Advancement of Extreme Environment Additively Manufactured Alloys for Next Generation Space Propulsion Applications

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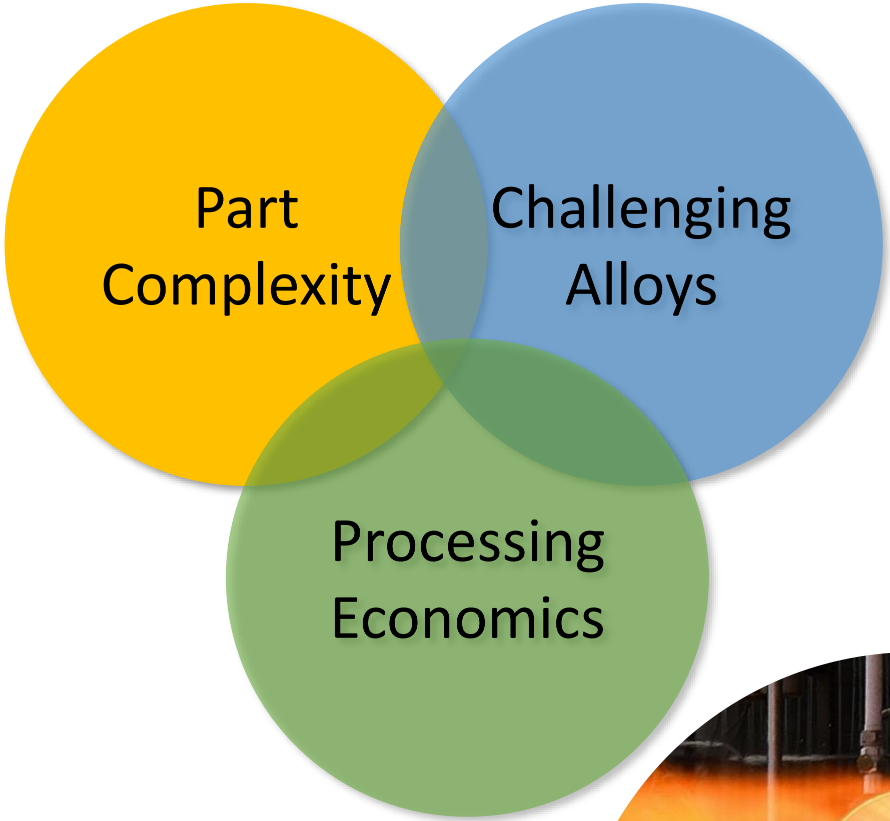
The Case for Additive Manufacturing in Propulsion

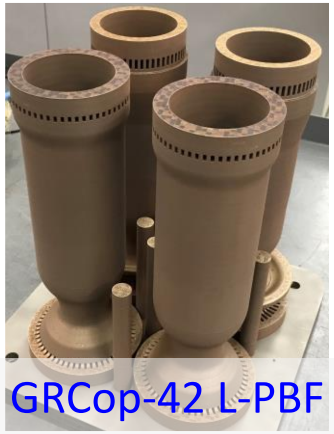
- Metal Additive Manufacturing (AM) provides significant advantages for lead time and cost over traditional manufacturing for rocket engines
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities



Opportunity to allow for better process economics and advance enabling alloys through rapid development not previously possible with traditional manufacturing techniques

New Alloy Development to Improve Performance

Max. Use Temp. (°C)	Alloy Family	Purpose	Novel AM Alloys	Propulsion Use
200	Aluminum	Light weighting	-	Various
750	**Copper**	**High conductivity; strength at temperature**	**GRCop-42 GRCop-84**	**Combustion Chambers**
800	**Iron-Nickel**	**High strength and hydrogen resistance**	**NASA HR-1**	**Nozzles, Powerheads**
900	Nickel	High strength to weight	-	Injectors, Turbines
1100	**ODS Nickel**	**High strength at elevated temp; reduced creep**	**GRX-810 Alloy 718-ODS**	**Injectors, Turbines**
1850	**Refractory**	**Extreme temperature**	**C-103, C-103-CDS, Mo, W**	**Uncooled Chambers**


GRCop-42 L-PBF


NASA HR-1 LP-DED

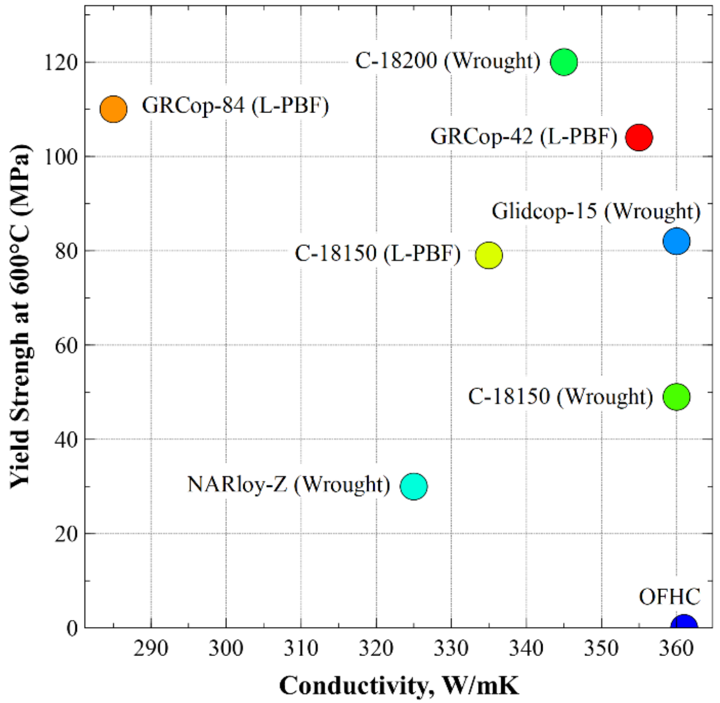

GRX-810 L-PBF


C103 L-PBF

New alloy development using various additive manufacturing processes (PBF and DED) can yield performance improvements over traditional alloys

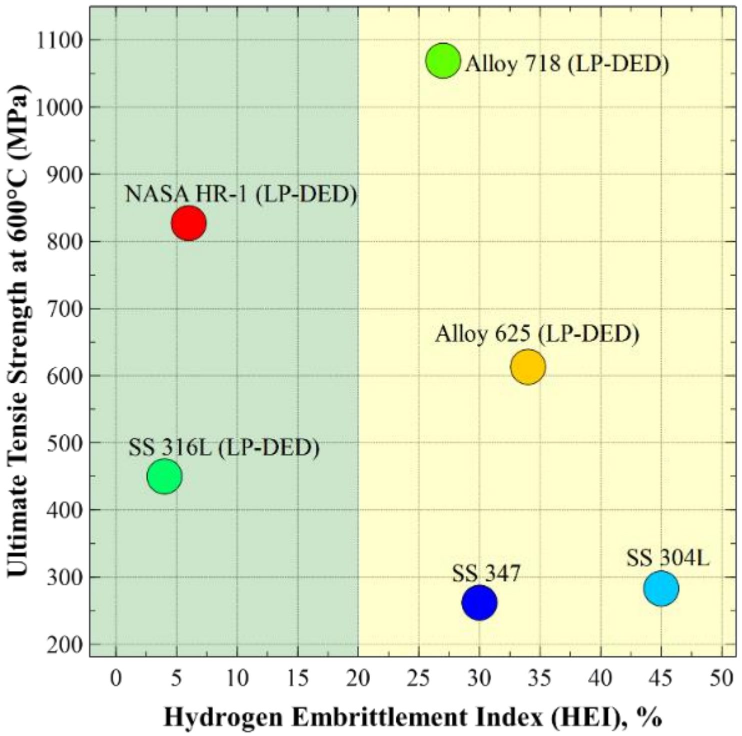
GRCop-42 and GRCop-84 for High Conductivity

- GRCop-42 and GRCop-84 (Cu-Cr-Nb) offer high conductivity (>350 W/mK) and high strength at elevated temperatures (up to 800 °C).
- Oxidation and blanching resistance during thermal and oxidation-reduction cycling.
- Established powder supply chain and commercial supply chain.
- Significant maturity in characterization and hot-fire testing (high TRL).
- Over 41,000 seconds of hot-fire time and 1,100 starts on >30 chambers

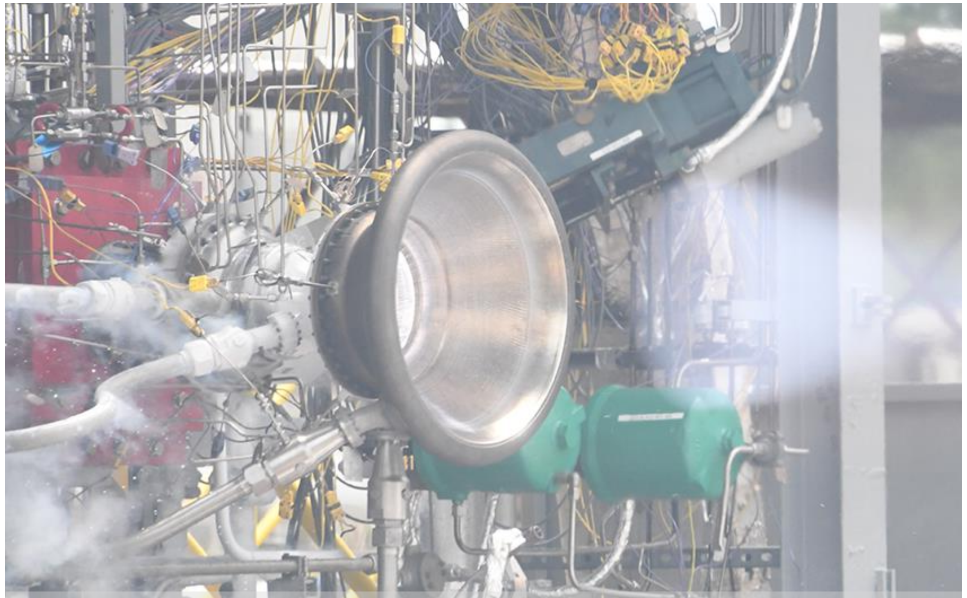


NASA HR-1 Hydrogen Resistant Alloy

- NASA HR-1 (Fe-Ni-Cr) is a hydrogen resistant high strength superalloy.
- Formulated for AM processes for low cycle fatigue, ductility, and H2 resistance properties.
- Targeted use is Laser Powder Directed Energy Deposition (LP-DED) for large scale nozzles.
- Supply chain maturity for powder feedstock, build parameters, and demonstrator builds.
- Single NASA HR-1 LP-DED nozzle accumulated 207 starts and >6,800 secs.



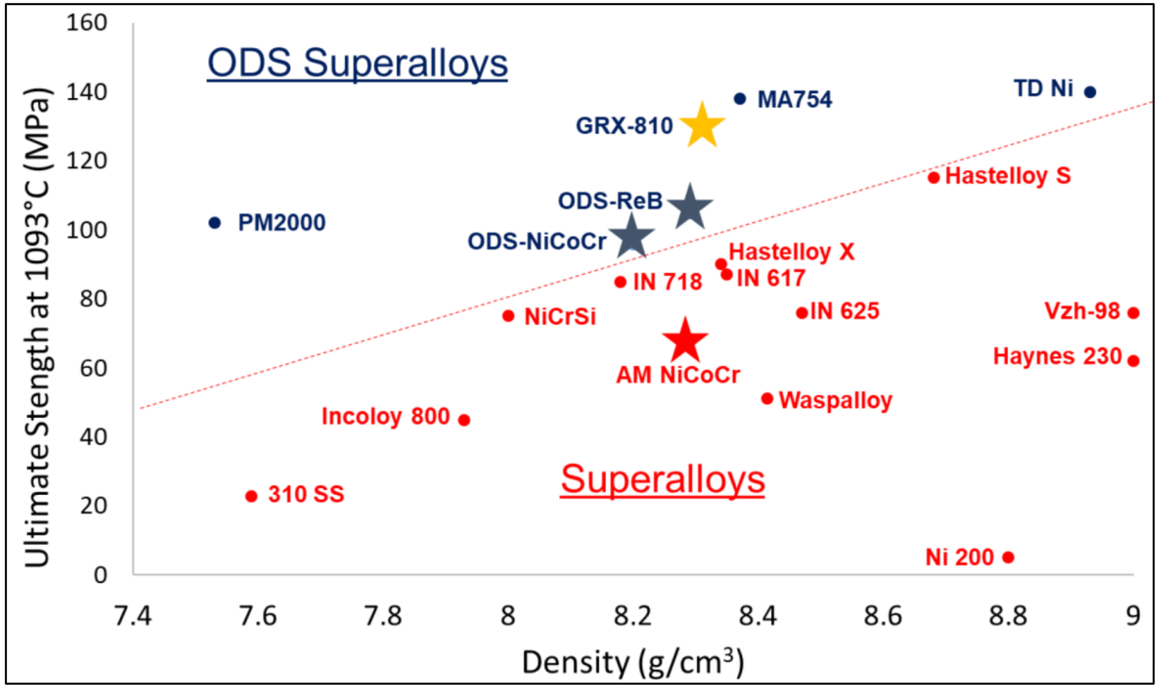
1.52 m dia. x 1.78 m height

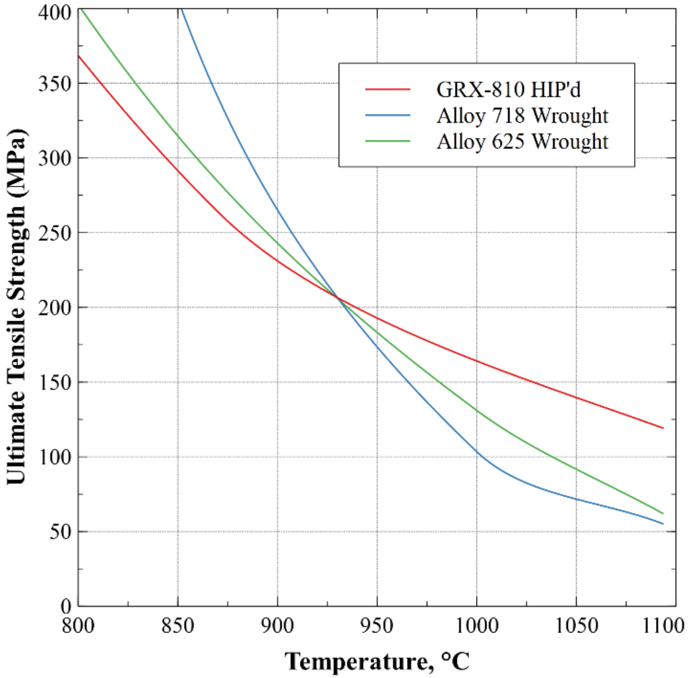


Hot-fire Testing of 156 KN LP-DED Cooled Nozzle

GRX-810 for Extreme Temperature and High Strength

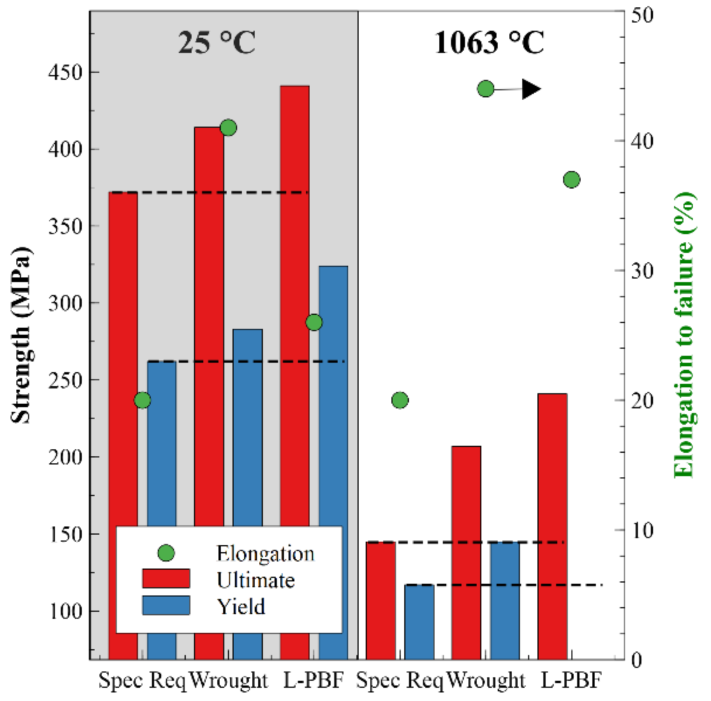
- GRX-810 (**G**lenn **R**esearch Center E**X**treme -810) is an oxide dispersion strengthened (ODS) Ni-Co-Cr alloy specifically formulated for AM using Y_2O_3 nanoparticles.
- 2x strength of standard superalloys approaching 1100 °C.
- Orders of magnitude better oxidation resistance compared to superalloys.
- Demonstrated process parameters and feasibility of powder feedstock.



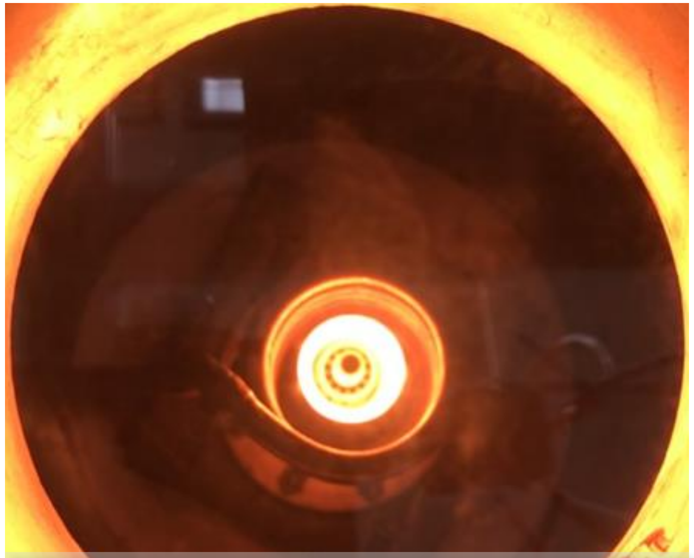


Refractory Alloys for Ultra High Temperature

- Refractory alloy development for AM allows for significant reduction in feedstock cost.
- Tungsten, C-103 has been matured with L-PBF and LP-DED processes along with feedstock.
- Mechanical properties shown to exceed specification minimums and density >99.98%.
- W, Mo, Ta, Re, and Nb alloys being developed under Refractory Alloy Additive Manufacturing Build Optimization (RAAMBO) project.



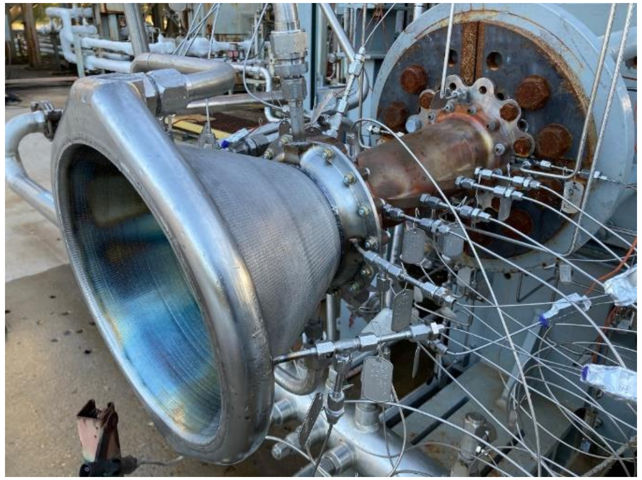
L-PBF C-103 Demonstrator Parts



L-PBF W 1N green chamber heated to 2300 °C

Summary

- NASA has formulated and matured novel alloys specifically intended for use with additive manufacturing for high temperature and harsh environments.
- Alloys include GRCop-42, GRCop-84, NASA HR-1, GRX-810, Refractory-based (C103).
- AM processes to manufacture components and material properties required have matured.
- NASA has accumulated over 50,000 secs and 1400 starts of hot-fire testing on these alloys.
- 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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LP-DED Large Scale Nozzle Development


NASA HR-1

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

90 day deposition


JBK-75

95” (2.41 m) dia and 111” (2.82 m) height

Near Net Shape Forging Replacement

Reference: P.R. Gradl, T.W. Teasley, C.S. Protz, C. Katsarelis, P. Chen, Process Development and Hot-fire Testing of Additively Manufactured NASA HR-1 for Liquid Rocket Engine Applications, in: AIAA Propuls. Energy 2021, 2021: pp. 1–23. https://doi.org/10.2514/6.2021-3236.

References

- [1] Blakey-Milner B, Gradl P, Snedden G, Brooks M, Pitot J, Lopez E, et al. Metal additive manufacturing in aerospace: A review. Mater Des 2021;209:110008. https://doi.org/10.1016/j.matdes.2021.110008.
- [2] Bhat BN, editor. Aerospace Materials and Applications. Reston ,VA: American Institute of Aeronautics and Astronautics, Inc.; 2018. https://doi.org/10.2514/4.104893.
- [3] Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney C. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. J Mater Eng Performance, Springer 2021. https://doi.org/10.1007/s11665-022-06850-0.
- [4] Paul R. Gradl, Omar R. Mireles, Christopher S. Protz, Chance P. Garcia. Metal Additive Manufacturing for Propulsion Applications. 1st ed. Reston, VA: American Institute of Aeronautics and Astronautics, Inc.; 2022. https://doi.org/10.2514/4.106279.
- [5] Gradl PR, Greene SE, Protz C, Bullard B, Buzzell J, Garcia C, et al. Additive manufacturing of liquid rocket engine combustion devices: A summary of process developments and hot-fire testing results. 2018 Jt. Propuls. Conf., American Institute of Aeronautics and Astronautics Inc, AIAA; 2018. https://doi.org/10.2514/6.2018-4625.
- [6] Gradl PR, Protz CS, Ellis DL, Greene SE. Progress in additively manufactured copper-alloy GRCop-84, GRCop-42, and bimetallic combustion chambers for liquid rocket engines. Proc. Int. Astronaut. Congr. IAC 2019, vol. October 21, 2019, p. 21–5.
- [7] Gradl PR, Protz CS. Technology advancements for channel wall nozzle manufacturing in liquid rocket engines. Acta Astronaut 2020;174. https://doi.org/10.1016/j.actaastro.2020.04.067
- [8] Smith TM, Thompson AC, Gabb TP, Bowman CL, Kantzos CA. Efficient production of a high-performance dispersion strengthened, multi-principal element alloy. Sci Reports 2020 101 2020;10:1–9. https://doi.org/10.1038/s41598-020-66436-5.
- [9] National Research Council (U.S.). Committee on Integrated Computational Materials Engineering. Integrated computational materials engineering : a transformational discipline for improved competitiveness and national security 2008:137.
- [10] Seifi M, Salem A, Beuth J, Harrysson O, Lewandowski JJ. Overview of Materials Qualification Needs for Metal Additive Manufacturing. JOM 2016;68:747–64. https://doi.org/10.1007/s11837-015-1810-0.
- [11] Song Q song, Zhang Y, Wei Y feng, Zhou X yi, Shen Y fu, Zhou Y min, et al. Microstructure and mechanical performance of ODS superalloys manufactured by selective laser melting. Opt Laser Technol 2021;144:107423. https://doi.org/10.1016/J.OPTLASTEC.2021.107423.
- [12] Kerstens F, Cervone A, Gradl P. End to end process evaluation for additively manufactured liquid rocket engine thrust chambers. Acta Astronaut 2021;182:454–65. https://doi.org/10.1016/j.actaastro.2021.02.034
- [13] Minneci RP, Lass EA, Bunn JR, Choo H, Rawn CJ. Copper-based alloys for structural high-heat-flux applications: a review of development, properties, and performance of Cu-rich Cu–Cr–Nb alloys. Int Mater Rev 2020. https://doi.org/10.1080/09506608.2020.1821485
- [14] Lee J. Hydrogen embrittlement. 2016.
- [15] Li M, Zinkle SJ. Physical and Mechanical Properties of Copper and Copper Alloys. Compr Nucl Mater 2012;4:667–90. https://doi.org/10.1016/B978-0-08-056033-5.00122-1.
- [16] De Groh HC, Ellis DL, Loewenthal WS. Comparison of GRCop-84 to Other Cu Alloys With High Thermal Conductivities n.d.

References

- [17] Gradl PR, 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. AIAA Propuls. Energy Forum Expo. 2019, American Institute of Aeronautics and Astronautics Inc, AIAA; 2019. https://doi.org/10.2514/6.2019-4228.
- [18] Wadsworth J, Nieh TG, Stephens JJ. Recent advances in aerospace refractory metal alloys. Http://DxDoiOrg/101179/Imr1988331131 2013;33:131–50. https://doi.org/10.1179/IMR.1988.33.1.131.
- [19] Katsarelis C, Chen P, Gradl PR, Protz C, Jones Z, Marshall N, et al. Additive Manufacturing of NASA HR-1 Material for Liquid Rocket Engine Component Applications. JANNAF Jt Propuls Conf 2019:https://ntrs.nasa.gov/search.jsp?R=20200001007.
- [20] Chen PS, Katsarelis CC, Medders WM, Gradl PR. Segregation Evolution and Diffusion of Titanium in Directed Energy Deposited. 2021.
- [21] Gradl PR, Teasley TW, Protz CS, Katsarelis C, Chen P. Process Development and Hot-fire Testing of Additively Manufactured NASA HR-1 for Liquid Rocket Engine Applications. AIAA Propuls. Energy 2021, 2021, p. 1–23. https://doi.org/10.2514/6.2021-3236.
- [22] Chen P-S, Mitchell M. Aerospace Structural Metals Handbook ALLOY NASA-HR-1 Nickel Base Alloys-Ni. 2005.
- [23] Brif Y, Thomas M, Todd I. The use of high-entropy alloys in additive manufacturing. Scr Mater 2015;99:93–6. https://doi.org/10.1016/j.scriptamat.2014.11.037
- [24] Chen S, Tong Y, Liaw PK. Additive manufacturing of high-entropy alloys: A review. Entropy 2018;20. https://doi.org/10.3390/e20120937.
- [25] Weng F, Chew Y, Zhu Z, Yao X, Wang L, Ng FL, et al. Excellent combination of strength and ductility of CoCrNi medium entropy alloy fabricated by laser aided additive manufacturing. Addit Manuf 2020;34:101202. https://doi.org/10.1016/j.addma.2020.101202.
- [26] Smith TM, Thompson AC, Gabb TP, Bowman CL, Kantzos CA. Efficient production of a high-performance dispersion element alloy. Sci Rep 2020:1–9. https://doi.org/10.1038/s41598-020-66436-5.
- [27] Smith TM. Additive Manufactured Alloys for HighTemperature Applications. NASA T2 Webinar 2022.
- [28] Mireles O. Additive Manufacture of Refractory Metals for Aerospace Applications. AIAA Propuls. Energy 2020 Forum, 2021, p. 1–9. https://doi.org/10.2514/6.2021-3234.
- [29] Mireles OR, Rodriguez O, Gao Y, Philips N. Additive manufacture of refractory alloy C-103 for propulsion applications. AIAA Propuls. Energy 2020 Forum, American Institute of Aeronautics and Astronautics Inc, AIAA; 2020, p. 1–13. https://doi.org/10.2514/6.2020-3500.
- [30] Talignani A, Seede R, Whitt A, Zheng S, Ye J, Karaman I, et al. A review on additive manufacturing of refractory tungsten and tungsten alloys. Addit Manuf 2022;58:103009. https://doi.org/10.1016/J.ADDMA.2022.103009
- [31] Awasthi PD, Agrawal P, Haridas RS, Mishra RS, Stawovy MT, Ohm S, et al. Mechanical properties and microstructural characteristics of additively manufactured C-103 niobium alloy. Mater Sci Eng A 2022;831:142183. https://doi.org/10.1016/J.MSEA.2021.142183.
- [32] Romnes CJ, Stubbins JF, Mireles OR. Tuning the Properties of Additively Manufactured Tungsten Ultra-fine Lattices by Adjusting Laser Energy Density and Lattice Geometry. J Mater Eng Perform 2022 2022:1–14. https://doi.org/10.1007/S11665-022-07126-3.