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Advancement of Novel Additively Manufactured Alloys for Space Applications

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Agenda

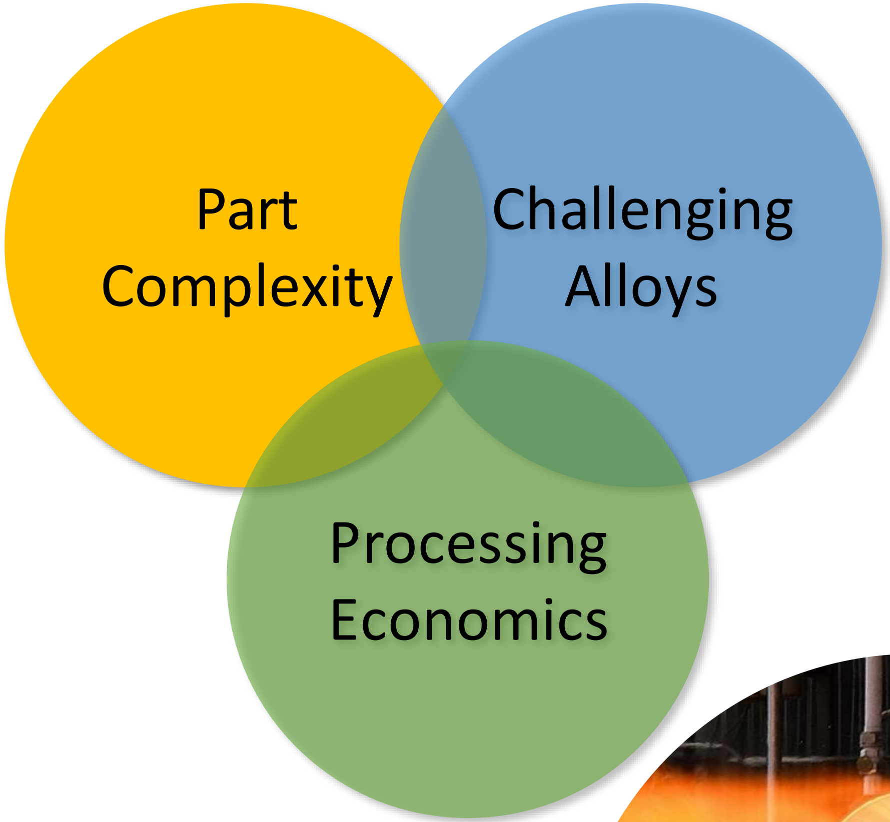
- Introduction and need for AM
- New alloys for propulsion applications
  - NASA HR-1 and JBK-75
  - GRCop-42 and GRCop-84
- Types of AM Processes
- Examples of components developed with alloys
- High duty cycle testing of alloys
- Summary

The Case for Additive Manufacturing in Propulsion

- Metal Additive Manufacturing (AM) provides 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**



Environment and Requirements for Rocket Engines

Combustion chambers and regeneratively-cooled nozzles

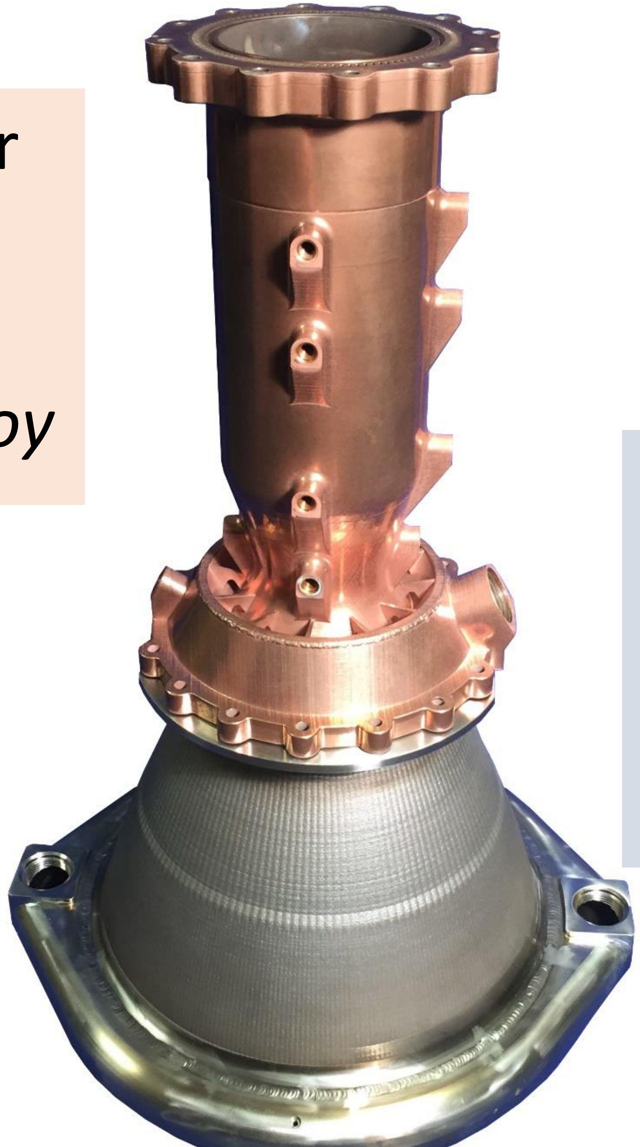
- High heat flux and combustion temperatures (>3300 °C), high wall temperatures (wall T >700°C), high chamber pressure (410 bar)
- Complex loads from thermal, static, and dynamic
- Compatibility with propellants (e.g. hydrogen)
- Thin-walls to maintain adequate wall temperatures
- High thermal gradients (>230°C across hotwall)
- High conductivity
- Reusability – typically >50 starts
- Minimize overall mass (high strength to weight)

Require alloys that can be built using AM with complex internal features and maintain high strength at elevated temperatures with adequate fatigue life

High Strength Copper and H2 Resistant Alloys

GRCop-42 / GRCop-84 for combustion chambers

- *High strength, high conductivity Cu-Cr-Nb alloy*



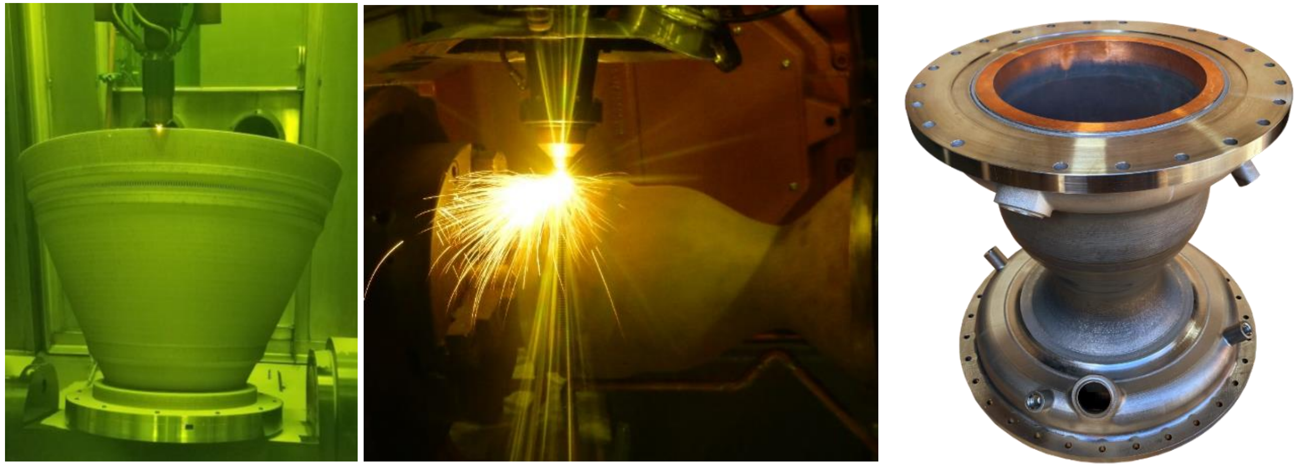
NASA HR-1 and JBK-75 for nozzles and other components

- *Hydrogen resistant Fe-Ni-Cr high strength superalloys*

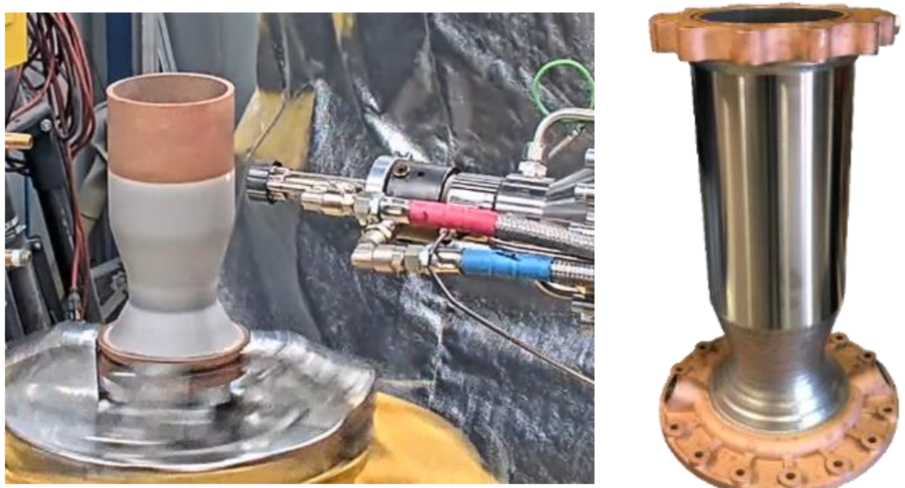
AM Processes evaluated to produce components

Laser Powder Bed Fusion (L-PBF)

Laser Powder Directed Energy Deposition (LP-DED)



Cold Spray

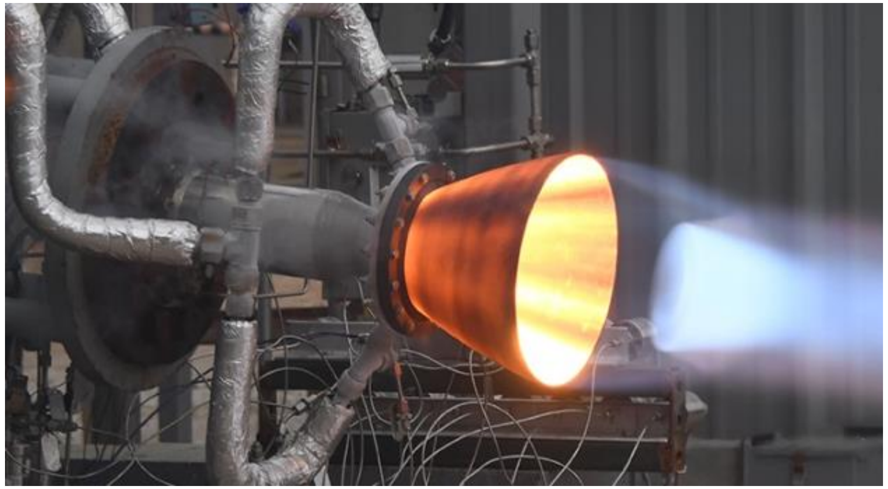


Arc Wire Directed Energy Deposition (AW-DED)

GRCop-alloys using Laser Powder Bed Fusion (L-PBF)

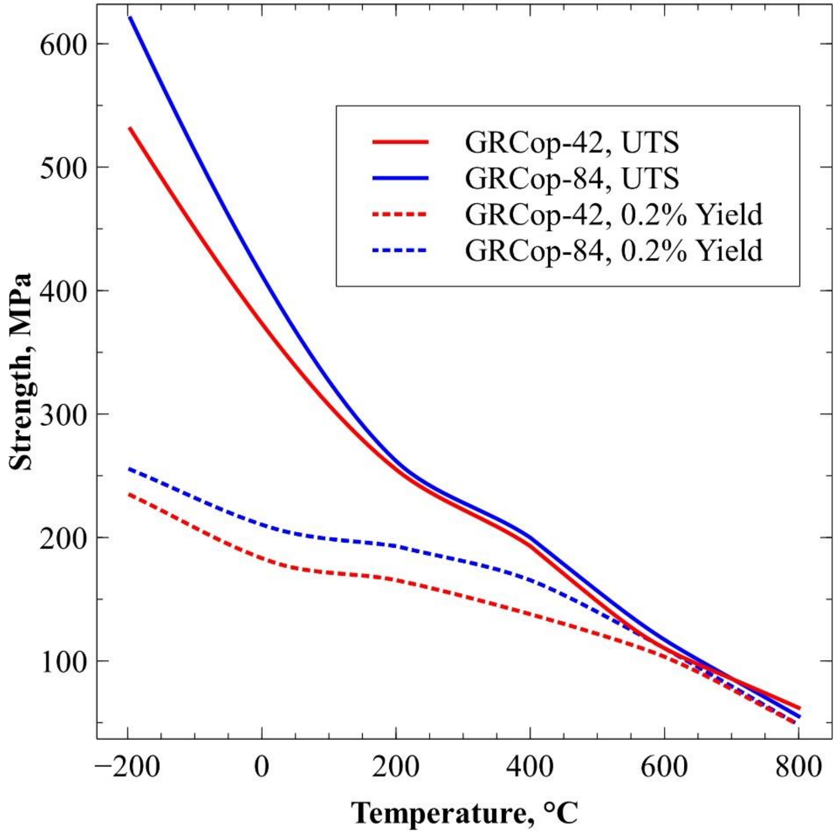
- Oxidation and blanching resistance during thermal and oxidation-reduction cycling.
- A maximum use temperature around 800°C, depending upon strength and creep requirements.
- Good mechanical properties at high use temperatures (2x of typical copper).
- Lower thermal expansion to reduce thermally induced stresses and low cycle fatigue (LCF).
- Established powder supply chain and commercial supply chain.
- Significant maturity in characterization and hot-fire testing (high TRL).



Comparison GRCop-84 and GRCop-42

Element	GRCop-42 Wt %	GRCop-84 Wt %
Cu	Balance	Balance
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 <250 ppm*	*Target <250 ppm*
Al	*Target <100 ppm*	*Target <100 ppm*
Si	*Target <100 ppm*	*Target <100 ppm*
Cr:Nb Ratio, %wt	1.13 – 1.18	1.13 – 1.18



GRCop-42 and GRCop-84 for different applications:

- GRCop-42 has improved thermal conductivity (20-30%)
- GRCop-84 has slightly higher strength and improved LCF properties
- GRCop-42 has matured supply chain and lower cost
- Both only require Hot Isostatic Pressing (HIP) post-build

Bimetallic GRCop-alloys for combustion chambers

- NASA has advanced bimetallic and multi-alloy GRCop-alloy to superalloy AM for combustion chambers for radial and axial joints
- Advancements were made through evaluations of various multi-alloy AM processes, material characterization, and successful component manufacturing and hot-fire testing

LP-DED Jacket

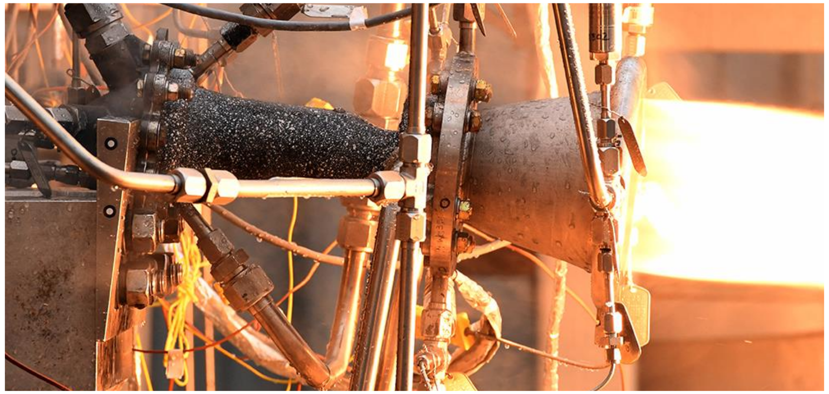
Cold spray Jacket

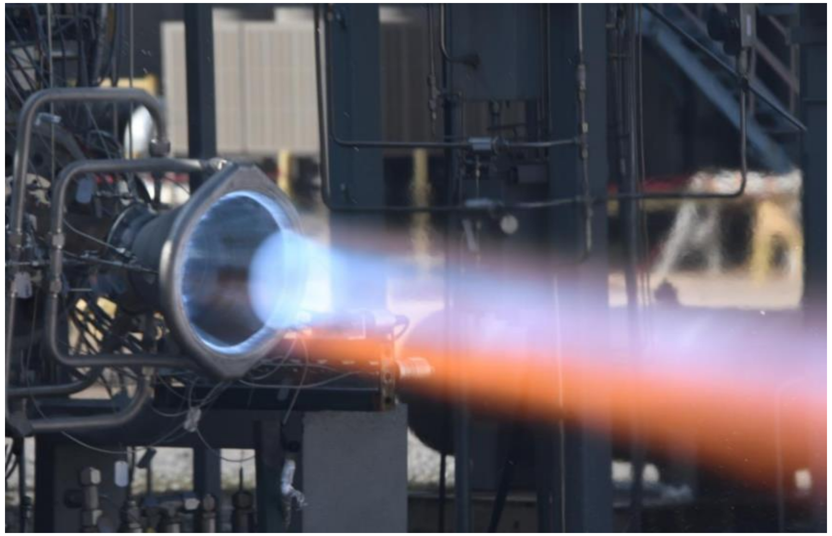
Direct Deposit NASA HR-1 Nozzle

EBW-DED Jacket

Hot-fire Testing and Development

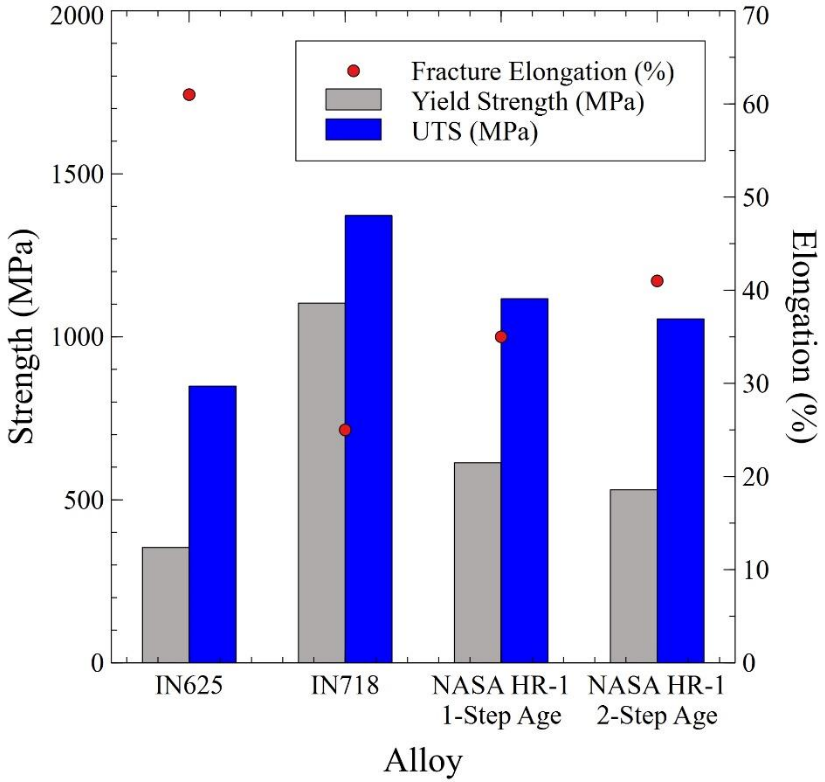
- High TRL and maturity of material properties and component development
- Completed hot-fire testing using propellants LOX/H2, LOX/RP-1, LOX/CH4 and thrust classes 8.9 to 155.7 kN (chamber pressures >96 bar)
- Over 40,933 seconds of hot-fire time and 1,010 starts on >30 chambers
- Single chamber unit achieved 296 starts and >10,600 seconds and another unit achieved 168 starts and >7,400 sec – remain in excellent condition
- Peak temperatures >727°C

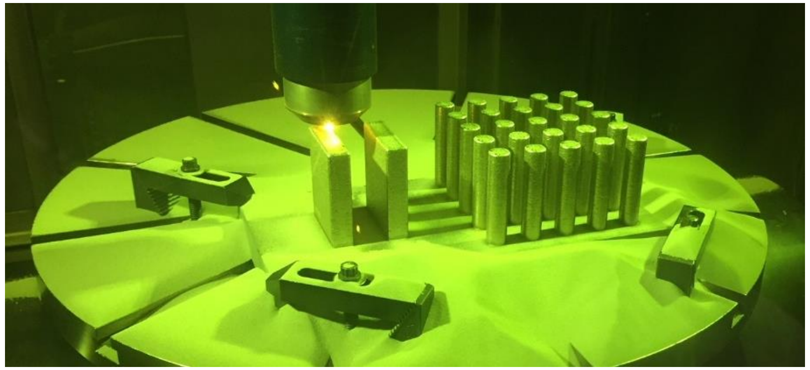





NASA HR-1 Alloy developed for LP-DED Process

- NASA HR-1 is an Fe-Ni-Cr alloy developed for high pressure hydrogen environments.
- Derived from JBK-75 and designed for higher strength and improved weldability
- Reformulated for AM LP-DED to reduce titanium segregation.
- Advanced using LP-DED at different deposition rates to allow for variations in wall thickness and deposition time.
- Recently optimized heat treatments to mitigate η-phase and improve properties.

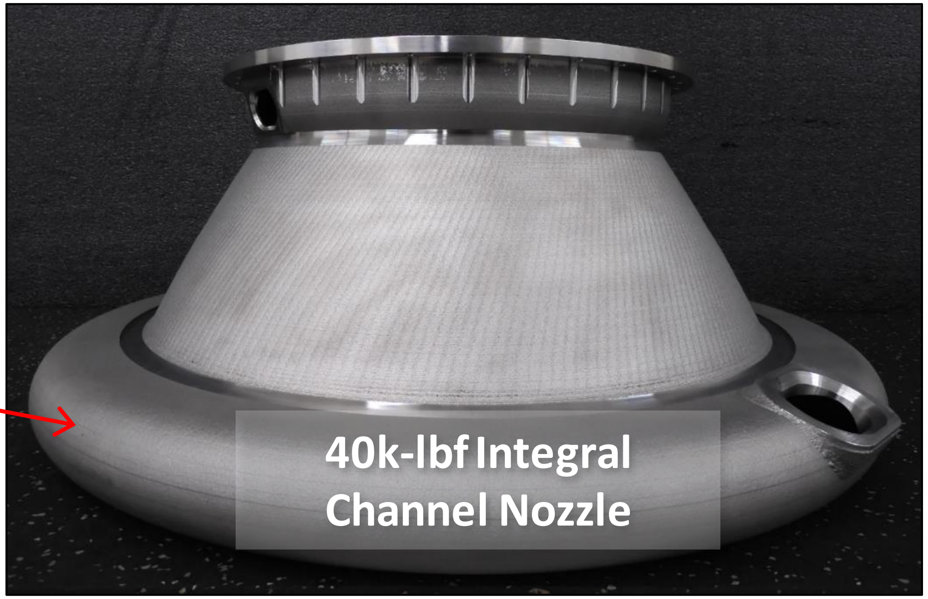




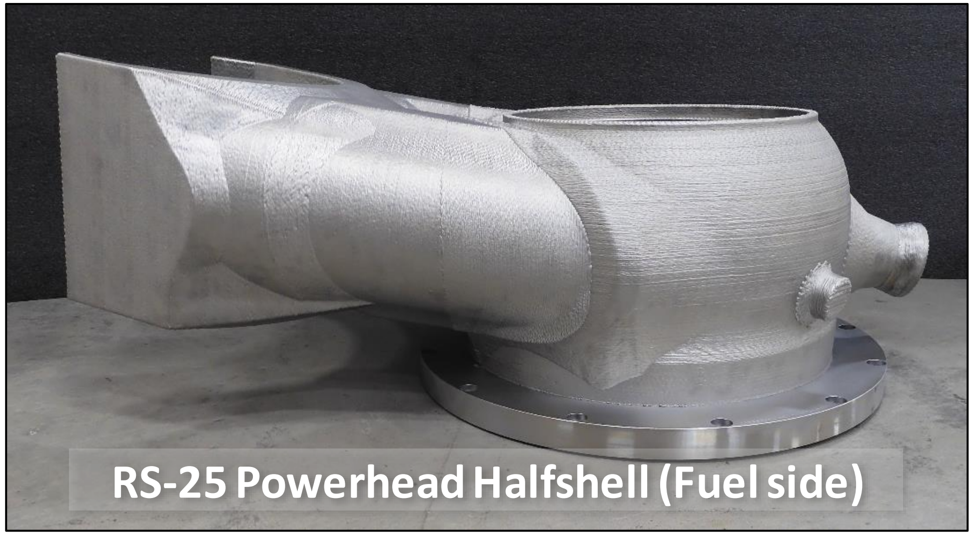
Various Components Fabricated using LP-DED


RS-25 Powerhead liner


40k-lbf nozzle manifold (610 mm dia)


40k-lbf Integral Channel Nozzle


RS-25 Powerhead Halfshell (LOX side)


RS-25 Powerhead Halfshell (Fuel side)


2.5k-lbf spiral tube-like DED nozzle

LP-DED NASA HR-1 and JBK-75 Nozzles

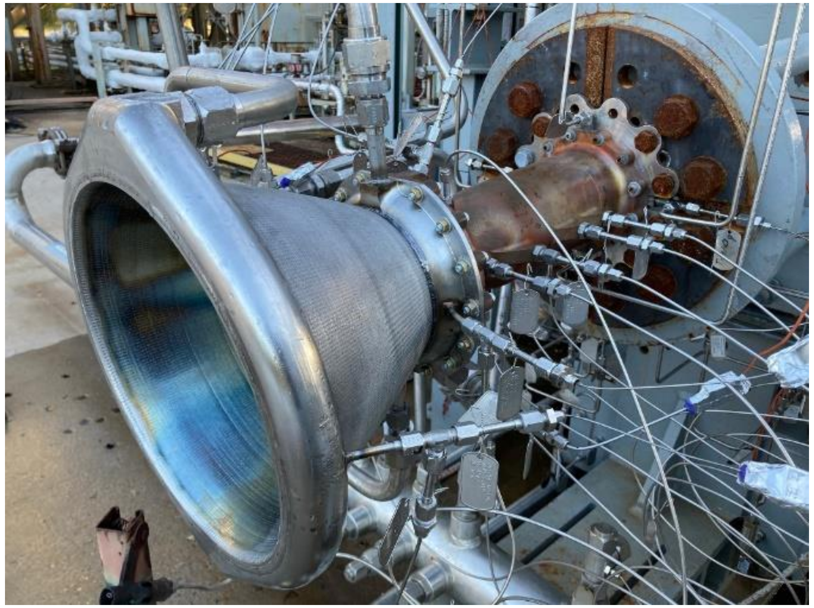
1.52 m diameter and 1.78 m height with <u>integral channels</u>
90 day deposition

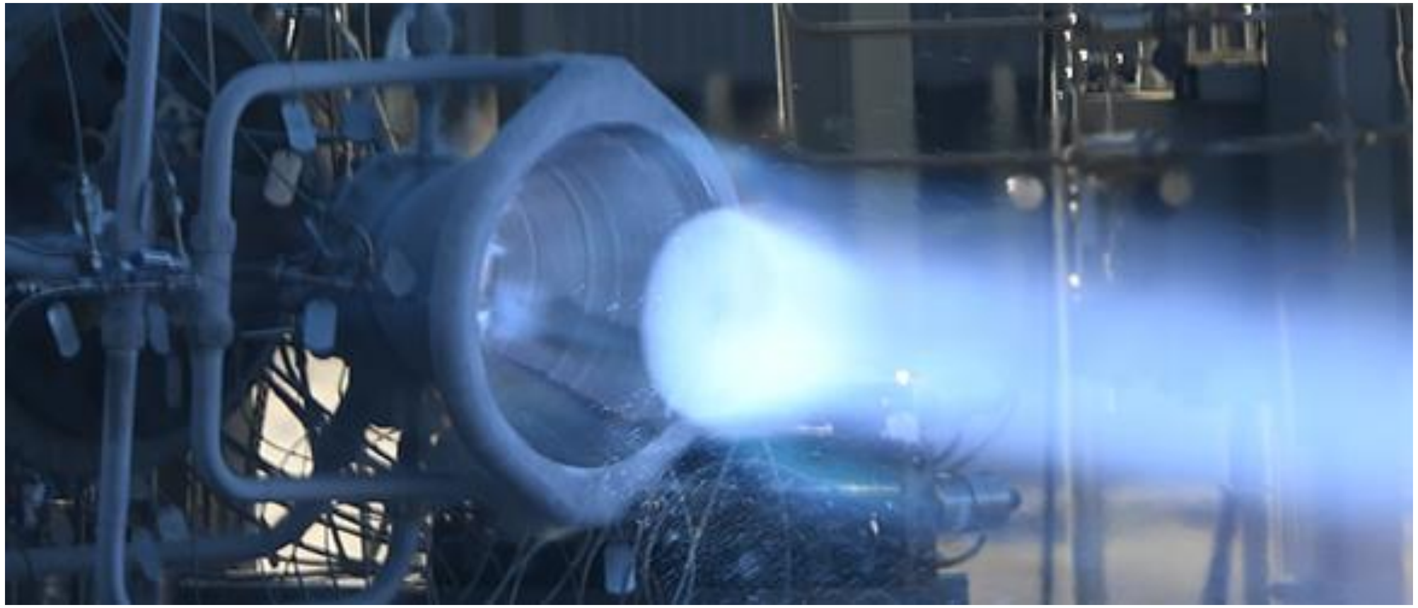
2.41 m dia and 2.82 m height
Near Net Shape Forging Replacement

<u>Reference:</u> Gradl, P. R., Teasley, T. W., Protz, C. S., Garcia, M. B., Ellis, D., & Kantzos, C. (2021). Advancing GRCop-based Bimetallic Additive Manufacturing to Optimize Component Design and Applications for Liquid Rocket Engines. *AIAA Propulsion and Energy 2021*, 1–28. https://doi.org/10.2514/6.2021-3231

Hot-fire Testing of NASA HR-1 and JBK-75

- Completed various hot-fire test series with LOX/H2 and LOX/CH4 at 8.9 to 35.6 kN (chamber pressures >76 bar)
- Accumulated >14,876 sec and >400 starts on NASA HR-1 and JBK-75 AM nozzles
- NASA HR-1 integral channel unit 207 starts and >6,976 sec and JBK-75 with 114 starts and >4,170 seconds
- Wall temperatures exceeding 732°C

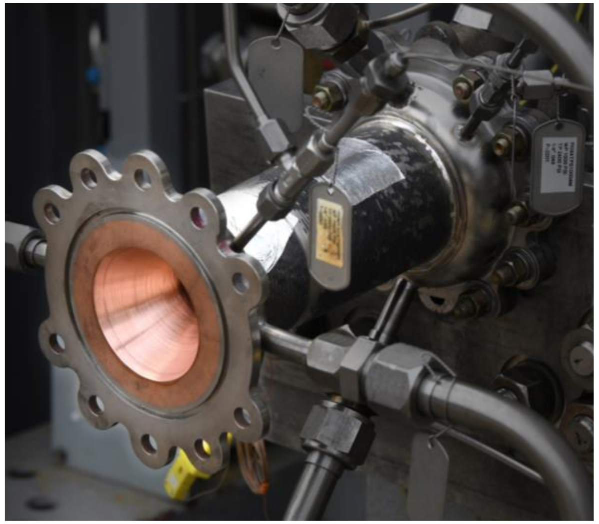




Summary

- High performance chambers and nozzles in extreme environments require novel alloys.
- NASA has matured GRCop-42, GRCop-84, NASA HR-1 and JBK-75 using L-PBF and LP-DED.
- AM processes producing geometry and material properties required have matured.
- NASA has demonstrated high duty cycle hot-fire tests on a GRCop-42 L-PBF combustion chamber with 296 starts and NASA HR-1 LP-DED nozzle with 207 starts.
- Commercial space is actively using these alloys for development and flight infusion.
- Data and properties available to commercial and government partners.



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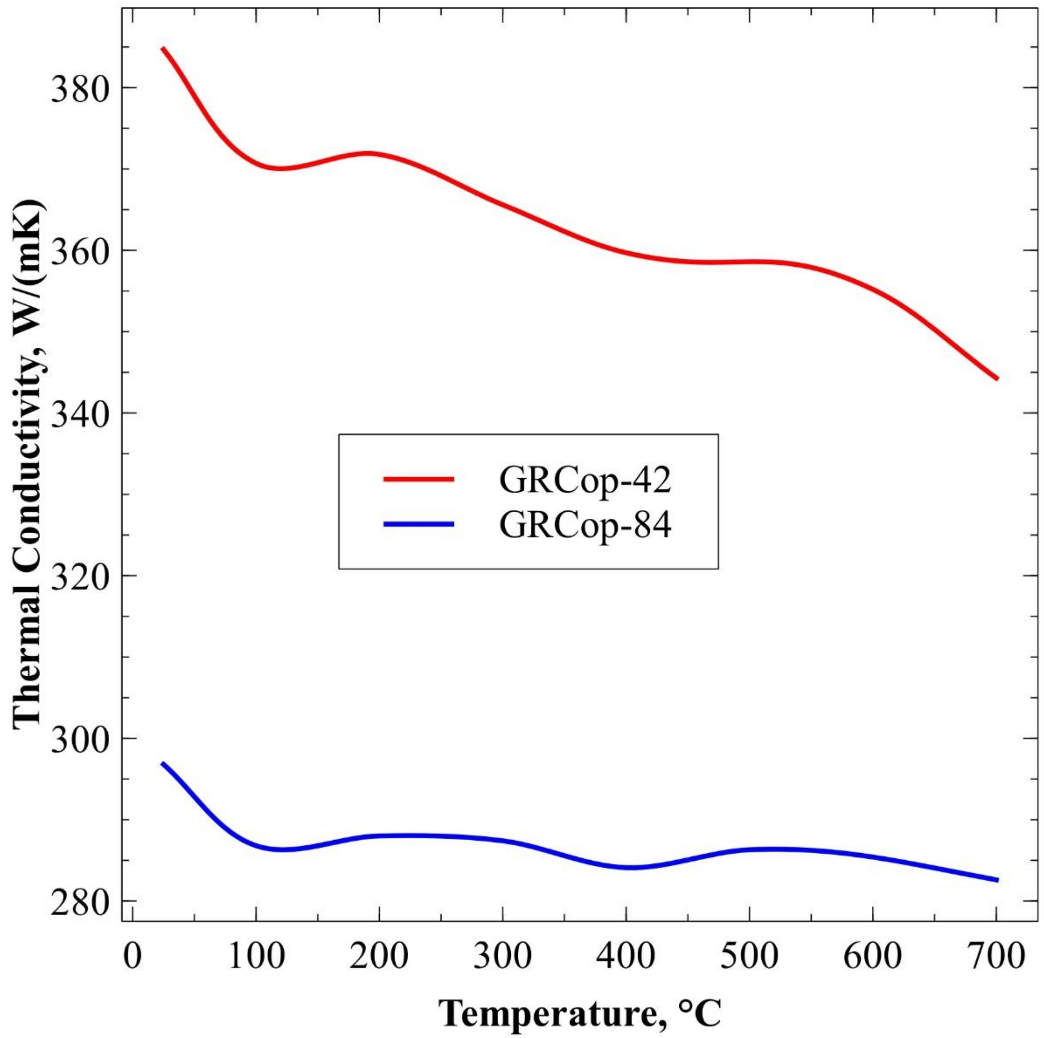
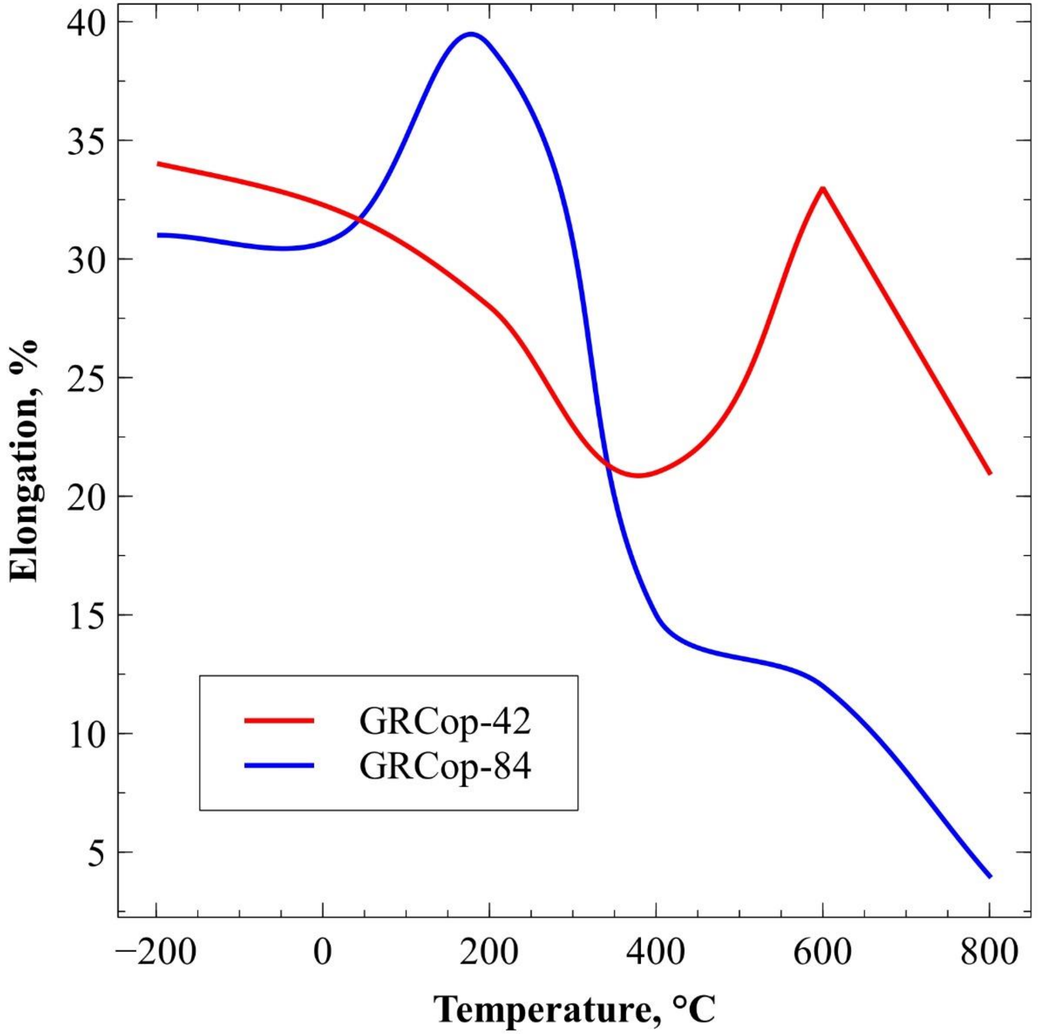
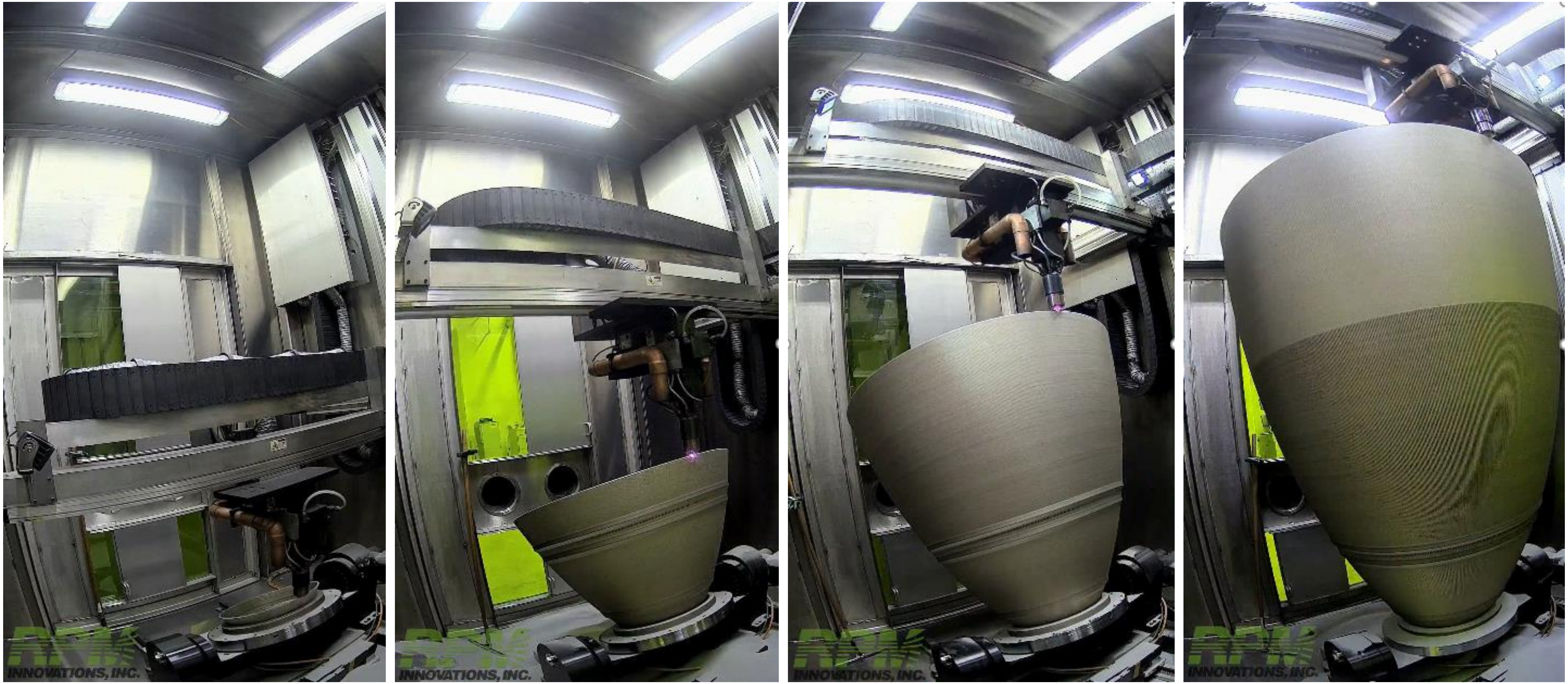
Comparison of GRCop-84 and GRCop-42





Large scale Integrated Channel DED NASA HR-1 Nozzle



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

90-day deposition