Process Development and Hot-fire Testing of Additively Manufactured NASA HR-1 for Liquid Rocket Engine Applications

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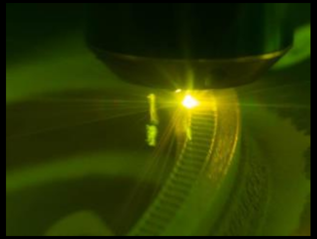
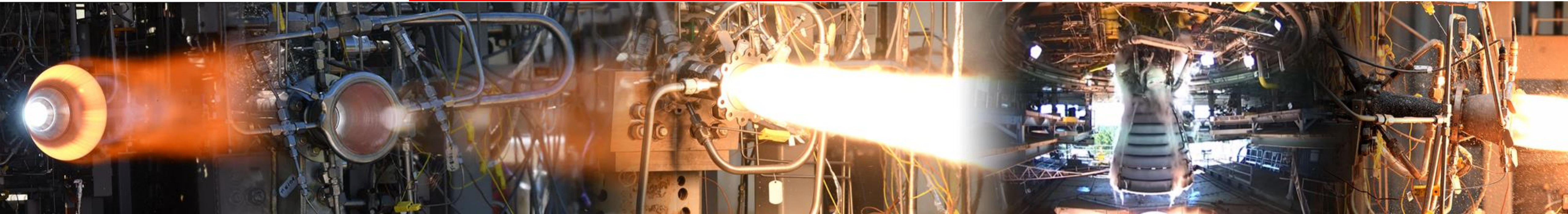
Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

Laser Powder Bed Fusion (L-PBF) Copper Alloys and Multi-Alloy

Directed Energy Deposition

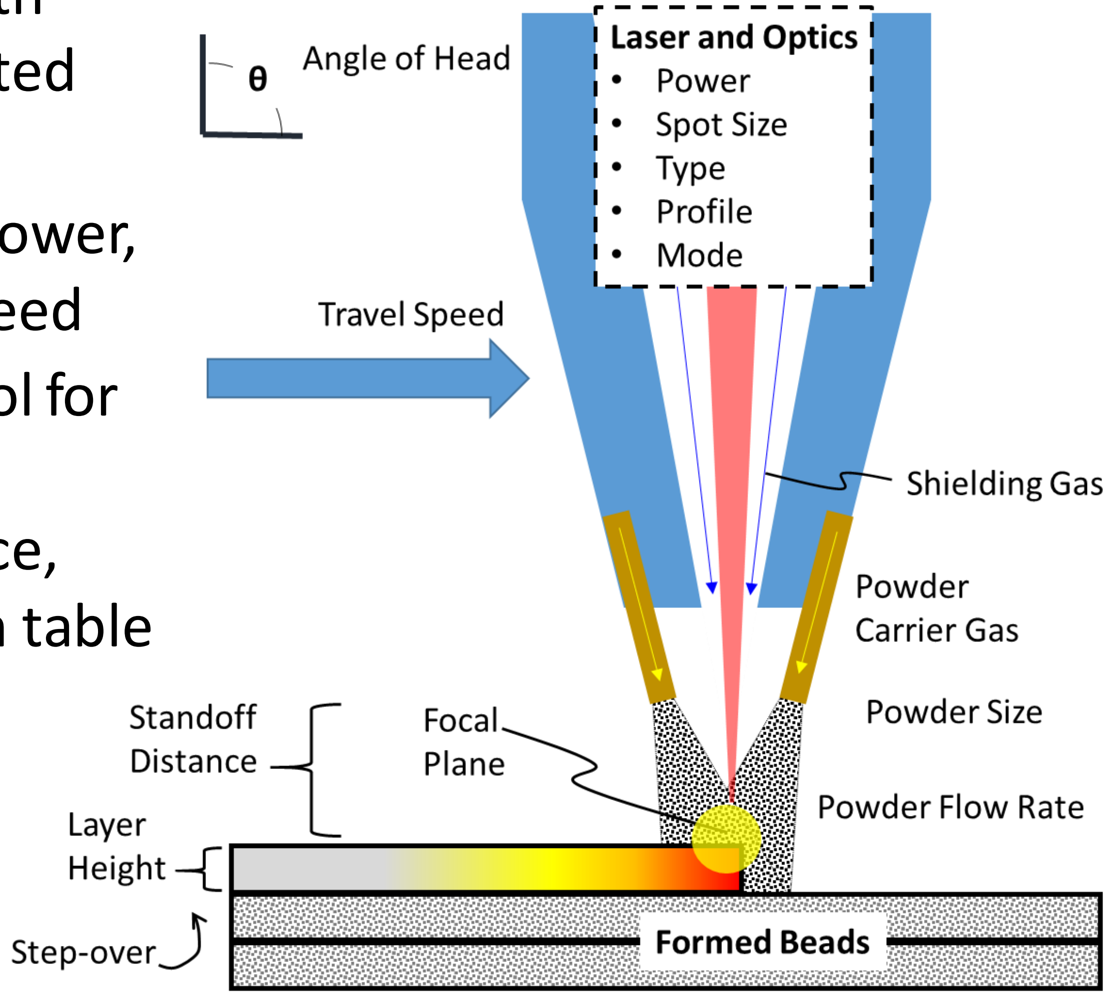


L-PBF of complex components, new alloy developments for harsh environment

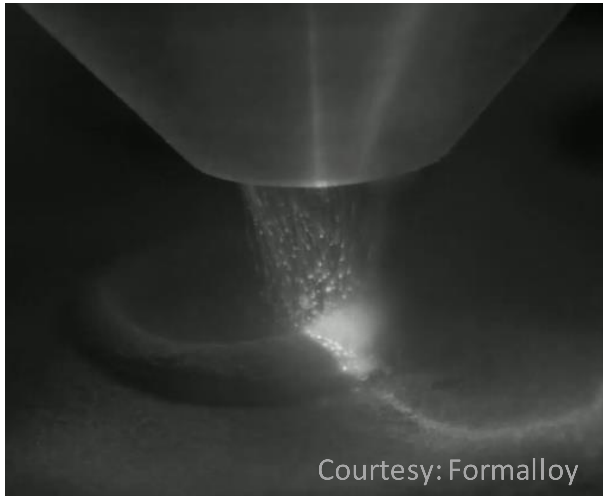


LP-DED Process Overview

- Powder and laser beam path (sometimes optics) integrated into deposition head
- Basic parameters include power, powder feedrate, travel speed
- Additional geometry control for layer height, step over (hatching), standoff distance, angle of head and trunnion table
- Can vary spot size



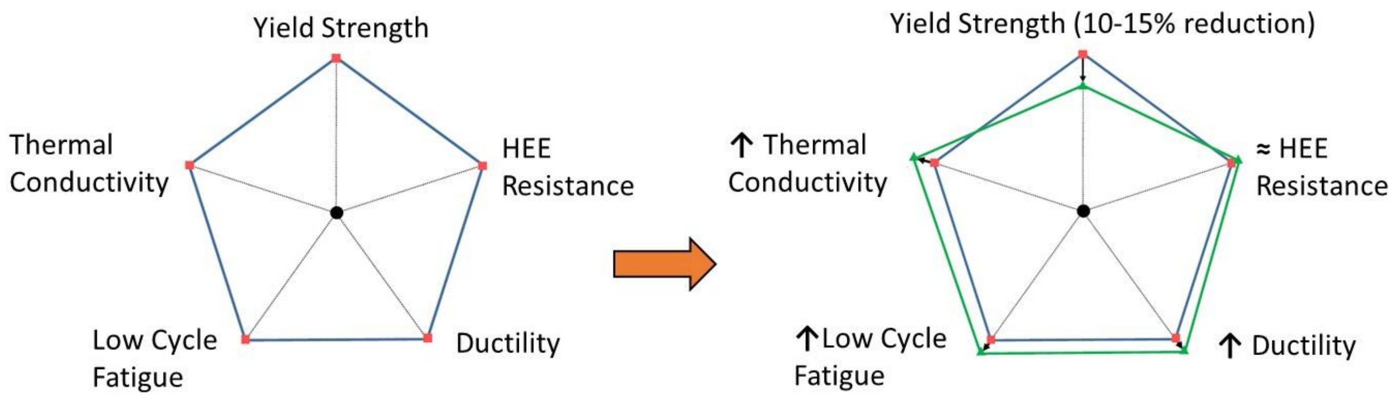
AIAA: Metal Additive Manufacturing for Propulsion Systems, Gradl et al (unreleased)

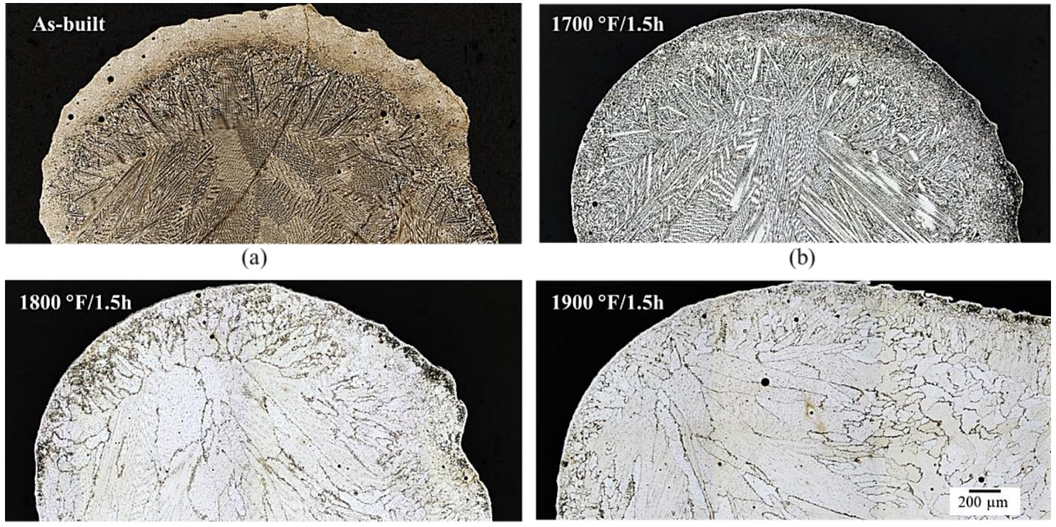


- Gradl, P. R., & Protz, C. S. (2020). Technology advancements for channel wall nozzle manufacturing in liquid rocket engines. *Acta Astronautica*. https://doi.org/10.1016/j.actaastro.2020.04.067
- AIAA Book: Metal Additive Manufacturing for Propulsion Systems, P.Gradl, C.Protz, O.Mireles, C.Garcia (Unreleased)

NASA HR-1 Alloy developed for LP-DED Process

- NASA HR-1 is an Fe-Ni-Cr alloy developed for hydrogen environments
- Developed as a derivative of JBK-75 with added W and Co for high strength
- Reformulated for AM DED to reduce Ti-segregation
- Advanced using LP-DED at different deposition rates to allow for variations in wall thickness and deposition time
- Recently advanced heat treatments to mitigate η-phase issues during heat treatment and improve properties

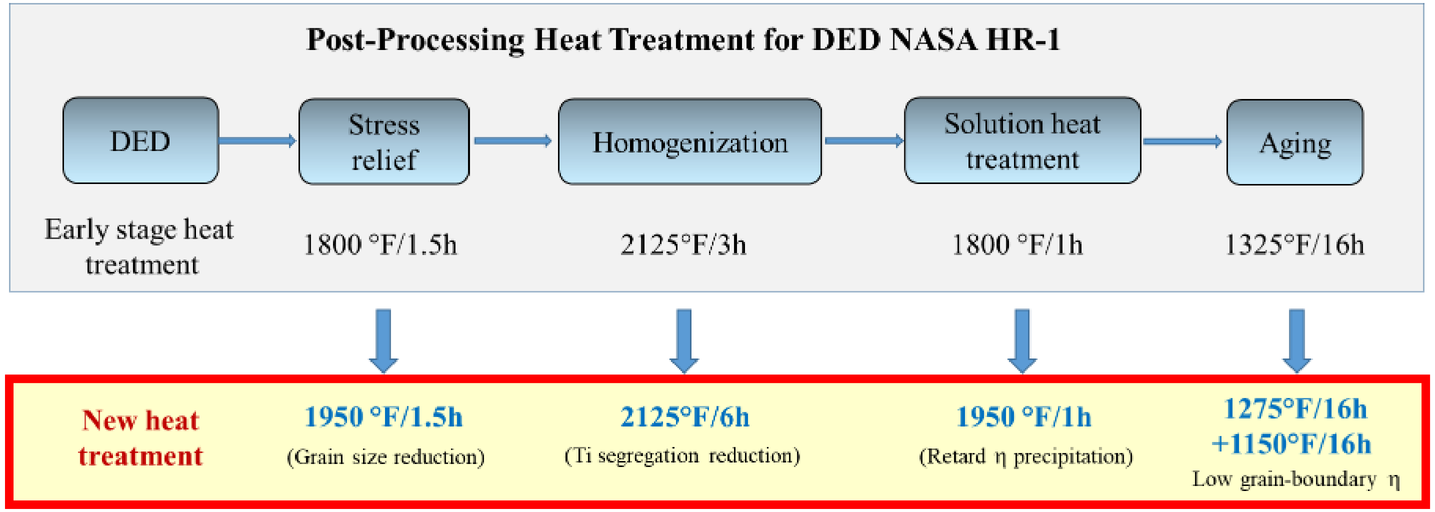


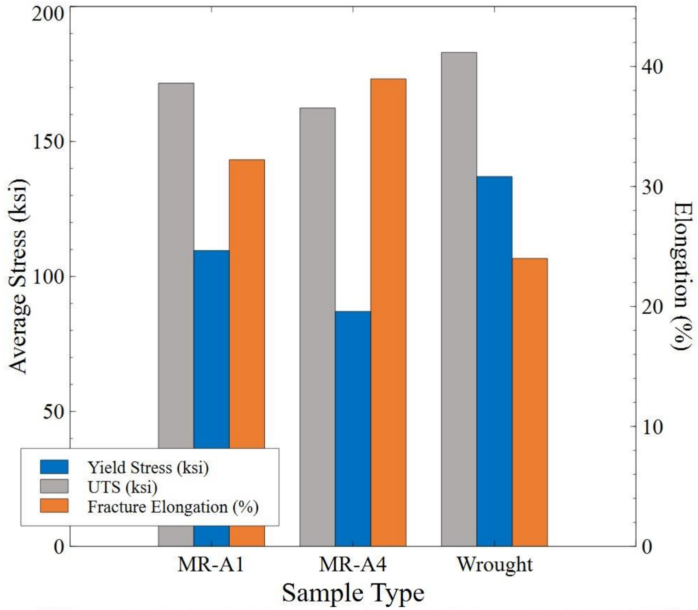


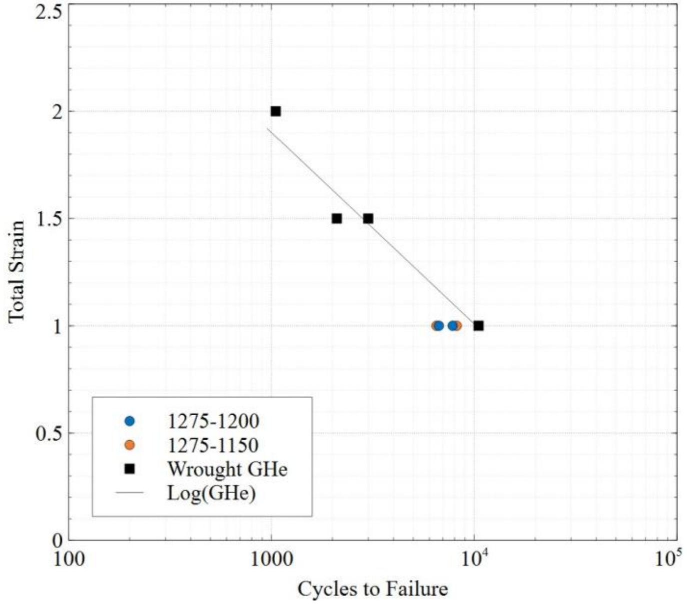
(a) (b) (c) (d)

Preliminary NASA HR-1 (Rev 3 Properties)

- A thorough characterization was completed to determine an optimal heat treatment to optimize desired properties
- LP-DED NASA HR-1 exhibits expected trends in strength and ductility



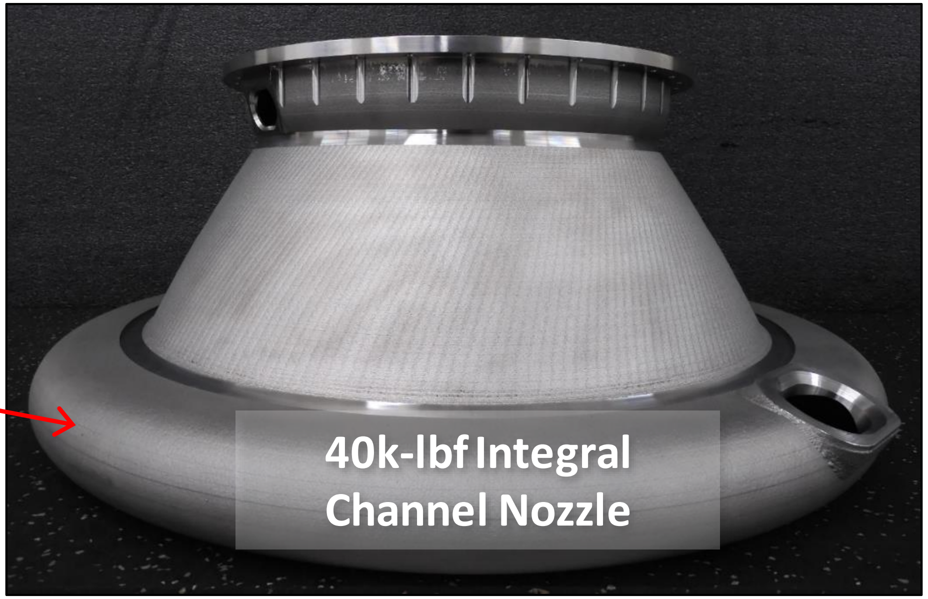




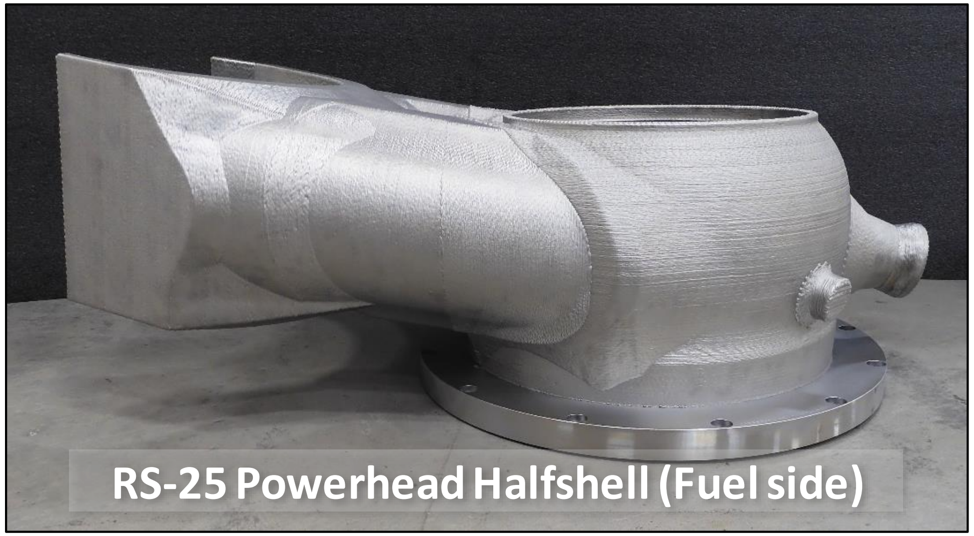
Various Components Fabricated using LP-DED


RS-25 Powerhead liner


40k-lbf nozzle manifold (~24" dia)


40k-lbf Integral Channel Nozzle


RS-25 Powerhead Halfshell (LOX side)

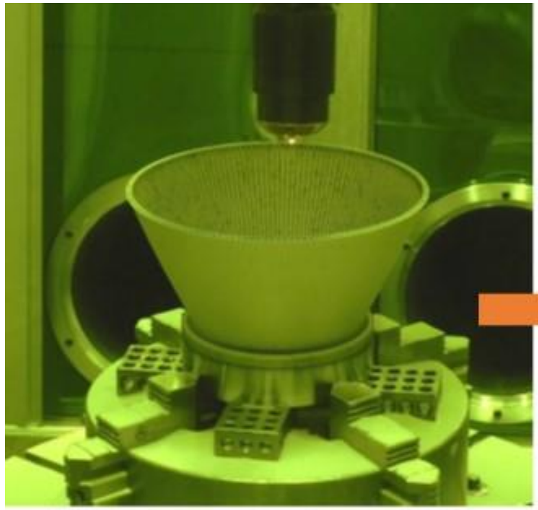

RS-25 Powerhead Halfshell (Fuel side)


2.5k-lbf spiral tube-like DED nozzle

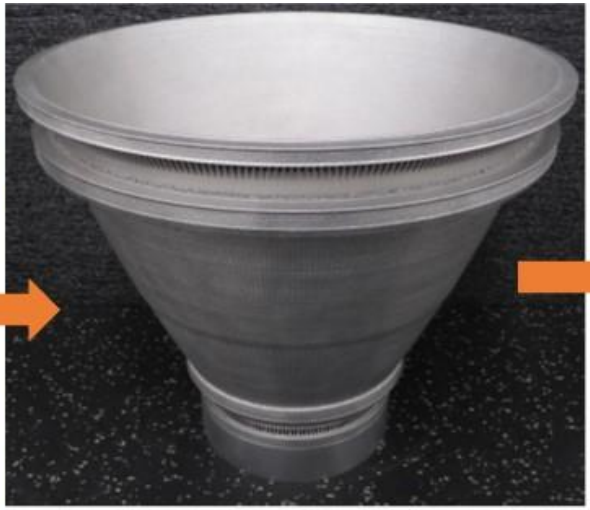
LP-DED Large Scale Nozzle with Fine Features

60” (1.52 m) diameter and >70” (1.78 m) height
90 day deposition

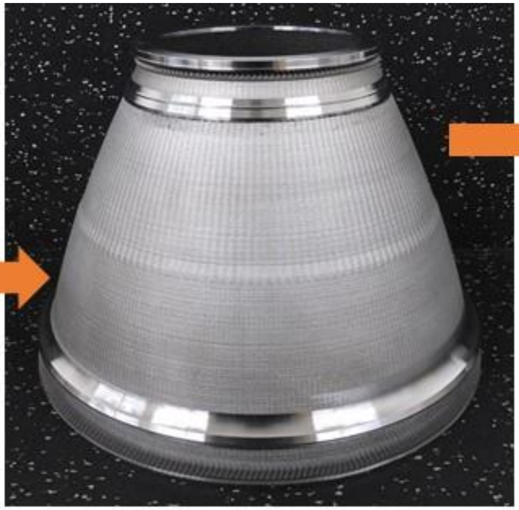
Typical Process flow for LP-DED Nozzles



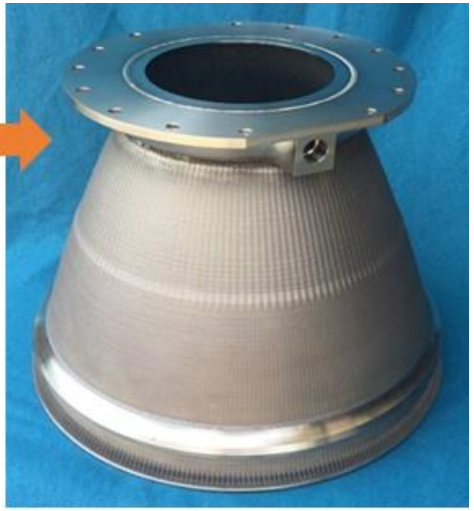
LP-DED



Post LP-DED



Machining Forward and Aft Weld Preps



EB Welding Forward Manifold

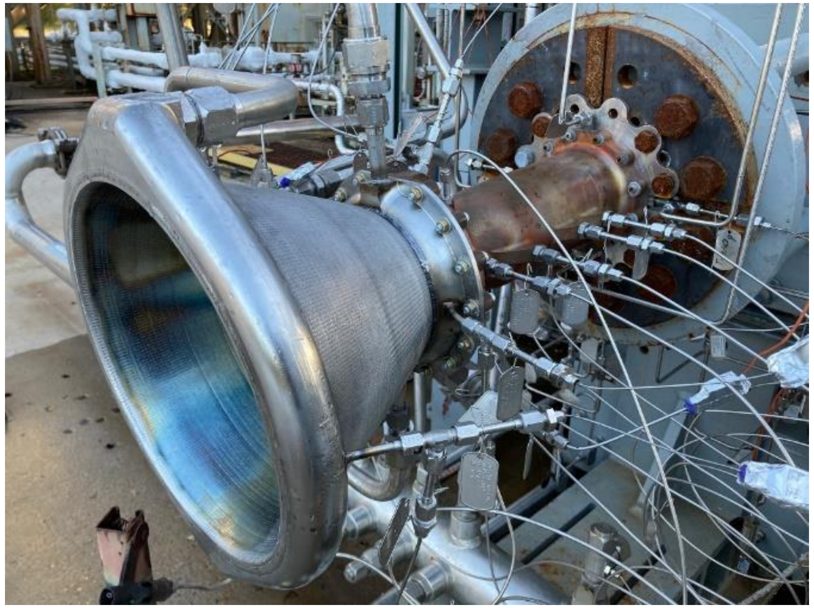
GTAW of Aft manifold

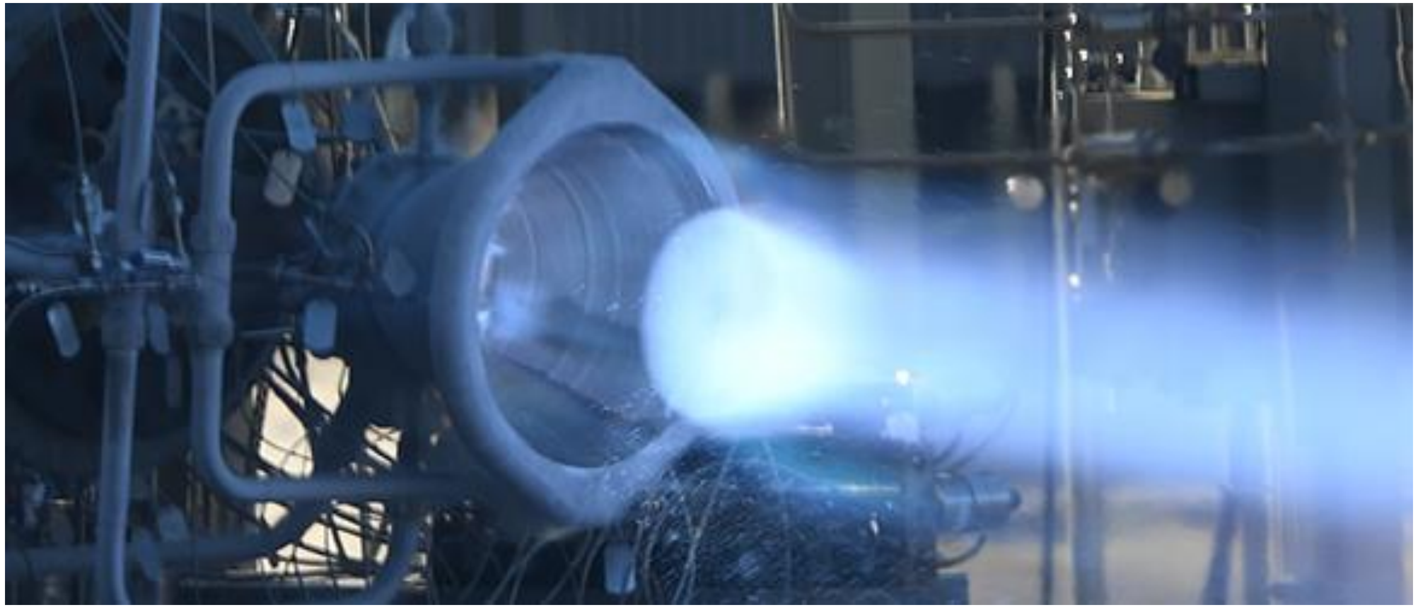
Polishing Hotwall

Proof testing

Hot-fire Test Setup for 7,000-lb$_f$ LP-DED Nozzle

- LOX/Methane with Pc = 750 psig and nominal MR = 3.0 at MSFC TS115
- Nozzle and chamber cooled with LCH4
- Integrated with GRCop-42 L-PBF chamber and L-PBF Inconel 625 Impinging injector
- Accumulated a total of 40 tests and 568 seconds
- Low pressure drop in channels
- No issues with nozzle and performance as-expected

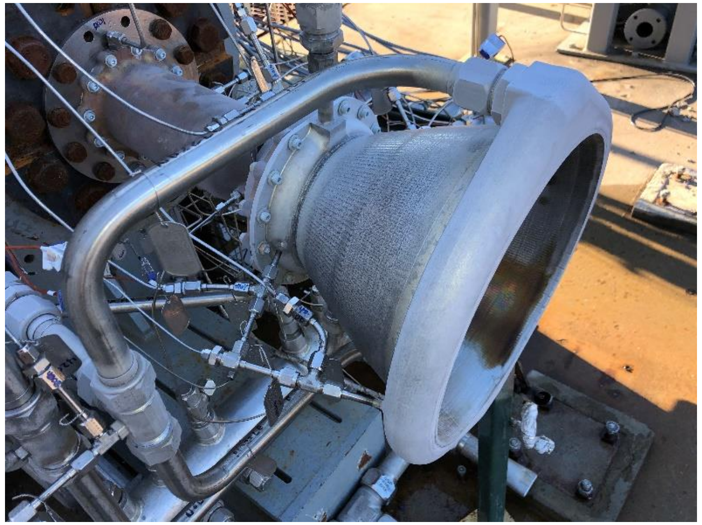




Conclusions / Summary

- LP-DED is a viable process to design, fabricate and test large scale components for liquid rocket engines
- LP-DED provides a scale not possible with other metal AM techniques
- NASA HR-1 has been demonstrated as a high strength alloy for channel wall nozzles and other components in hydrogen-environments
- Hot-fire testing accumulated 40 starts and 568 seconds at 7,000-lbf scale
- Various projects to complete hot-fire testing (2.5k to 40k-lbf) using LP-DED
- Data and properties available to commercial and government partners



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References

- Gradl, P. “Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles.” AIAA-2016-4771, Paper presented at 52nd AIAA/SAE/ASEE Joint Propulsion Conference, July 27, 2016. Salt Lake City, UT.
- Gradl, P. R., & Protz, C. S. (2020). Technology advancements for channel wall nozzle manufacturing in liquid rocket engines. *Acta Astronautica*, *174*, 148-158. https://doi.org/10.1016/j.actaastro.2020.04.067
- Gradl, P.R., Greene, S.E., Brandsmeier, W., Johnston, I. Hot-fire Testing and Large-scale Deposition Manufacturing Development Supporting Liquid Rocket Engine Channel Wall Nozzle Fabrication, Paper presented at 65th JANNAF Propulsion Meeting/10th Liquid Propulsion Subcommittee, May 21-24, 2018. Long Beach, CA.
- Kerstens, F., Cervone, A., Gradl., P. (2021). End to end process evaluation for additively manufactured liquid rocket engine thrust chambers. Acta Astronautica. 182, 454-465. https://doi.org/10.1016/j.actaastro.2021.02.034
- 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.
- Gradl, P., Protz, C., Cooper, K., Garcia, C., Ellis, D., Evans, L. GRCop-42 Development and Hot-fire Testing using Additive Manufacturing Powder Bed Fusion for Channel-cooled Combustion Chambers. 55th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. August 19-21, Indianapolis, IN. AIAA-2019-4228
- Gradl, P., Protz, C., Wammen, T. Additive Manufacturing Development and Hot-fire Testing of Liquid Rocket Channel Wall Nozzles using Blown Powder Directed Energy Deposition Inconel 625 and JBK-75 Alloys. 55th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. August 19-21, Indianapolis, IN. AIAA-2019-4362
- Gradl, P., Protz, C., Fikes, J., Clark, A., Evans, L., Miller, S., Ellis, D.L., Hudson, T. Lightweight Thrust Chamber Assemblies using Multi-Alloy Additive Manufacturing and Composite Overwrap. AIAA Propulsion and Energy Forum. August 24-26. Virtual. (2020). AIAA-2020-3787.
- ASTM International. (2016). *ASTM F3187 - 16 Standard Guide for Directed Energy Deposition of Metals*. ASTM.Org. https://www.astm.org/Standards/F3187.htm
- Anderson, R., Terrell, J., Schneider, J., Thompson, S. and Gradl, P., 2019. Characteristics of Bi-metallic Interfaces Formed During Direct Energy Deposition Additive Manufacturing Processing. *Metallurgical and Materials Transactions B*, pp.1-10.
- Onuike, B., Heer, B. and Bandyopadhyay, A., 2018. Additive manufacturing of Inconel 718—copper alloy bimetallic structure using laser engineered net shaping (LENS™). *Additive Manufacturing*, *21*, pp.133-140.
- Bandyopadhyay, A. and Heer, B., 2018. Additive manufacturing of multi-material structures. *Materials Science and Engineering: R: Reports*, *129*, pp.1-16
- Gradl, P., Protz, C., Wammen, T. “Additive Manufacturing Development and Hot-fire Testing of Liquid Rocket Channel Wall Nozzles using Blown Powder Directed Energy Deposition Inconel 625 and JBK-75 Alloys”. 55th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. August 19-22. Indianapolis, IN. (2019).
- Gradl, P., Mireles, O. and Andrews, N., 2019. Introduction to Additive Manufacturing for Propulsion Systems. M19-7605. AIAA Propulsion and Energy Forum and Exposition; August 19, 2019 - August 22, 2019; Indianapolis, IN; United States. 10.13140/RG.2.2.13113.93285
- Hauser, C. Additive Manufacturing Seminar: Blown Powder Activities. TWI Materials and Joining Technologies. Retrieved from: *www.twi-global.com/_resources*. (2015)
- Karczewski, K., Pęska, M., Ziętala, M. and Polański, M., 2017. Fe-Al thin walls manufactured by laser engineered net shaping. *Journal of Alloys and Compounds*, *696*, pp.1105-1112.

References

- K.S. Chan, M. Koike, R.L. Mason, and T. Okabe, Fatigue Life of Titanium Alloys Fabricated by Additive Layer Manufacturing Techniques for Dental Implants, Metall. Trans. A., 2013, 44A, p 1010– 1022.
- DebRoy, T., Wei, H.L., Zuback, J.S., Mukherjee, T., Elmer, J.W., Milewski, J.O., Beese, A.M., Wilson-Heid, A., De, A. and Zhang, W., 2018. Additive manufacturing of metallic components–process, structure and properties. *Progress in Materials Science*, *92*, pp.112-224.
- Sames, W.J., List, F.A., Pannala, S., Dehoff, R.R. and Babu, S.S., 2016. The metallurgy and processing science of metal additive manufacturing. *International Materials Reviews*, *61*(5), pp.315-360.
- P. S. Chen, B. Panda, and B.N. Bhat, " NASA HR-1, A New Hydrogen Resistant Fe-Ni Base Superalloy", Hydrogen Effects in Materials, edited by A.W. Thompson and N.R. Moody, Minerals, Metals, and Materials Sciety (TMS), 1996.
- A.W. Thompson, J.A. Brooks, "Hydrogen Performance of Precipitation-Strengthened Stainless Steels Based on A-286." Metallurgical Transactions A, Vol. 6, No. 7, 1975, p. 1431. doi:10.1007/BF02641935.
- P.S. Chen, C.C. Katsarelis, W.M. Medders, P.R. Gradl, "Segregation Evolution and Diffusion of Titanium in DED NASA HR-1", NASA/TM–20210013649.
- M. Morinaga, N. Yukawa, and H. Adachi, "Alloying Effect on the Electronic Structure of Ni3Al (γ')," J. Phys.Soc. Japan, 1984, vol. 53, No. 2, pp.653-63.
- M. Morinaga, N. Yukawa, H. Ezaki, "Solid Solubilities in Transition-Metal Based FCC Alloys," Phil. Mag. A, 51 (1985), No. 2, pp.223-246.
- M. Morinaga, N. Yukawa, and H. Adachi, and H. Ezaki, "New PHACOMP and Its Application to Alloy Design," Superalloys,1984, edited by M. Gell, MC.S. Kortovich, R.H. Bricknell, W. B. Kent and J.F. Radavich, The Metallurgical Society of AIME , 1984, pp.523-532.
- M. Morinaga, N. Yukawa, and H. Adachi, "Alloying Effect on the Electronic Structure of BCC Fe,"J. Phys.F: Met. Phys. 15 (1985), pp. 1071-1084.
- "η-Phase TTP Diagram Development for DED NASA HR-1," Internal Research, NASA Marshall Space Flight Center, Huntsville, AL.
- "Progress in Thermal Process Development and Ti Segregation Mitigation for AM NASA HR-1," Internal Research, NASA Marshall Space Flight Center, Huntsville, AL.
- Katsarelis, C., Chen, P., Gradl, P., Protz, C., Jones, Z., Ellis, D., and Evans, L. Additive Manufacturing of NASA HR-1 Material for Liquid Rocket Engine Component Applications. *JANNAF Dec*.
- Chen, P., and Mitchell, M. "ALLOY NASA-HR-1." No. April 2005, 2005.
- Gradl, P.R., Protz, C. "Large-Scale Channel Wall Nozzle Development using DED and LWDC Additive Manufacturing Techniques." Paper presented at 2019 JANNAF 11th Liquid Propulsion Subcommittee (LPS), December 9-13. Tampa, FL. (2019).
- Gradl, P. R., Protz, C., Fikes, J., Clark, A., Evans, L., Miller, S., Ellis, D., & Hudson, T. (2020). Lightweight thrust chamber assemblies using multi-alloy additive manufacturing and composite overwrap. *AIAA Propulsion and Energy 2020 Forum*, 1–25. https://doi.org/10.2514/6.2020-3787

Large scale Integrated Channel DED Nozzle Build