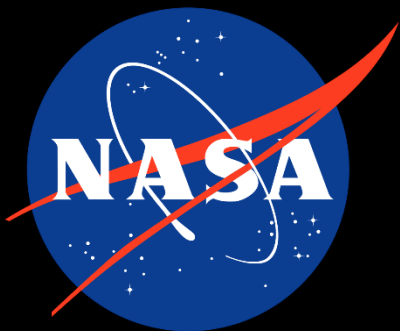




EXPLORE MOON *to* MARS

Progress of Additively Manufactured Hydrogen Resistant NASA HR-1 Material for Liquid Rocket Engine Applications

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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
- AM has significantly evolved over the last 10 years, but available materials are still limited in availability
- As AM continues to evolve, the variety and availability of materials will grow exponentially
- Applications should select materials based on application requirements and not just what is available currently using AM
- AM offers tremendous potential for unlimited materials and can be developed rapidly
 - Powder Supply Chain => AM Machines (service vendors)

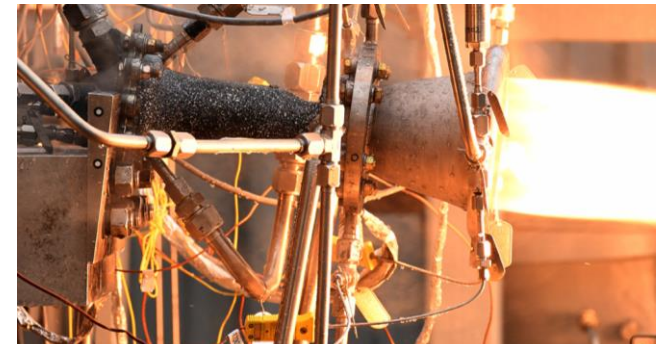
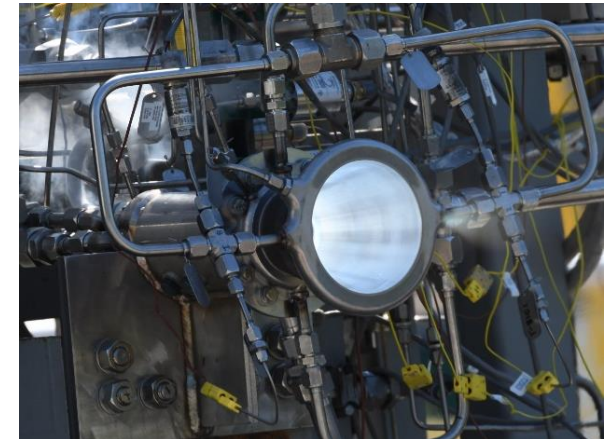
As Additive Manufacturing matures, new materials should be developed, characterized, and matured to allow to provide solutions for component applications. High strength hydrogen resistant alloy, NASA HR-1, fills one of these gaps for material needs.



Why the need for new materials?



- Extreme environments of liquid rocket engine (LRE) components provide challenges in material selection and availability of materials
 - Thermal, structural, dynamic loads
 - Propellant capability
- Regeneratively-cooled nozzles require materials to withstand excessive thermal gradients while maintaining high strength, multiple cycles, and resistance to corrosion and embrittlement
- Key requirements for components such as regeneratively-cooled rocket nozzles include:
 - Thermal Conductivity
 - Low Cycle Fatigue (LCF)
 - Yield Strength
 - Ductility
 - Hydrogen Environment Embrittlement (HEE) Resistance

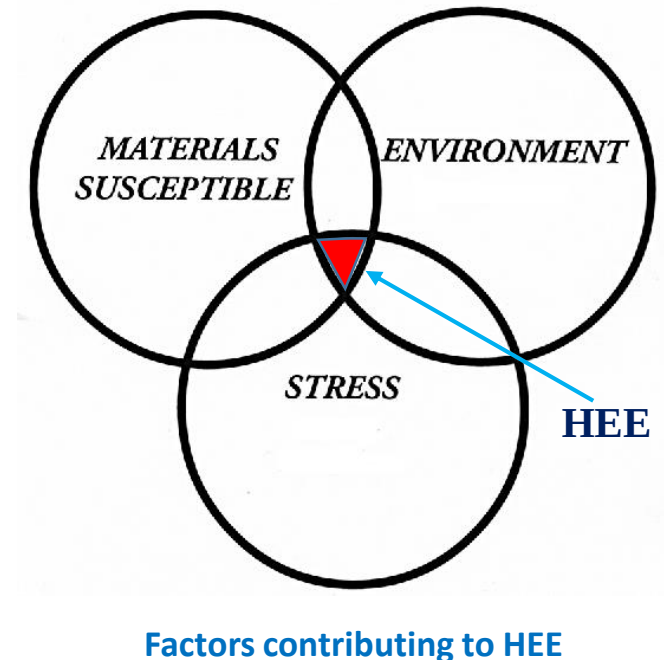




Overview of NASA HR-1 Material



- 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 Hydrogen-Resistant (HEE resistant)
- Originally derived from JBK-75, the development for NASA HR-1 started in late 1990 at the NASA Marshall Material and Process lab 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.





NASA HR-1, Comparison and Derivatives



NASA HR-1 is derived based on historical H2-resistant materials and developed for performance improvements

- 1) Like JBK-75, NASA HR-1 has excellent HEE resistance (no ductility loss)
 - 1) Testing was done in a 5 ksi GH₂ environment
- 2) NASA HR-1 is up to 25% stronger than JBK-75
 - 1) Its higher strength permits the fabrication and use of lighter components
 - 2) It is a very versatile alloy that has good weldability, castability, and cold-workability
- 3) NASA-HR-1 extends the compositional ranges for existing Fe-Ni-base superalloys
 - 1) It is an excellent replacement for many structural alloys that become embrittled in hydrogen.

Nominal chemical composition Wt%

	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



Formulation of NASA HR-1 Material



- Additive manufacturing has provided the opportunity for rapid material characterization and optimization of NASA HR-1
- Optimal properties can be adjusted for the application
- Revisions of the NASA HR-1 material are being explored based on component requirements

AM NASA HR-1 Powder Composition Revisions (Wt%)			
	R1	R2	R3
Fe	Bal	Bal	Bal
Ni	33.7 – 34.3	33.0 – 35.0	33.7 – 34.3
Co	3.1 – 3.5	3.0 – 3.5	3.6 – 4.0
Cr	15.2 – 15.7	14.0 – 16.0	14.3 – 14.9
Mo	2.0 – 2.4	1.8 – 2.2	1.6 – 2.0
V	0.3 – 0.34	0.3 – 0.5	0.28 – 0.32
W	1.9 – 2.3	1.5 – 2.0	1.4 – 1.8
Ti	2.3 – 2.7	2.4 – 2.8	2.2 – 2.6
Al	0.23 – 0.3	0.1 – 0.4	0.23 – 0.27

NASA HR-1 Revisions:

Rev. 1 – Original Alloy

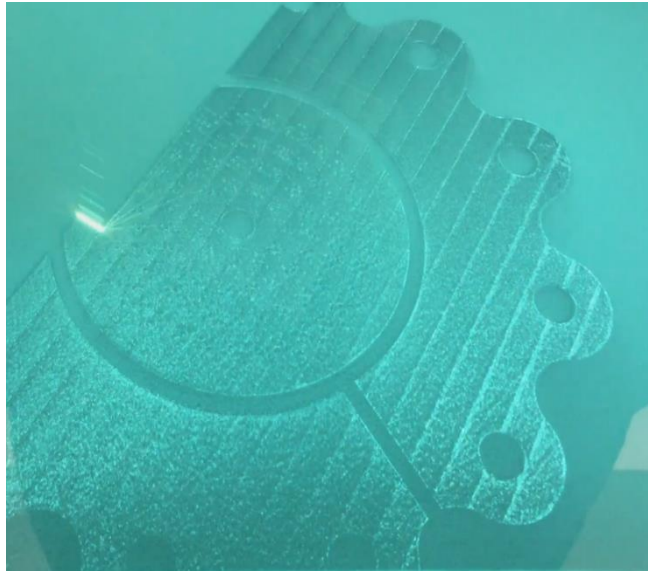
Rev. 2 – Proposed for additive processes

Rev. 3 – Explored to maximize key properties for nozzles such as conductivity and fatigue

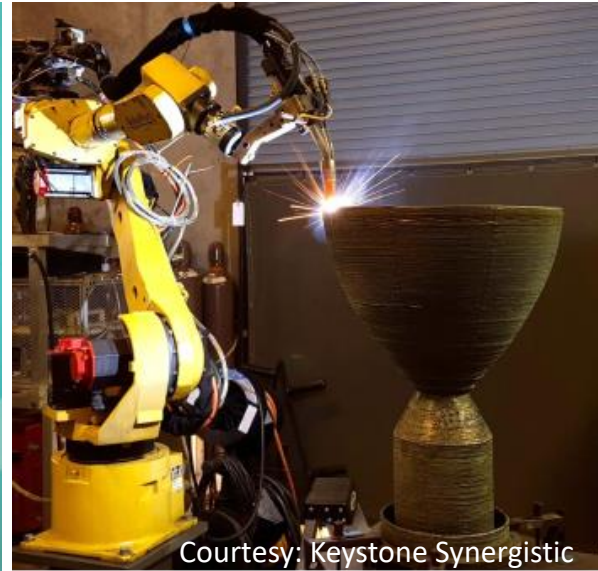
- Various AM processes being explored using NASA HR-1 for various component applications
- Each process has advantages and disadvantages using NASA HR-1 and the material responds differently for each of the heat treatments



**Blown Powder
Directed Energy
Deposition (BP-DED)**

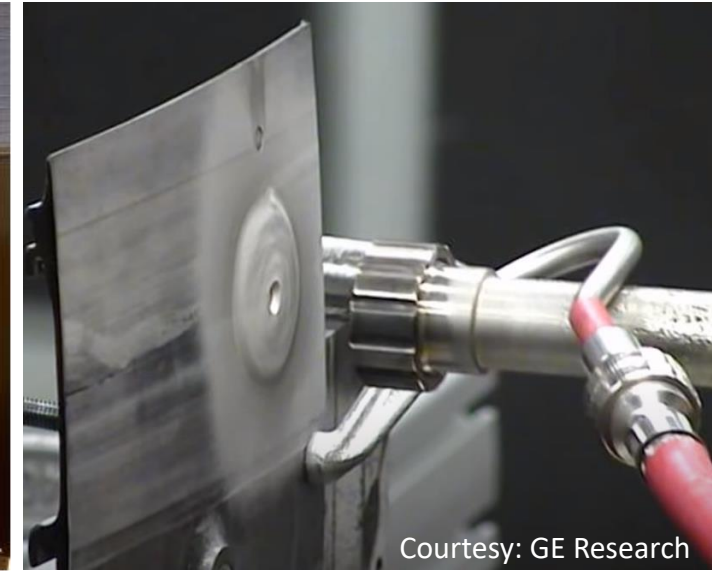


**Laser Powder Bed
Fusion (L-PBF)**



Courtesy: Keystone Synergistic

**Arc-based Directed
Energy Deposition
(Wire Arc AM)**



Courtesy: GE Research

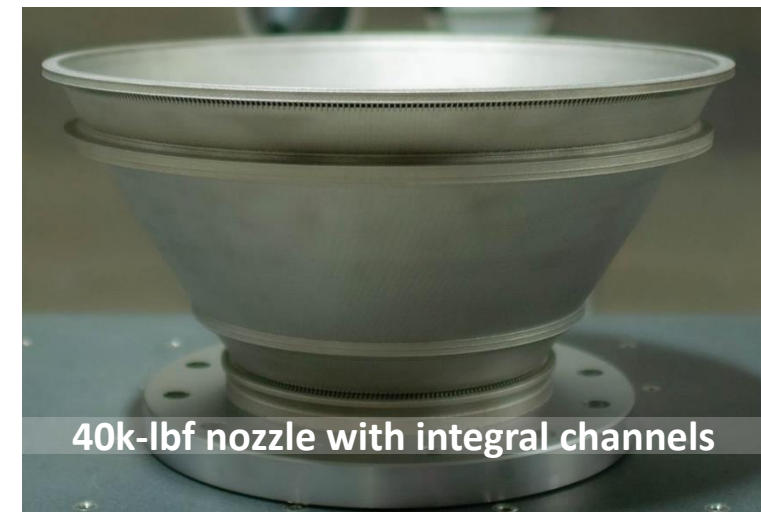
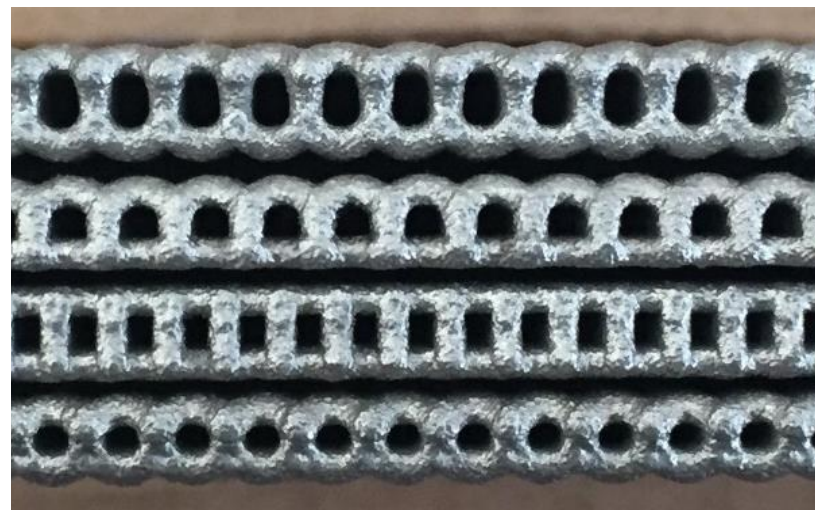
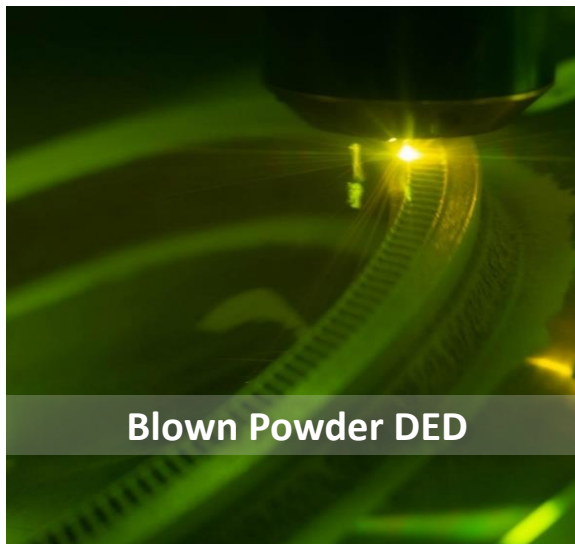
Gas Cold Spray

Overview of NASA HR-1 Microstructure

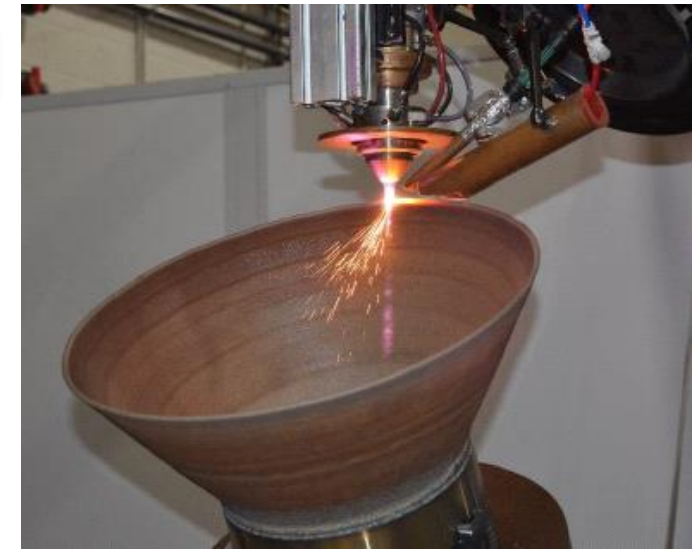
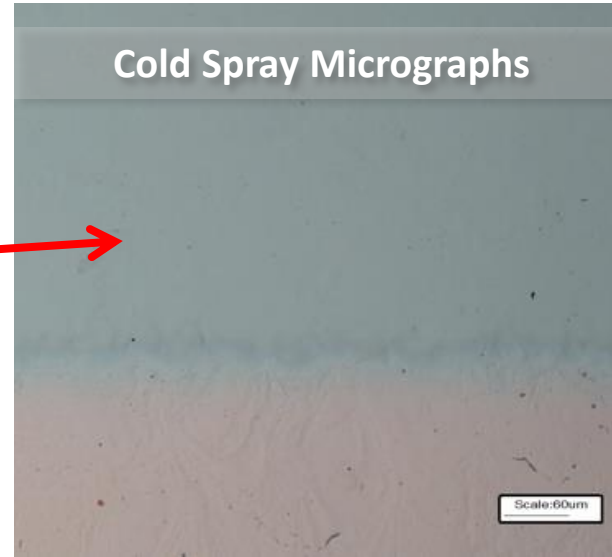
- All AM processes exhibit different grain structure and responses to heat treatment vary slightly
- Microstructure examined at various stages of heat treatment (Stress Relief, HIP / homogenization, Solution, Aging)
- Trends of AM specific processes are as expected
 - L-PBF smaller grain size
 - BP-DED exhibited larger grains and prone to high aspect ratio grains.



Development work with NASA HR-1 material



Development work with NASA HR-1





Development work with NASA HR-1



- Development of final aging cycle for AM NASA HR-1 to minimize η -phase
- Mechanical testing of DED and L-PBF to characterize mechanical properties
 - Room and elevated temperature
 - Hydrogen testing for HEE resistance
- Qualitative and quantitative welding trials
 - Focus on DED material initially
- Powder composition revision characterization
 - Adjusted powder specification in an effort to improve thermal conductivity, ductility, HEE, and LCF
- Component fabrication and hot-fire testing of 2K-lb_f, 7K-lb_f, 40K-lb_f hardware at NASA Marshall Test Stand 115 and TS116
- Further Demonstration of hardware development and post-processing steps



Conclusions and Future Development



- NASA HR-1 has potential for high-pressure, high-temperature hydrogen applications
 - Enabled by AM technologies such as blown powder DED, L-PBF, Cold Spray, and Arc-DED to be more affordable
 - Each AM technology has different advantages for fabrication of NASA HR-1
- Each AM process yields slightly different microstructure, as-expected, but can yield high density NASA HR-1 alloy
- Desirable microstructure is attainable, but η -phase needs to be controlled during aging cycle to ensure optimal mechanical properties and HEE resistance
 - Grain structure shown to be impacted by melt pool size and scan pattern
- Further characterization of AM NASA HR-1 still needed to determine final heat treatments, mechanical properties, and performance
- Final hardware characterization and hot-fire testing is ongoing to characterize material in relevant hot-fire environments

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