National Aeronautics and Space Administration

Development and Hot-fire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications

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Objectives

Develop AM Processes to Reduce Costs/Schedules for Liquid Engine Components

➡ Reduce Overall Mission Costs

➡ Transfer Technologies to Industry to Enable Long Term Supply Chains

Techniques Evaluated:

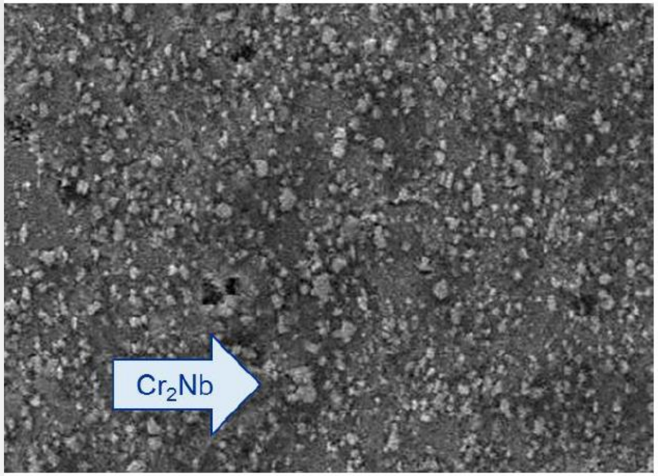
- Additive Manufacturing (AM) / Selective Laser Melting (SLM) GRCop-84 (Cu-8Cr-4Nb)
  - Also evaluating C-18150 (CuCrZr) and Glidcop
- Direct Metal Laser Sintering (DMLS) Copper & Nickel Alloys
- Bimetallic AM Chambers
  - Laser Cladding
    Direct Metal Deposition (DMD)
  - Electron Beam Freeform Fabrication (EBF^3)
  - Arc-based Deposition
  - Freeform Blown Powder Deposition/Directed Energy Deposition

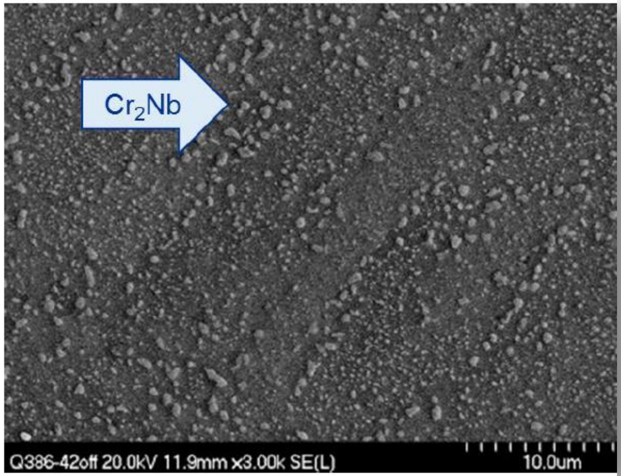
Approach:

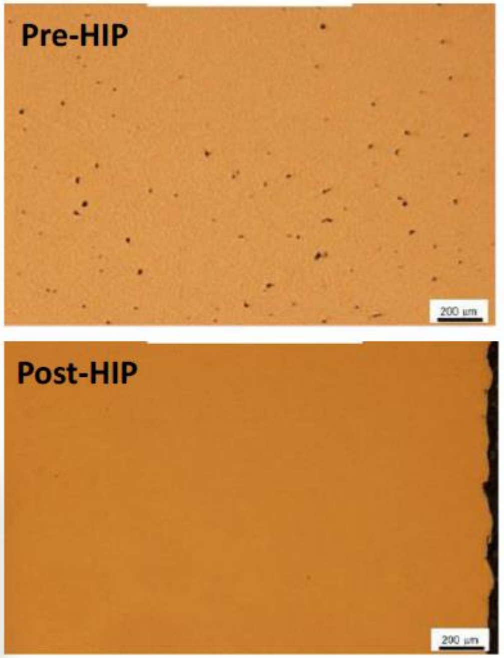
- Fabricate Various Thrust Chamber Designs with Multiple Techniques
  - Develop Process Parameters with Samples & Components
  - Characterize Material Properties
  - Proof Test Samples & Components
  - Apply Lessons Learned for Timely Design Mods
- Hot-fire Test Chambers in Relevant Environments

Development of SLM GRCop-84 Material Processing

- Challenges in SLM processing for copper-alloys
  - Copper is highly reflective in red and near-IR spectrums
  - High conductivity so heat is rapidly conducted away from melt pool
- GRCop-84 was easily melted using SLM (14 vol.% Cr_2Nb)
  - SLM process did not result in segregation of Cr_2Nb precipitates
  - Cr_2Nb appears to have been refined in size



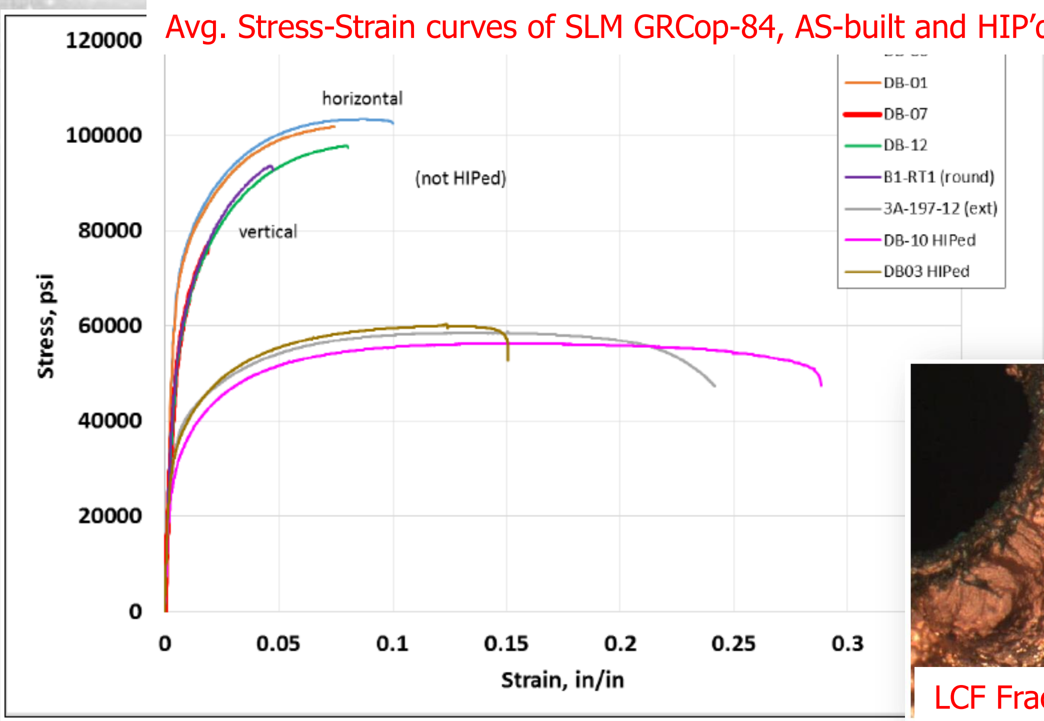




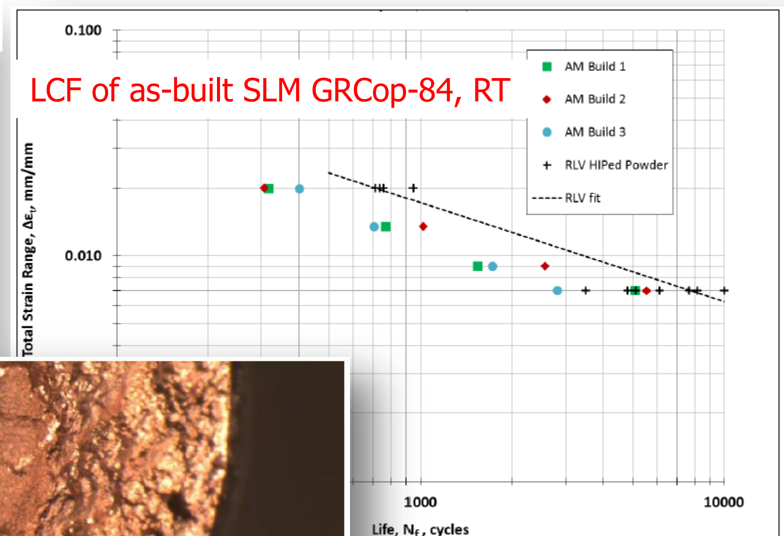
HIP process developed, well above annealing temperature (600°C / 1112°F)

Mechanical Properties of SLM GRCop-84

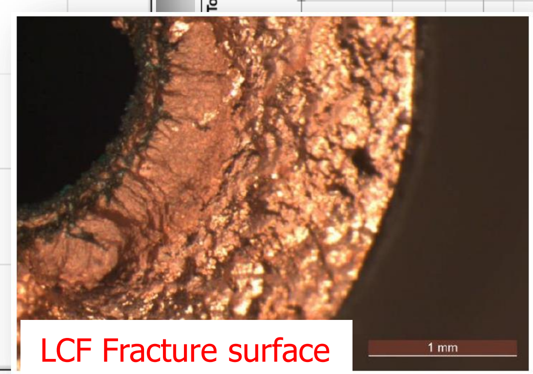
- Strength values similar to extruded GRCop-84, elongation increased significantly with HIP cycle
  - Differences observed in horizontal and vertical build orientations
- LCF testing completed in as-built condition (simulated channel)
  - Cracking initiated in as-built surface
  - LCF of as-built surface is lower than extruded, not unexpected



Avg. Stress-Strain curves of SLM GRCop-84, AS-built and HIP'd

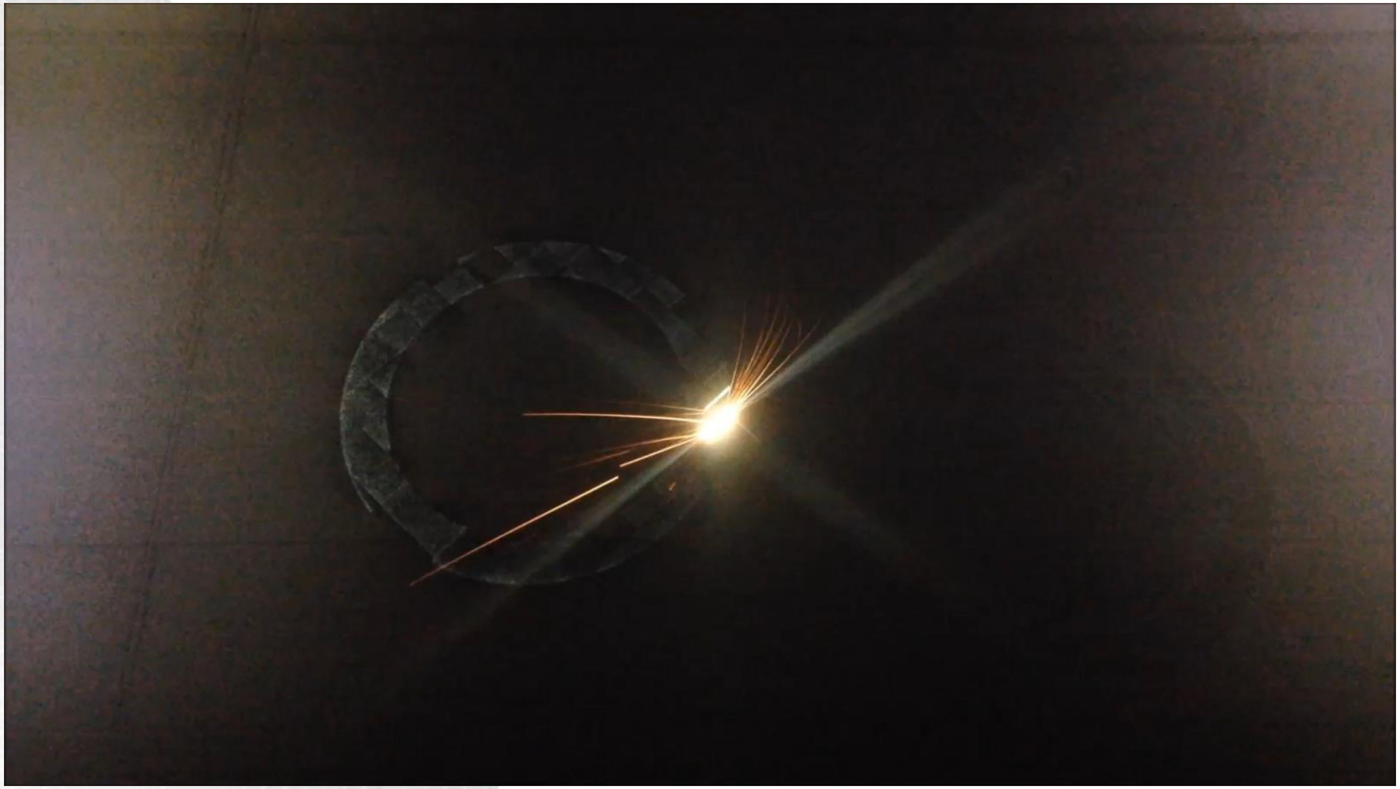


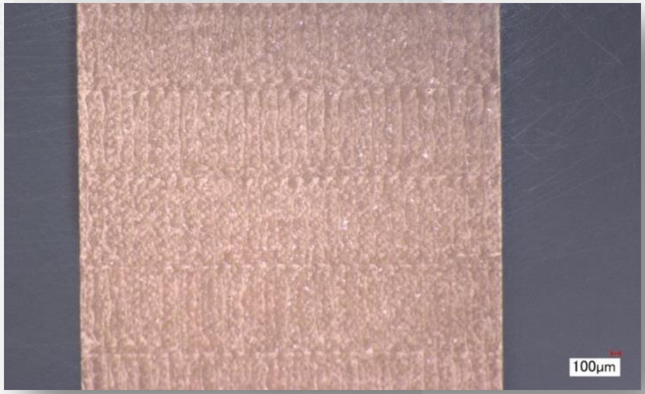
LCF of as-built SLM GRCop-84, RT

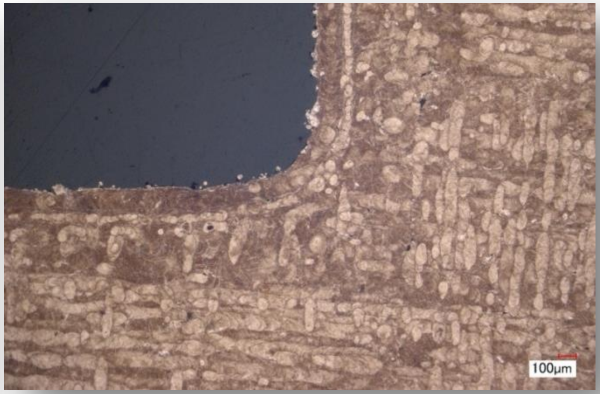


LCF Fracture surface

Additively Manufactured SLM Material is Unique







SLM GRCop-84 Copper-alloy in the as-built condition (ASTS, Huntsville)

Low Cost Upper Stage Propulsion (LCUSP) Program

Multi-Center NASA Program under NASA STMD Game Changing

MSFC

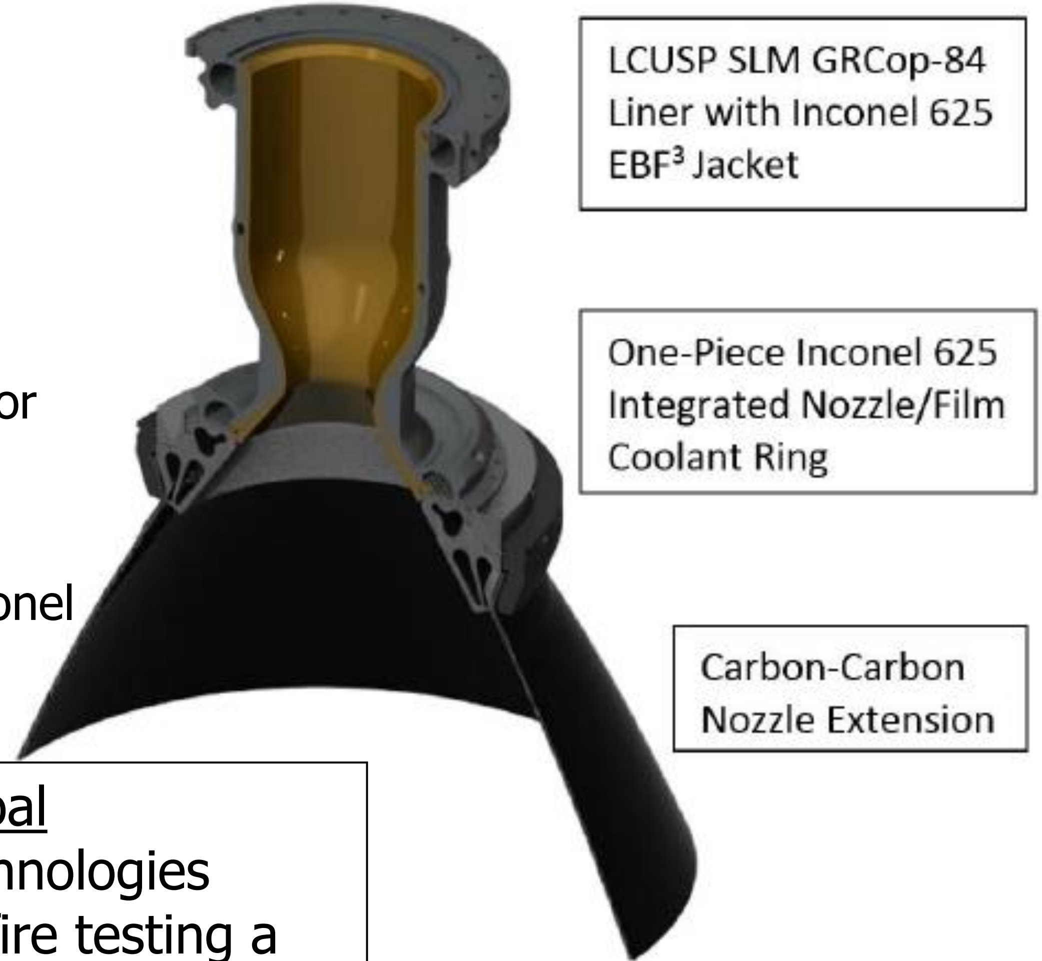
- Project Management
- Component Design
- SLM GRCop-84 Chamber Liner
- C-C Nozzle Development

GRC

Material Property & Characterization for SLM GRCop-84 & EBF^3 Inconel

LaRC

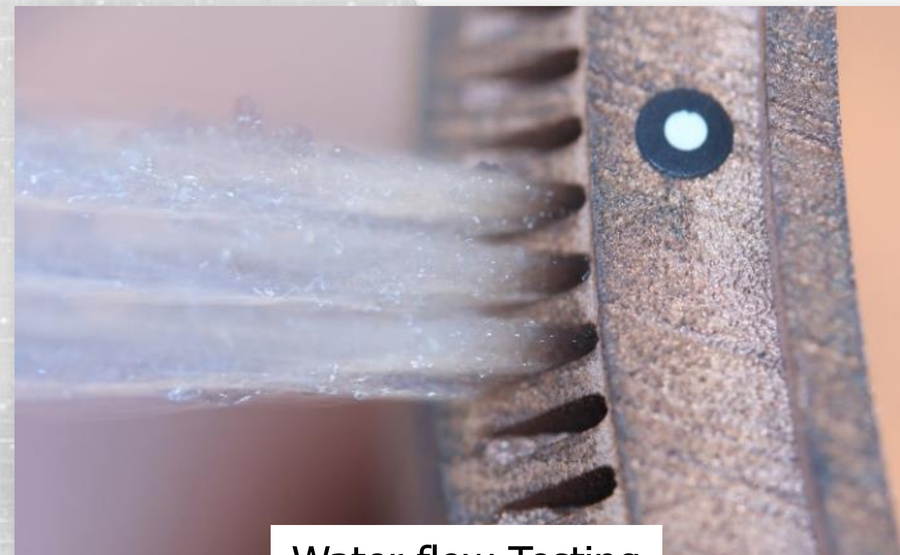
EBF^3 development to direct deposit Inconel jacket onto SLM GRCop-84 Liner



Program Goal

Advance select technologies by fabricating & hot-fire testing a 35K lb_f Regeneratively Cooled LOX/H2 Thrust Chamber Assembly (TCA)

LCUSP Chamber Fabrication



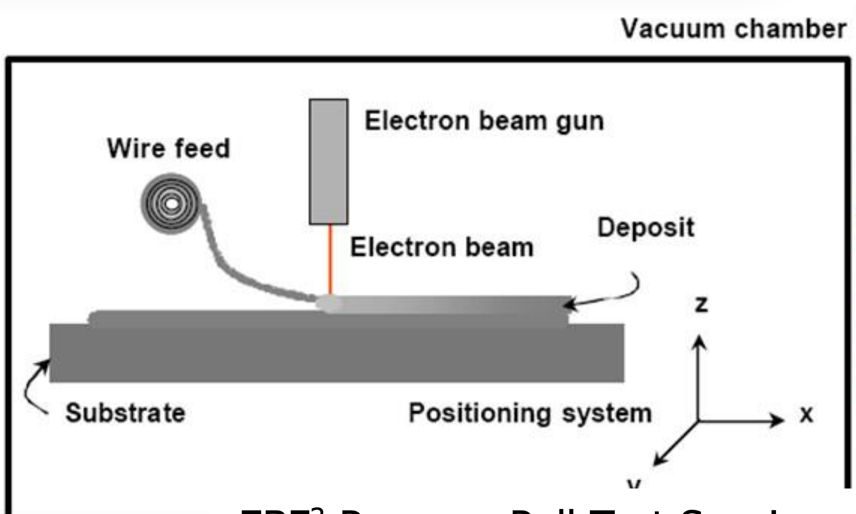
Water flow Testing

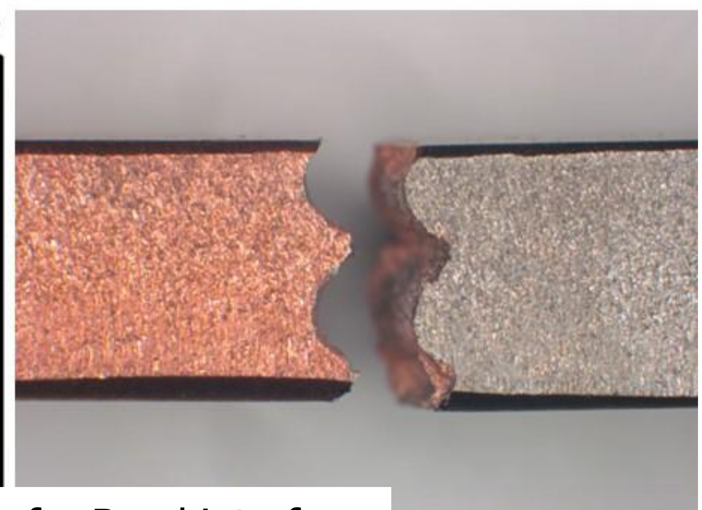
Print samples evaluated

- Hot wall thicknesses – successfully printed & proof tested
- Channel sizes as small as 0.030" with +/- .001" print tolerances

Mechanical evaluation samples

- Developed process using Electron Beam Freeform fabrication (EBF^3) to deposit Inco 625 directly onto SLM GRCop-84

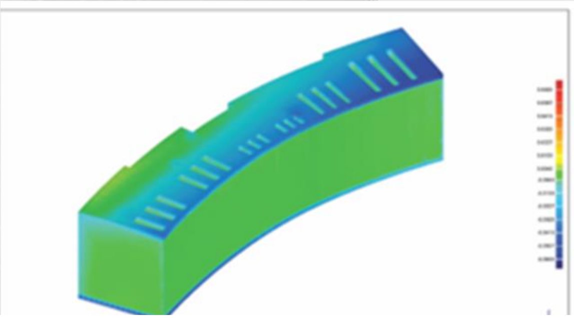




EBF^3 Process; Pull Test Specimen for Bond interface

LCUSP Chamber Fabrication

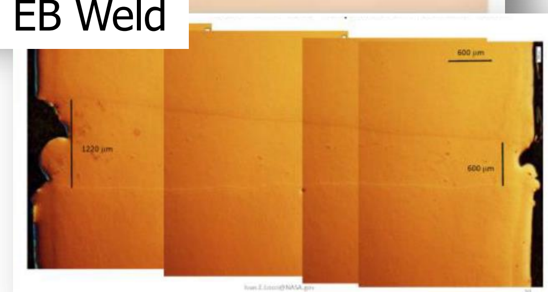
SLM GRCop-84 – Concept Laser M2 at MSFC



Wedge trial printed first – demo complex geometry
Structured light scan to compare print to model

Aft & Throat Sections on Build Plate
(with material samples)

Mid-section EB Weld

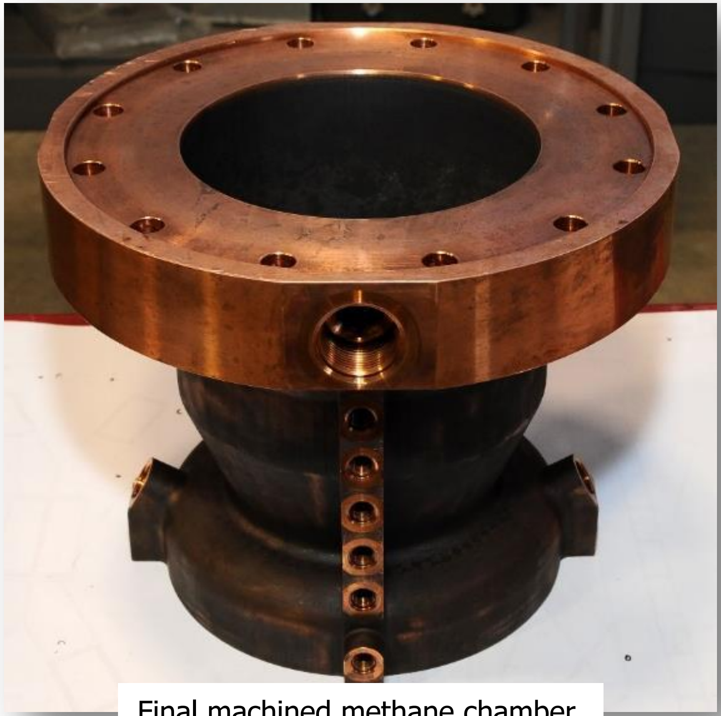


Sections Stacked; Mid-section weld
& EBF^3 Applied

AM GRCop-84 Regen (LCH4) Cooled Chamber

- SLM GRCop-84 at NASA-MSFC (Concept Laser M2)
- Multiple prints and design modifications required to produce successful part
  - Reshaping open volume manifold with proper angles
  - Developing support features
- Printed structure includes:
  - Inlet/exit manifold volumes, inlet boss for threaded interface
  - Integral instrumentation for discrete thermal and performance
  - Forward flange welded post-SLM processing

As-printed methane chamber

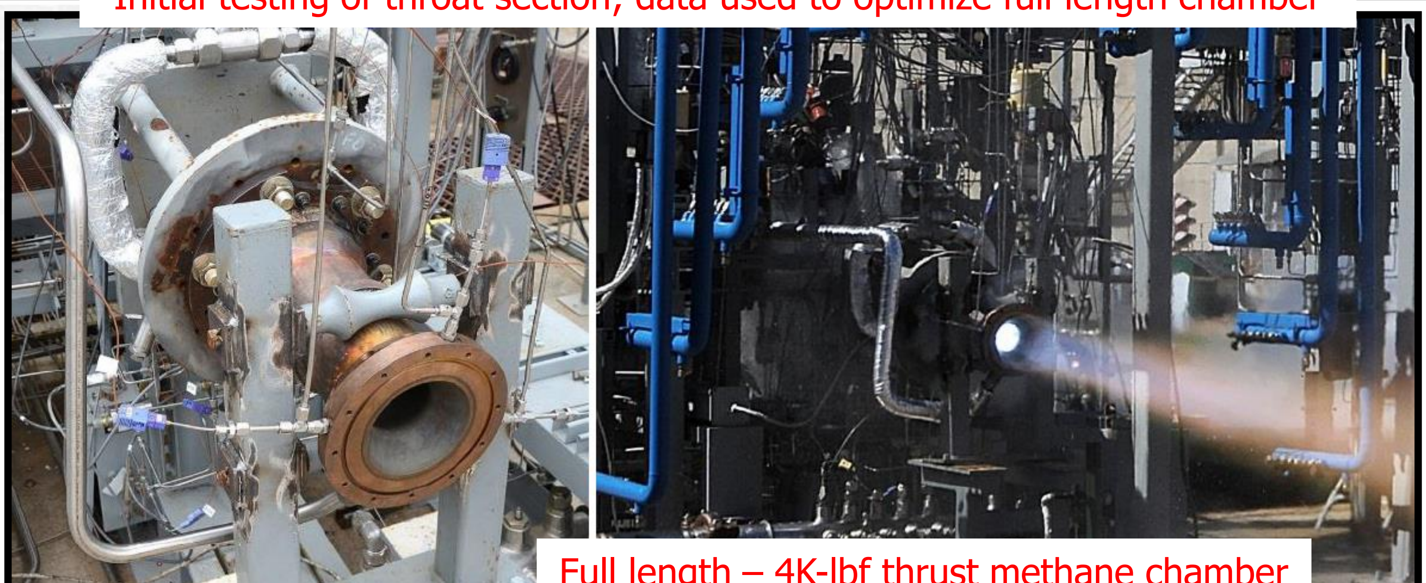


Final machined methane chamber

AM GRCop-84 LCH4 Cooled Chamber - Testing

Hot-fire testing with LCH4 cooling – Chambers in excellent condition post-test

Initial testing of throat section; data used to optimize full length chamber



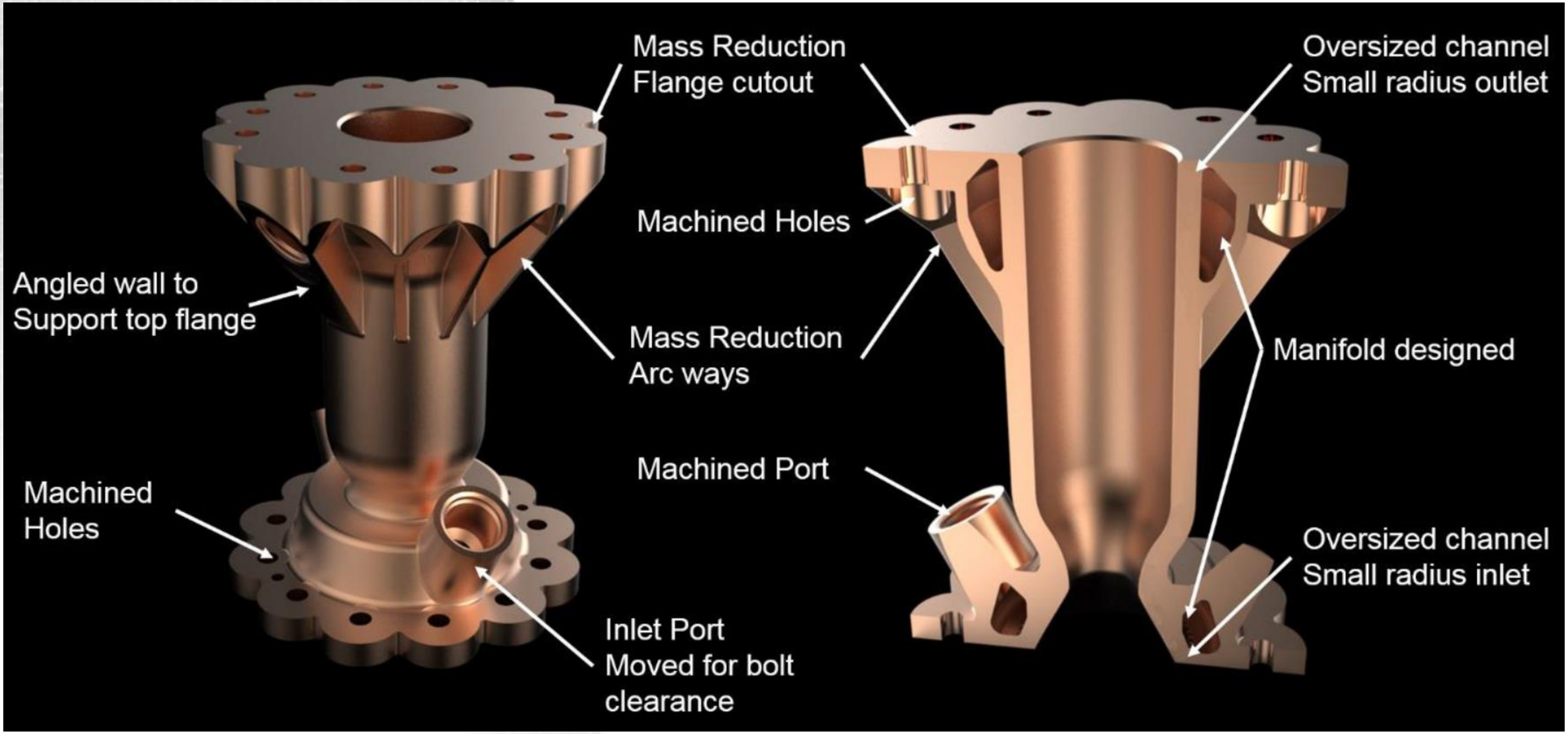
Full length – 4K-lbf thrust methane chamber

1.2K Additive Chamber Development

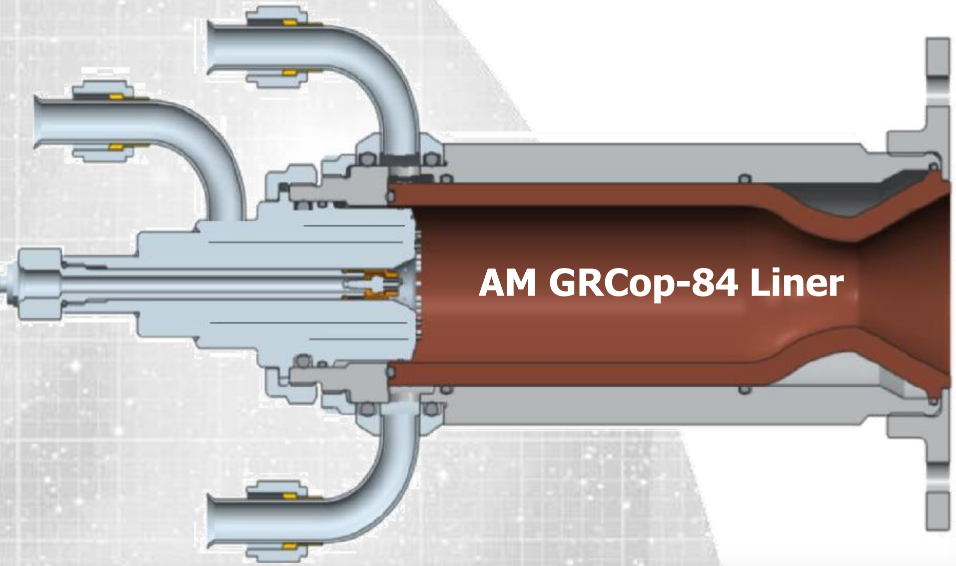
Designed to replace vintage subscale thrust chamber used for development testing since 1960's at MSFC.

Nominal Pc ~ 750 psig; Water cooled design supports LOX/H2, LOX/LCH4, LOX/RP1 injector testing.

Overall size allows for one piece build in available SLM machines.



1.2K AM Chamber Development – Hybrid Design



AM used to create GRCop-84 liner to slip into SS housing

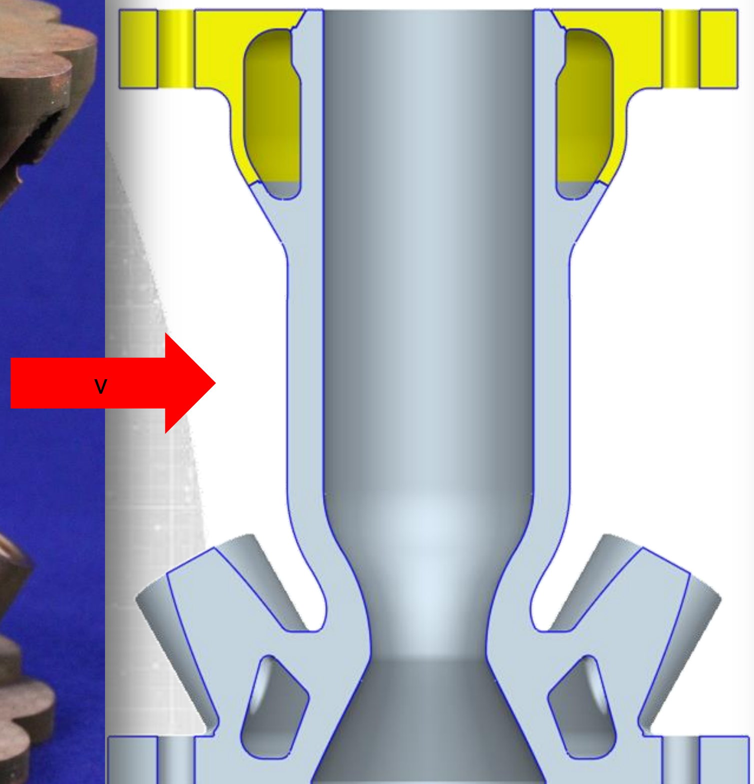
Hybrid Chamber with AM Liner Installed at MSFC TS115

Hot-fire tested with Carbon-Carbon Extension

During Subscale Nozzle Testing at MSFC AM GRCop-84 liner accumulated <u>2365 seconds (23 starts)</u> of LOX/H2 hot-fire exposure

1.2K AM 1-piece chamber design transitioned to 2-piece

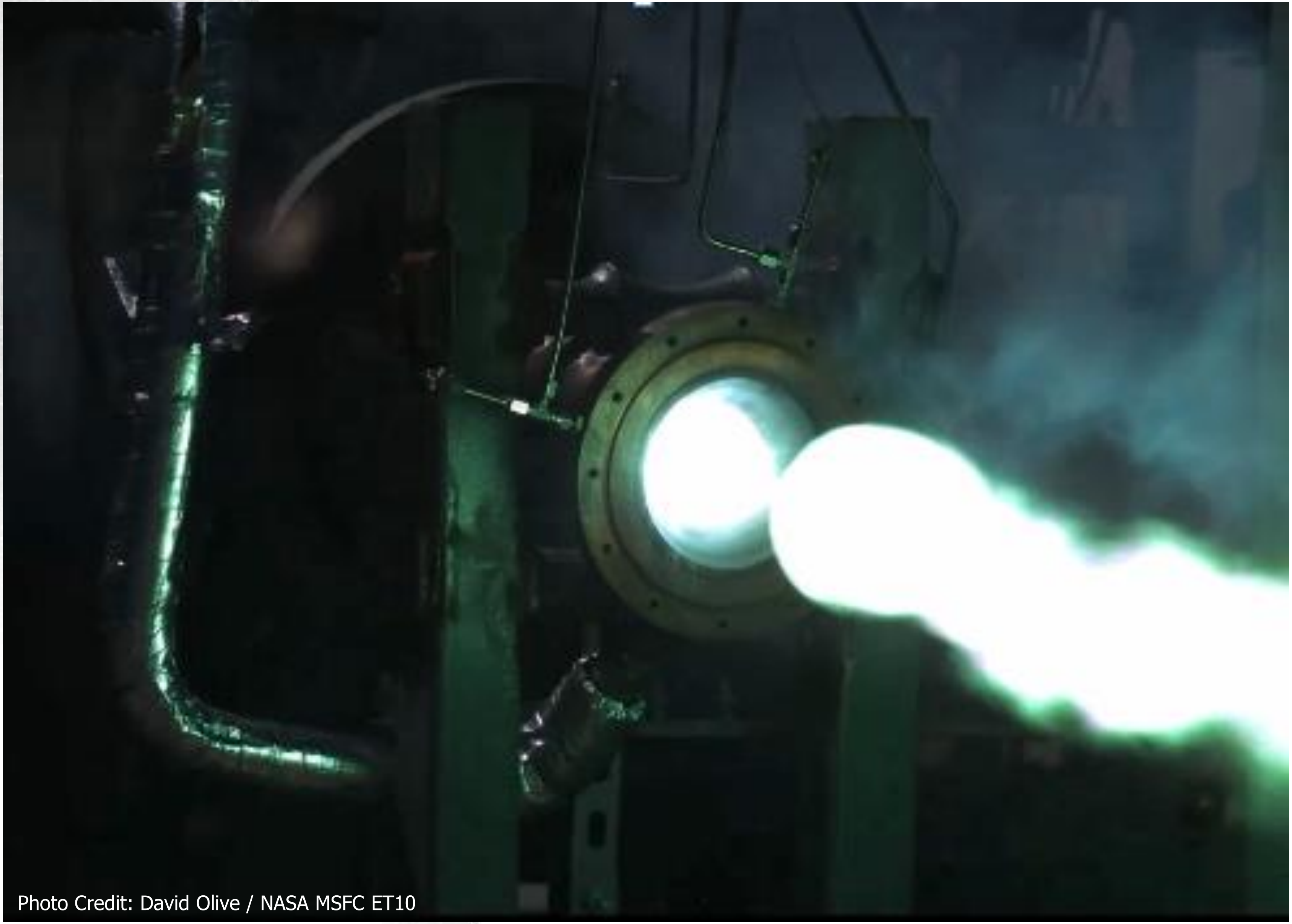
Allowed for easier removal of powder, simplified design, easier inspections, and reduced overall processing time



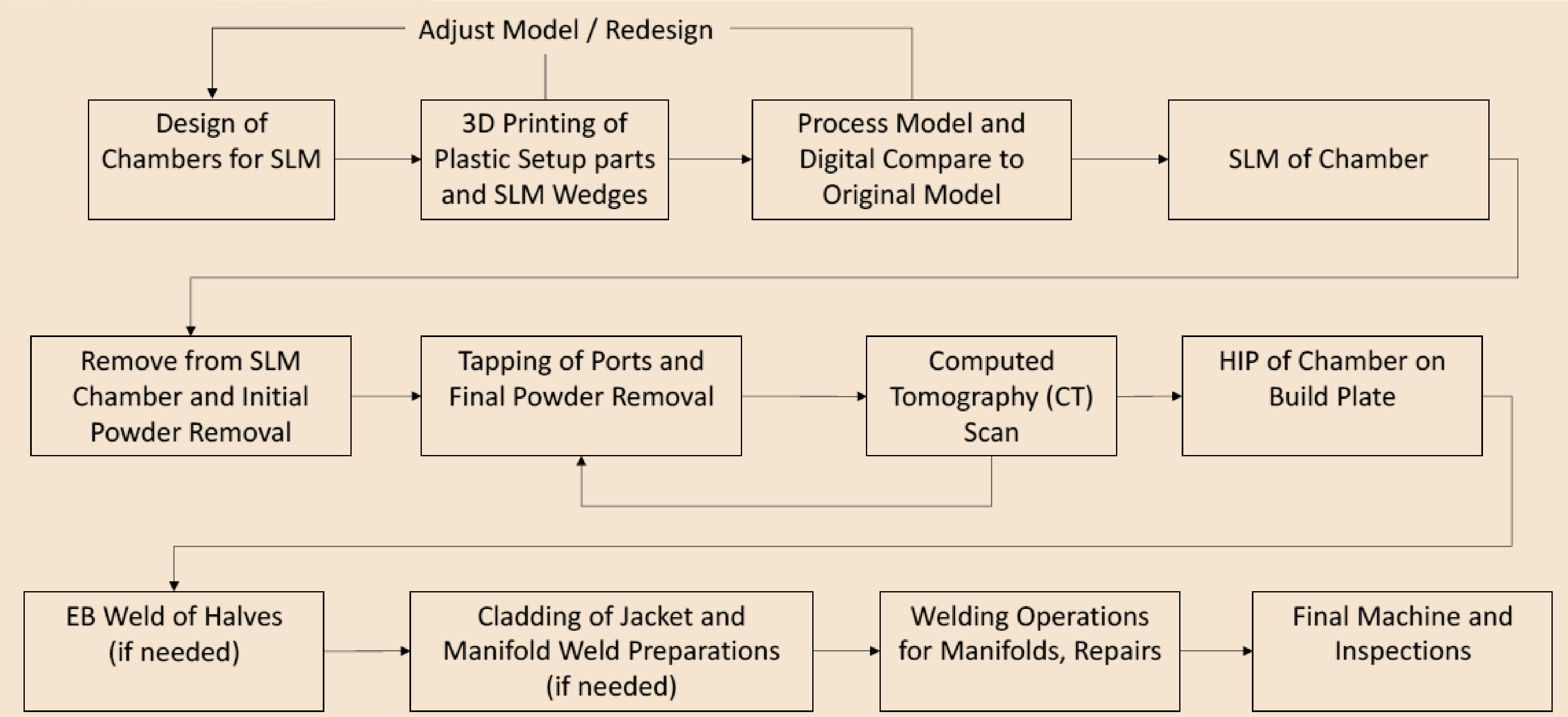
Printed at ASTS, Huntsville

Designs will evolve with additive through print trials, testing and design and analysis tools

Video of AM GRCop-84 Chamber Hot-fire Testing



Generic Flow for AM Chamber Fabrication Process



AM Chamber Lessons Learned – Design and Build

- Features maintain maximum 45˚ from vertical, less angle enables more successful builds
- Optimized AM design may not be single-piece
  - Welding multiple AM pieces
    reduces risk, eases powder removal, allows inspection of unique features
  - Inlet/outlet ports can easily be welded on;
    protruding features often experienced print failures
- Coolant channels –
  - Leave access for powder removal
  - Increase effective area to account for rough surfaces…
    600-800 μin are possible, although 200-300 μin is being demonstrated
  - Maintain access for interior powder removal
- Design copper EB weld joints for excess penetration and material heating
- Minimize thick areas to eliminate residual stresses (thick flanges can lift off the build plates)
- Part orientation is critical for coater blade, so optimize design to minimize potential damage
- Include enough stock for secondary bonding ops, run-outs, &/or final machining
- Builds can deform as vertical height increases further from the build plate
- Compare exported CAD files back to original model
- Structured Light (3D scanning) continuously throughout process

AM Chamber Lessons Learned – Design and Build

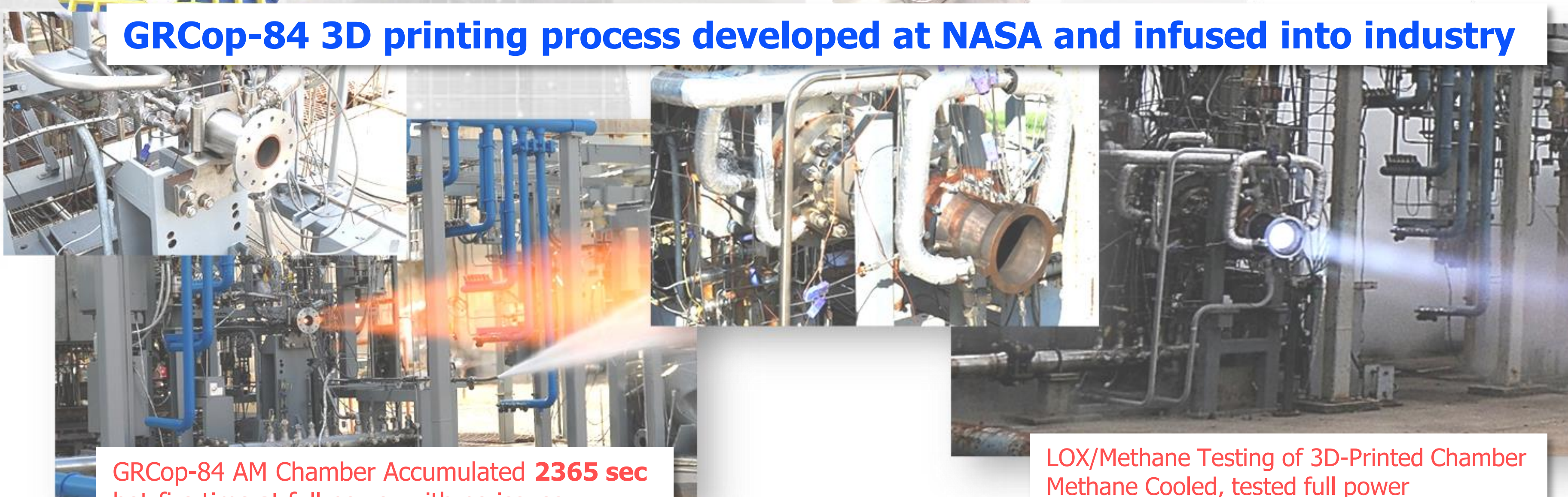
- Powder dose factor is critical as parts get taller.
- Design for Powder Removal
  - Physical efforts for powder removal can cause stress on the part.
    Mallet blows created microcracks in some components prior to HIP
  - High pressure (>500 psi) air/GN2 aided in powder removal
  - Alcohol evaporates and helped remove powder from select channels (although residual powder might clump when exposed to this fluid).
  - Include threaded ports that can be blocked off during powder removal to seal air flow properly (dry state/no oils).
  - CT scan continuously to verify powder removal.
  - Removing prior to HIP is ideal, but it can be removed after, since it does not all consolidate.
- Build direction is critical and overhangs may fail; 45 deg max build angles appear possible.
- Creating plastic models or building small wedges/slices to demonstrate parameters prior to metal designs can be helpful; identify potential issues prior to actual component builds.
- TIG braze repairs for debonds worked well; identical filler material is ideal.
  Include weld wire within SLML builds.
- Design for shrinkage/deformation in all process steps, such as welding and metal deposition.

Summary and Future Work for AM Copper Chambers

- **NASA has successfully demonstrated additive manufacturing of copper-alloy combustion chambers for liquid rocket engines**
  - Processing time and cost reductions have been demonstrated
- NASA has completed parameter development for GRCop-84 using additive manufacturing / selective laser melting
  - Parameters are available for industry use
  - Property development complete and reports will be available
- Design for additive manufacturing techniques have advanced with development of AM copper-alloys
- NASA has completed hot-fire testing of chambers in LOX/H2 and LOX/CH4
  - 2365+ seconds accumulated on LOX/H2 chambers
  - 35K LCUSP chamber tested in 2017
  - Methane chambers being continuously hot-fire tested
- Additional development to evaluate C-18150 and Glidcop
  - Increase scale available for chamber fabrication

QUESTIONS

GRCop-84 3D printing process developed at NASA and infused into industry



GRCop-84 AM Chamber Accumulated **2365 sec** hot-fire time at full power with no issues

LOX/Methane Testing of 3D-Printed Chamber
Methane Cooled, tested full power

Acknowledgments

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- MSFC Lander Office
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- Mike Shadoan
- John Vickers
- Linear Mold
- Stratasys
- ASTS, Huntsville

Backup

References

1 Kazaroff, J. M., and G. A. Repas. Conventionally cast and forged copper alloy for high-heat-flux thrust chambers. No. N-87-16902; NASA-TP-2694; E-3304; NAS-1.60: 2694. National Aeronautics and Space Administration, Cleveland, OH (USA). Lewis Research Center, 1987.
2 United Technologies Corporation. STE Thrust Chamber Technology Program. Final Report under Contract NAS8-37490. NASA CR-193919. October 31, 1993
3 Kazaroff, J.M. and Pavli, A.J. Advanced tube-bundle rocket thrust chambers. Journal of Propulsion and Power, 8(4), pp.786-791. (1992)
4 Gradl, P. "Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles", 52nd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2016-4771)
5 Popp, M., & Schmidt, G. (1996). Rocket engine combustion chamber design concepts for enhanced life. In 32nd Joint Propulsion Conference and Exhibit (p. 3303).
6 de Groh, H. C., Ellis, D. L., & Loewenthal, W. S. (2008). Comparison of GRCop-84 to other Cu alloys with high thermal conductivities. Journal of materials engineering and performance, 17(4), 594-606.
7 Pandey, A. B. "MPSA061. 2 High Strength Copper Alloys for Rocket Engine Applications." (2006).
8 Pells, G. P., and M. Shiga. "The optical properties of copper and gold as a function of temperature." Journal of Physics C: Solid State Physics 2, no. 10 (1969): 1835.
9 M. F. Ashby: Oxide Dispersion Strengthening, Proc. 2nd Bolton Landing Conf., G.S. Ansell, ed., Gordon and Breach, New York, NY, 1968, p. 143.
10 Protz, C., Bowman, R., Cooper, K., Fikes, J., Taminger, K., Wright, B. Additive Manufacturing of Low Cost Upper Stage Propulsion Components. Joint Army-Navy-NASA-Air Force (JANNAF) Liquid Propulsion Subcommittee (LPS) Advanced Materials Panel (AMP) Additive Manufacturing for Propulsion Applications Technical Interchange Meeting (TIM); 3-5 Sept. (2014.)
11 Gradl, P.R., Greene, S.E., Valentine, P., Crisanti, M. Subscale Carbon-Carbon Nozzle Extension Development and Hot Fire Testing in Support of Upper Stage Liquid Rocket Engines. Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.
12 Barnett, G., Bullard, B. Summary of Liquid Oxygen/Hydrogen, Direct Metal Laser Sintering Injector Testing and Evaluation Effort at Marshall Space Flight Center, 62nd JANNAF Propulsion Meeting and Joint Meeting of the 10th Modeling & Simulation Subcommittee (MSS) / 8th Liquid Propulsion Subcommittee (LPS) / 7th Spacecraft Propulsion Subcommittee (SPS), Nashville, TN, June 1-5, 2015
13 Bullard, B. Design, Fabrication and Hot-fire Test of an Additively Manufactured Liquid Oxygen/Hydrogen 35-klbf Swirl Coaxial Element Injector. Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.
14 Carter, R. W., Ellis, D.L., Locci, I.E., Evans, L.J., Lerch, B., Jones, Z.C., Cooper, K. G. Evaluation of GRCop-84 Produced Using Selective Laser Melting, 62nd JANNAF Propulsion Meeting and Joint Meeting of the 10th Modeling & Simulation Subcommittee (MSS) / 8th Liquid Propulsion Subcommittee (LPS) / 7th Spacecraft Propulsion Subcommittee (SPS), Nashville, TN, June 1-5, 2015.
15 Watson, J.K., Taminger, K.M.B., Hafley, R.A., and Petersen, D.D., Development of a Prototype Electron Beam Freeform Fabrication System, Proceedings of 13th. SFF Symposium, 458-465, (2002).
16 Taminger, K.M.B. and Hafley, R.A. Electron Beam Freeform Fabrication: A Rapid Metal Deposition Process, Proceedings of the 3rd Annual Automotive Composites Conference, (2003).
17 Elam, S.K; and Sprader, C.L: Test Summary Report for Test Program P2514-Six-Inch Liquid Oxygen/Liquid Methane Injector Demonstration. NASA TM 2008-215470. August 2008.
18 Elam, S.K; and Sprader: LOX/LCH4 Technology Demonstration - P8006A, NASA TM2009-216268, December 2009.
19 Elam, S.K.; Protz, C.; and Reynolds, D: Design and Demonstration of a Liquid Oxygen/Liquid Methane (LOX/LCH4) Impinging Injector. 54th JANNAF Propulsion Meeting, Denver, Colorado, May 2007.

References

20 Greene, S.E., "Summary of LOX/CH4 Technology Development at NASA/MSFC", 62nd JANNAF Propulsion Meeting and Joint Meeting of the 10th Modeling & Simulation Subcommittee (MSS) / 8th Liquid Propulsion Subcommittee (LPS) / 7th Spacecraft Propulsion Subcommittee (SPS), Nashville, TN, June 1-5, 2015

21 Greene, S.E., Protz, C., Garcia, C., Goodman, D., Baker, K., "Additively Manufactured Combustion Devices Components for LOX/Methane Applications", JANNAF AM for Propulsion Applications Technical Interchange Meeting, August 2016, Huntsville, AL.

22 Greene, S.E., Baker, K., "META4 – Methane Engine Thrust Assembly for 4K lbf", JANNAF In-Space Chemical Propulsion Technical Interchange Meeting, April 2017, Huntsville, AL.

23 Gradl, P.R., Brandsmeier, W. Alberts, D., Walker, B., Schneider, J.A. Manufacturing Process Developments for Large Scale Regeneratively-cooled Channel Wall Rocket Nozzles. Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

24 Elam, S.K., Sprader, C., "Test Summary Repot for Program P2359 "Cycle Life Testing on a VPS GRCop-84 Chamber Liner". NASA TR TD71-03-01. September 18, 2003.

25 Genson, K. "Metal Additive Manufacturing Structures for CAD/PAD Applications. NSWC IHEODTD. 11th CAD/PAD Technical Exchange Workshop. May 25, 2016.

26 Carter, R., Draper, S., Locci, I., Lerch, B., Ellis, D., Senick, P., Meyer, M., Free, J., Cooper, K., Jones, Z. Materials Characterization of Additively Manufactured Components for Rocket Propulsion. GRC-E-DAA-TN26762. International Astronautical Congress; 66th; Jerusalem; Israel. 12-16 Oct. (2015).

27 Gradl, P.R., Valentine, P.E. "Carbon-Carbon Nozzle Extension Development in Support of In-Space and Upper-Stage Liquid Rocket Engines" 53nd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. Atlanta, GA. July 10-12. (2017).

28 S. Elam, R. Holmes, T. McKechnie, R. Hickman, T. Pickens, "VPS GRCop-84 Chamber Liner Development Efforts", JANNAF 52nd Joint Propulsion Meeting, 1st Liquid Propulsion Subcommittee, May 2004, Las Vegas, NV.