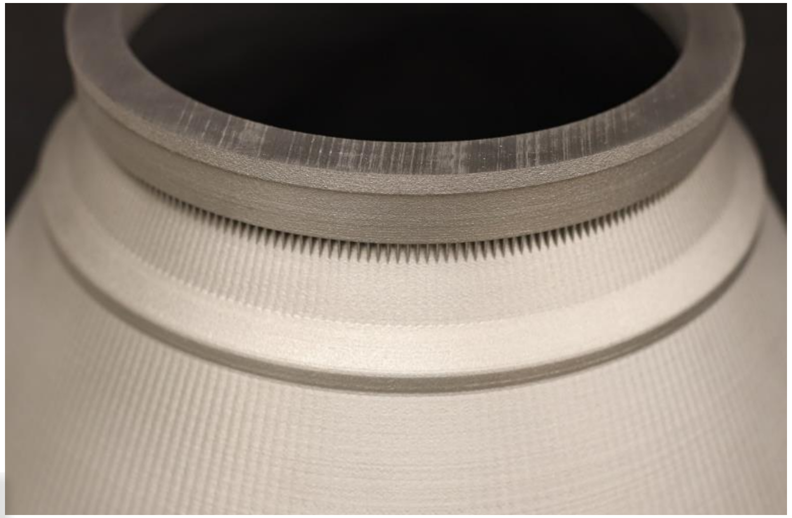
RPM Innovations (RPMI) under NASA-RAMPT Project

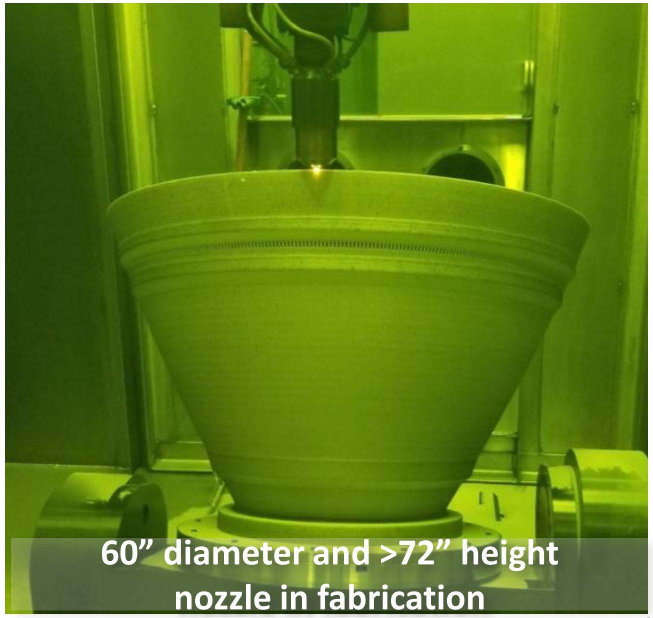
Hot-fire Testing of Integral-channel DED Nozzles

Large Scale Blown Powder DED for Regeneratively-cooled Nozzles

- Various BP-DED nozzle demonstrators and hardware completed for hot-fire testing
  - Significantly reduces number of parts and assembly time compared to traditional manufacturing
- Ongoing characterization of material and mechanical property testing
- Completed large scale milestone with 40” (1016 mm) diameter and 38” (965 mm) length nozzle in 30 day deposition time
  - Post-test inspections showed limited distortion and met intended geometry (<0.02”)
- 65% scale RS25 channel wall nozzle demonstrator being fabricated (60” dia / 72”)


40” diameter and 38” height


RPM Innovations (RPMI)


60” diameter and >72” height nozzle in fabrication

Examples of Blown Powder DED for Large Structures

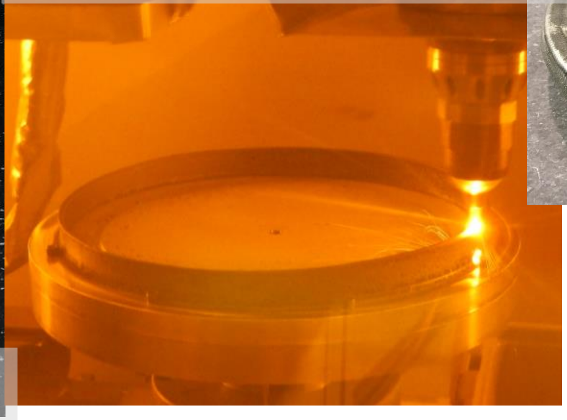
30k-lbf Class DED Liner, NASA HR-1

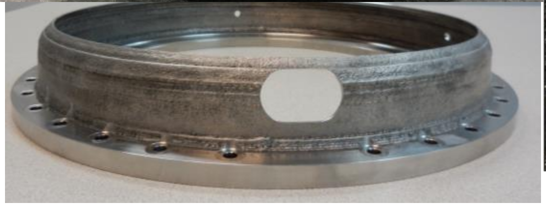
½ Scale RS25 Nozzle Liner

Rem Surface Engineering under SBIR

Exploratory Polishing Techniques for DED Processes

Integral Channel DED Nozzles

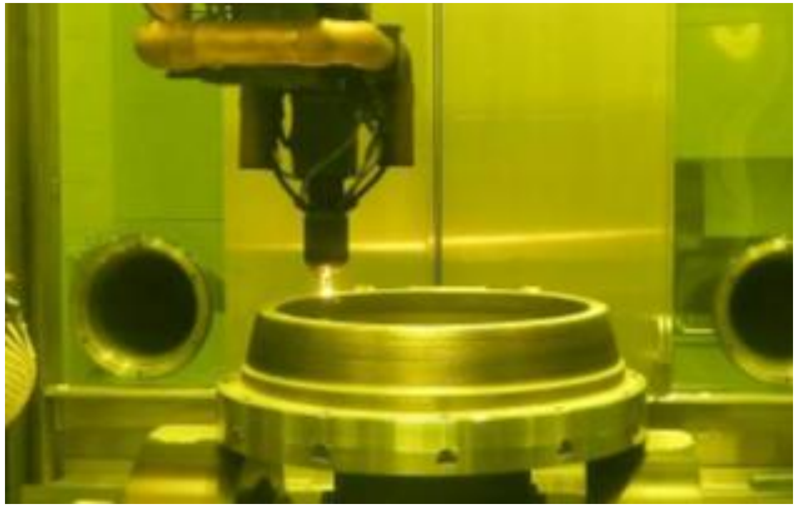
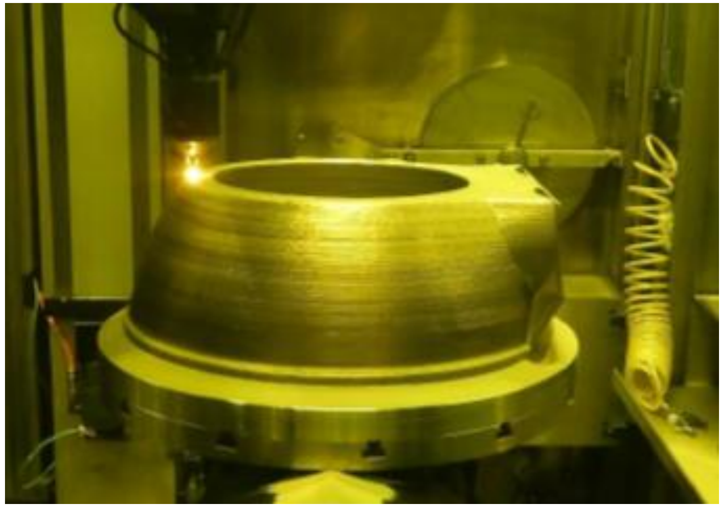
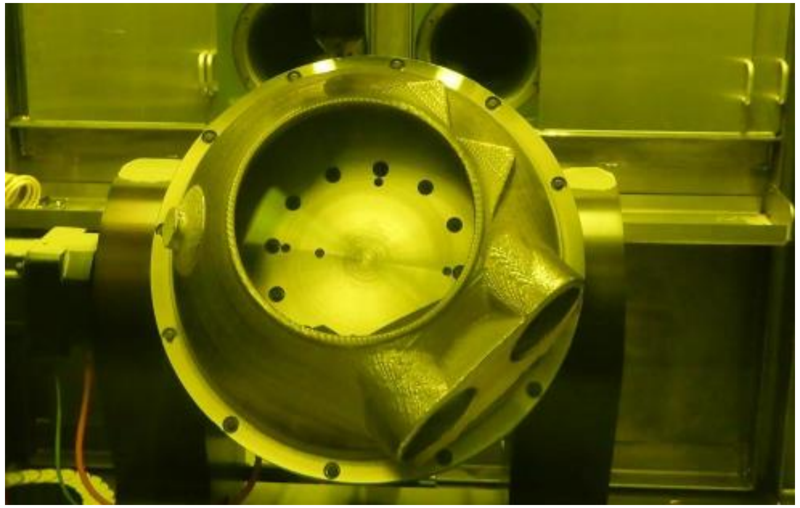
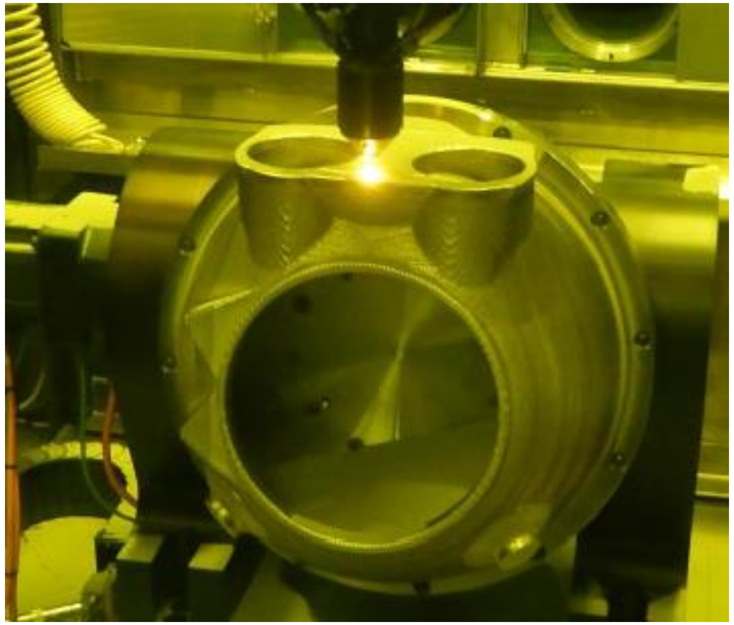
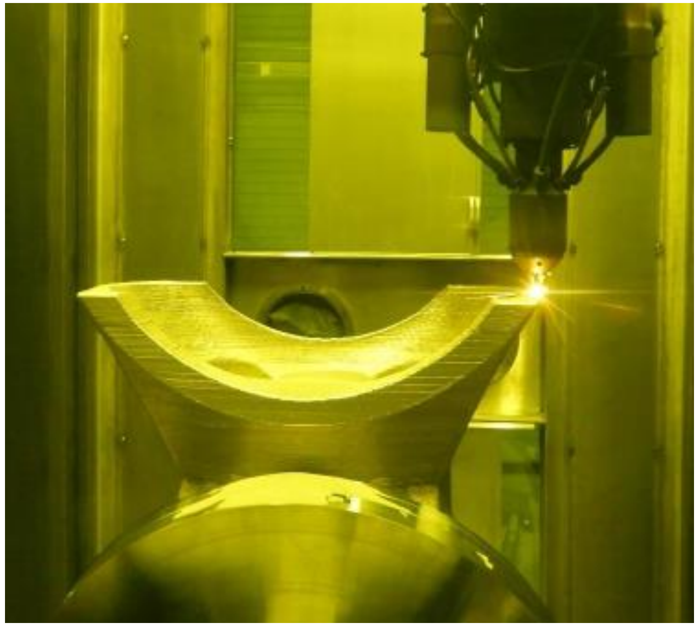




Blown Powder DED Manifolds

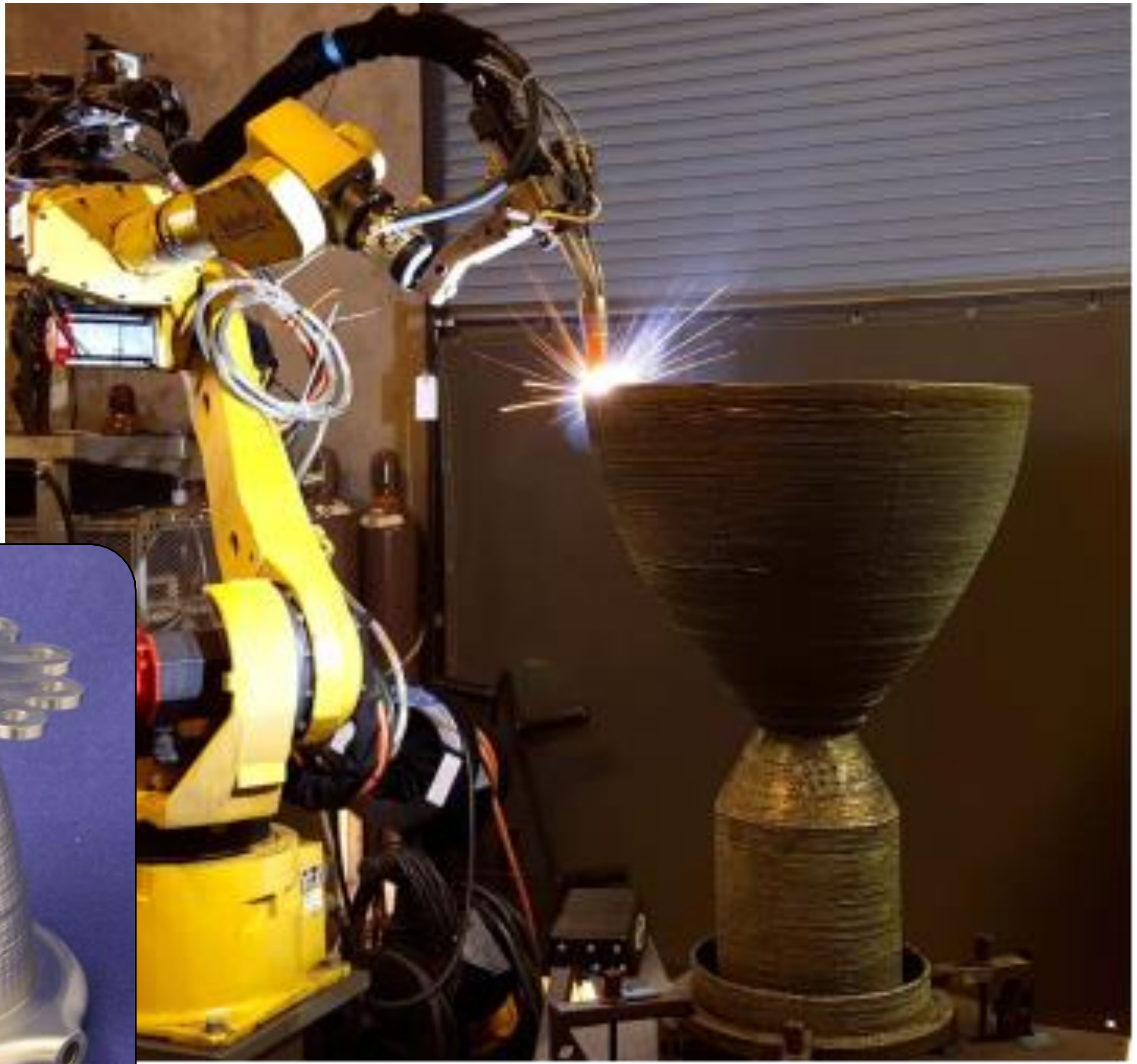
Bimetallic Nozzle with L-PBF and DED (RAMPT Project)

Development of Blown Powder DED Inconel 718


RPM Innovations (RPMI) under NASA SLS Artemis Program

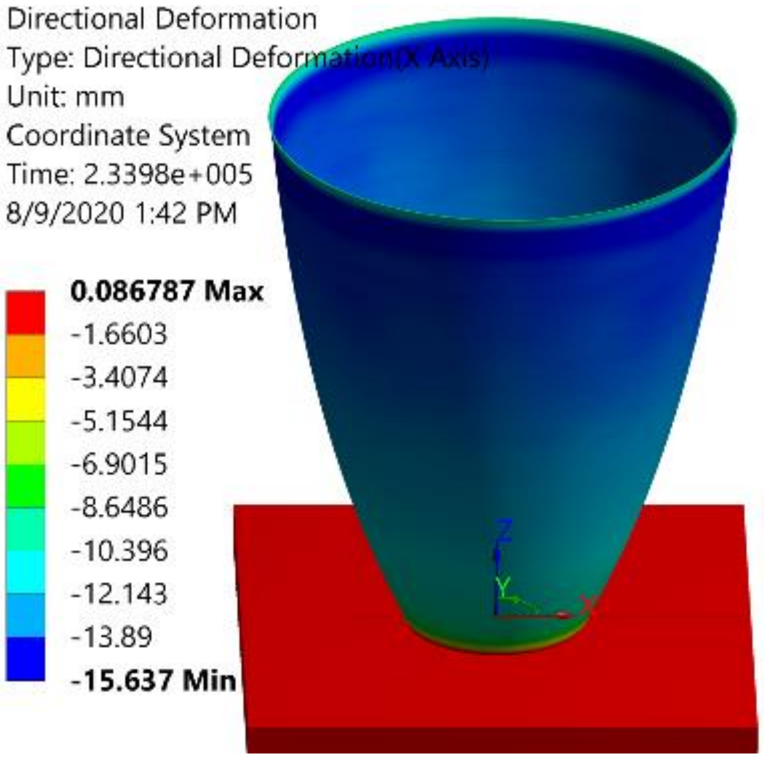
Wire Arc-Based Deposition
Wire Arc Additive Manufacturing (WAAM)

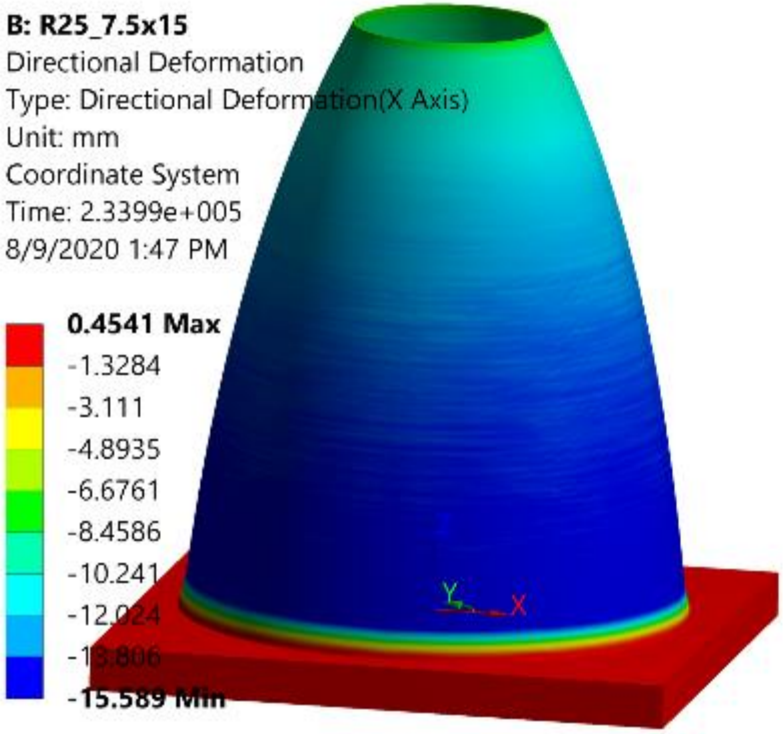


Keystone Synergistic under NASA SBIR and IRAD

Challenges in Large Scale AM

- Build durations are significantly increased with large scale AM due to amount of material being deposited
- Stops and starts will be more prevalent and re-starts may not be feasible
- Distortion is a concern with all AM processes, particularly at large scale

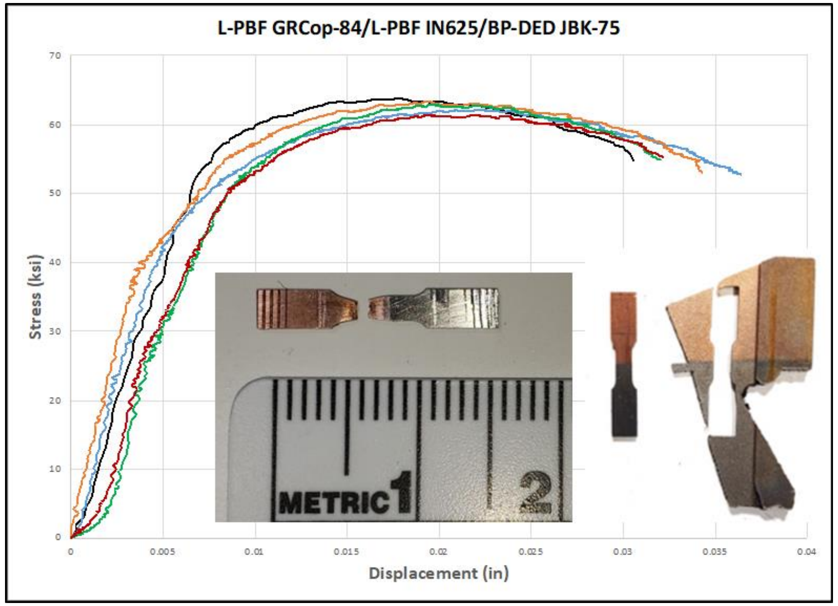




Ref: Kevin Wheeler / NASA Ames

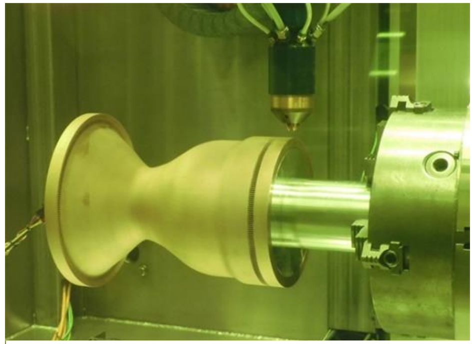
Bimetallic and Multi-metallic Additive Manufacturing for Thrust Chambers

- Bimetallic and multi-metallic joints may be necessary in some designs to minimize weight by using high strength-to-weight materials locally based on component load requirements
  - Locations include for joining manifolds on the chamber and axial joint between chamber and nozzle
- Evaluation of various processes including Cold Spray, Laser Hot Wire, and Blown Powder DED
- Demonstrating fundamental materials characterization and large scale hardware



Microtensile testing of Bimetallic/Multi-metallic Joints

Bimetallic Chamber Development for 40k-lbf



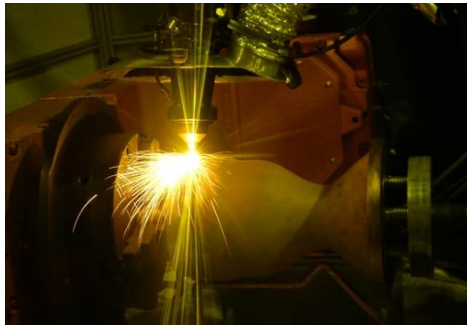
Images provided by RPMI

RPMI	
Chamber:	GRCop-42
Clad Process:	BP-DED
Material:	NASA HR-1*

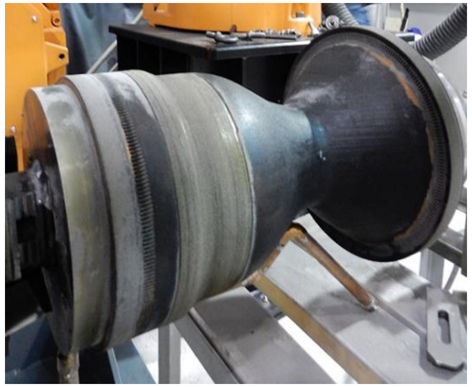
* Used an intermediate transition layer of Cu-Ni

Axial and radial shrinkage will be measured.

Used as weight comparison with composite overwrap structural jacket.



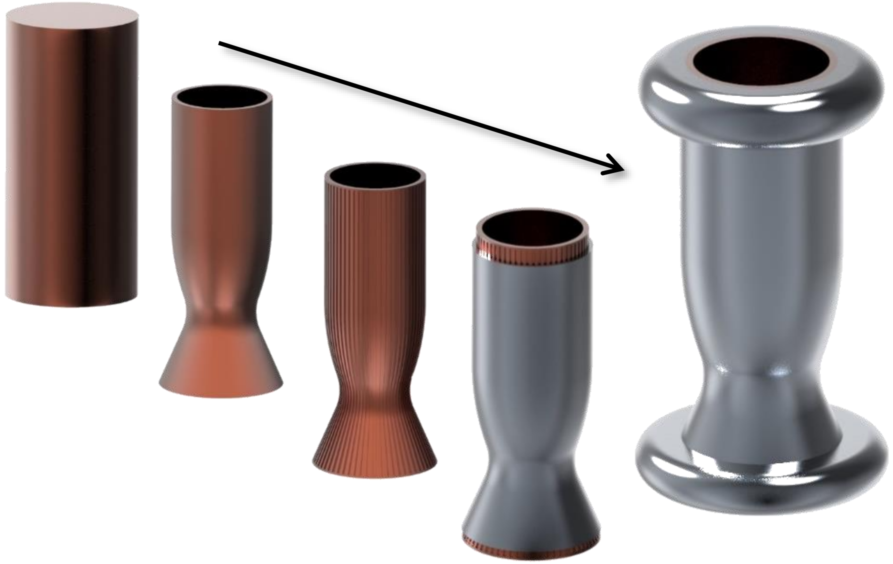
Images provided by DM3D



DM3D	
Chamber:	GRCop-42
Clad Process:	BP-DED
Material:	IN-625

Cost Evolution for Copper-Alloy Additive Chambers

Traditional Manufacturing



12-18 mos / $310k*

AM Development

6-8 mos / $200k*

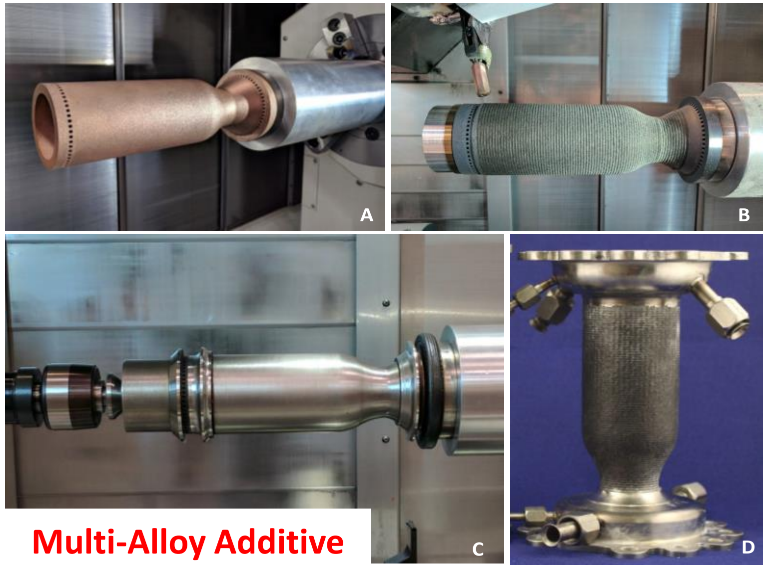
Evolving AM

3-5 mos / $125k**

As AM process technologies evolve using multi-materials and processes, additional design and programmatic advantages are being discovered

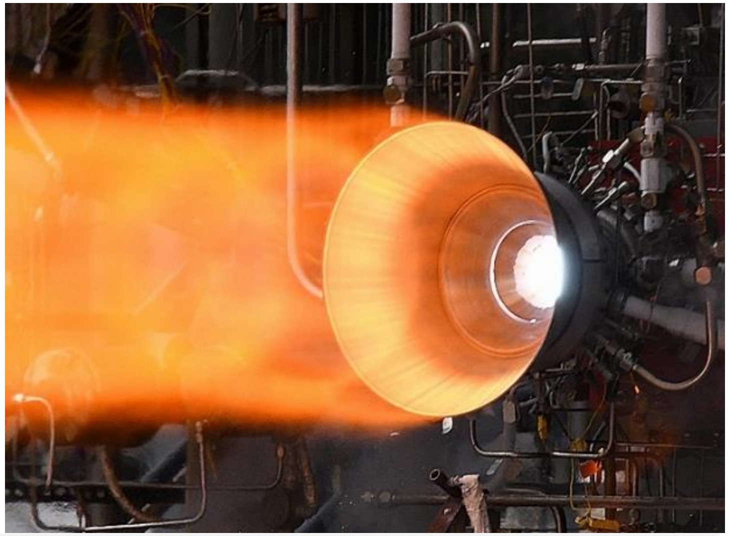
*Dollars in USD **Manifolds not shown, but included in cost

L-PBF GRCop-alloy Combustion Chambers

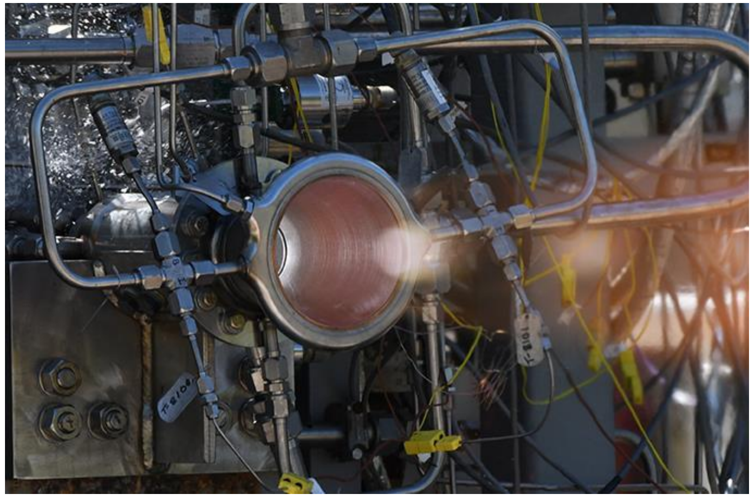


Multi-Alloy Additive

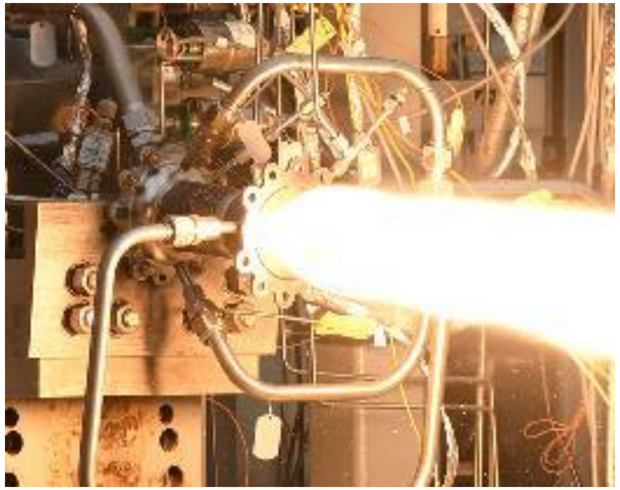
Combine L-PBF and DED



30k-lbf LCUSP GRCop-84 Bimetallic Chamber



GRCop-42 Chamber
(166 starts / >8,000 sec



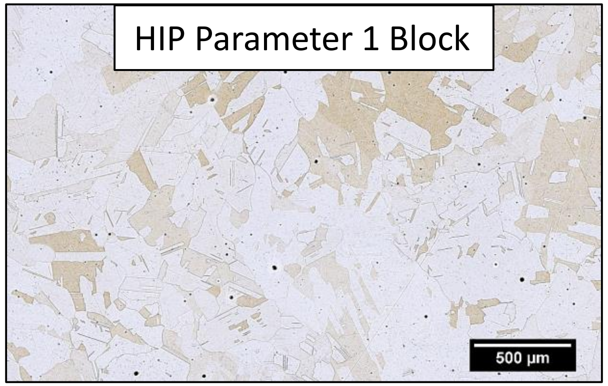
Commercially Produced
GRCop-84 bimetallic

~13" Diameter

New Materials using Additive Manufacturing NASA HR-1 and JBK-75

- 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 **H**ydrogen-**R**esistant (HEE resistant)
- Originally derived from JBK-75, the development for NASA HR-1 started in late 1990 NASA MSFC and HEE resistant composition was identified in 1992.
- In addition to its HEE resistance, NASA-HR-1 has approximately 25% higher yield strength than JBK-75 and exhibits no ductility loss in a 5 ksi high pressure hydrogen environment
- NASA-HR-1 is a unique alloy that extends the compositional range of existing HEE-resistant Fe-Ni-base superalloys.

	A-286	JBK-75	NASA HR-1
Fe	56.1	51.5	41.2
Ni	25.5	30.0	34.0
Co	-	-	3.3
Cr	14.8	14.8	15.0
Mo	1.3	1.3	2.0
W	-	-	1.8
Ti	2.1	2.2	2.5
Al	0.2	0.3	0.3



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Summary of Focuses in AM for Liquid Engines

- Large scale, small feature DED processes
  - Focus on blown powder DED, also investigating WAAM, coldspray
  - Continue development on laser wire DED for channel closeout
  - Materials include: NASA HR-1, JBK-75, GRCop-alloys, new alloys
- Large scale DED processes for forging and casting replacement
  - Manifolds, liners, ducts, complex geometry to reduce machining
- Bimetallic and multi-metallic deposition with a variety of processes
  - Combining L-PBF and DED, and other processes (coldspray)
- New alloy development and/or with new processes (L-PBF and DED)
  - Refractory, Superalloys for specific environments
- Full material characterization and property development (L-PBF and DED)
- Certification of AM processes for flight applications

National Aeronautics and
Space Administration

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Fraunhofer USA – CLA
BeAM Machines
The Lincoln Electric Company
ASB Industries
Elementum 3D
3DMT
Rem Surface Engineering
Procam
Powder Alloy Corp
HMI
ATI
Praxair
Formalloy
Tal Wammen

Test Stand 115 crew
Kevin Baker
Po Chen
Matt Medders
Colton Katsarelis
Kevin Wheeler / NASA Ames
Adam Willis
James Buzzell
Dale Jackson
Marissa Garcia
Nunley Strong
Brad Bullard
Gregg Jones
James Buzzell
Marissa Garcia
Dwight Goodman
Will Brandsmeier
Jonathan Nelson
Ken Cooper (retired)
Bob Witbrodt
Megan Le Corre
Brian West
John Ivester
John Bili
Will Tilson

Zach Jones
Bob Carter
Justin Milner
Ivan Locci
Jim Lydon
Keystone / Bryant Walker / Ray Walker
Laser Technology Associates / Albert Hammeke
Judy Schneider / UAH
PTR-Precision Technologies
AME
Westmoreland Mechanical Testing
David Myers
Ron Beshears
James Walker
Steve Wofford
Jessica Wood
Robert Hickman
Johnny Heflin
Mike Shadoan
Keegan Jackson
Many others in Industry, commercial space and others

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