Having a Come-Apart: Lessons Learned from Additively Manufactured Hardware Failures

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National Aeronautics and Space Administration (NASA)

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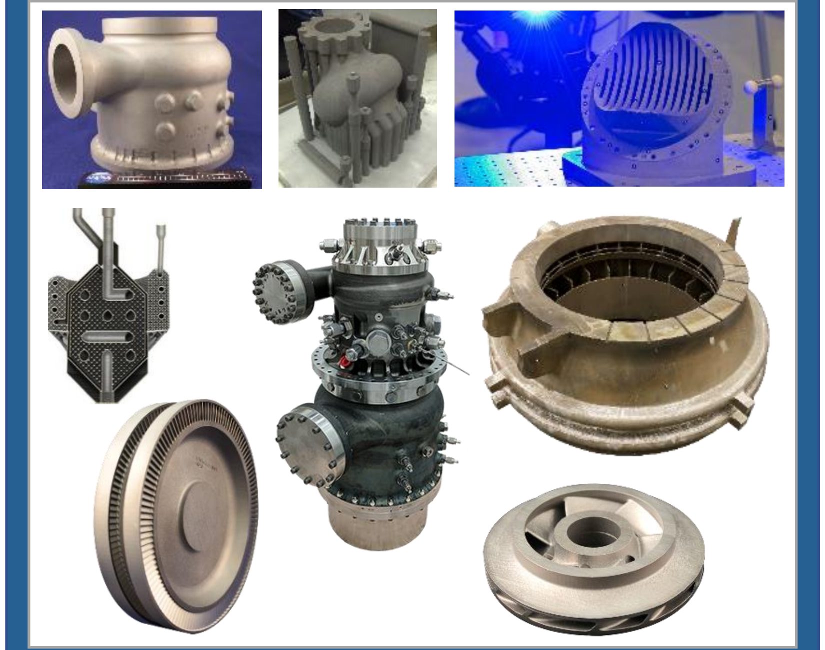
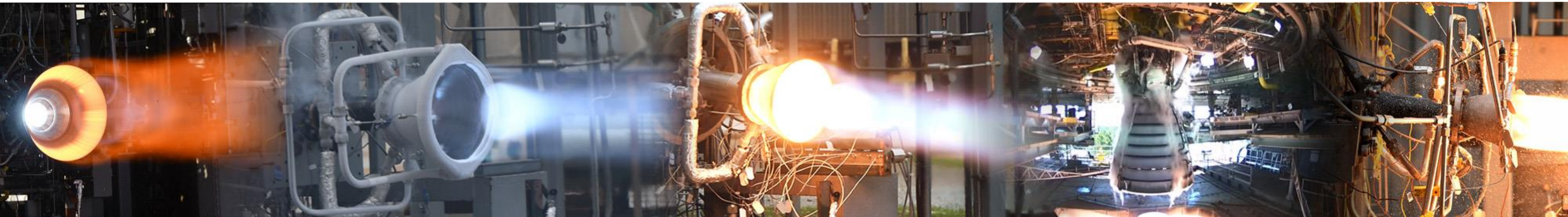
AM at NASA for Rocket Engine Applications

Laser Powder Bed Fusion (L-PBF) Copper Alloys combined with other AM processes to provide bimetallic

Directed Energy Deposition

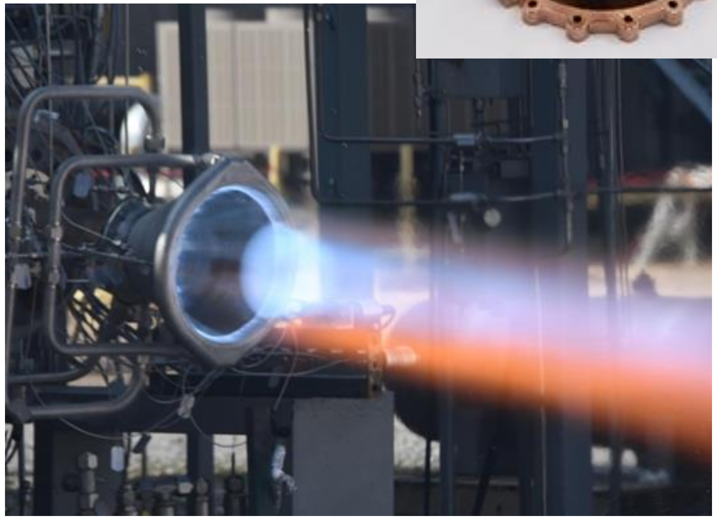


L-PBF of complex components, new alloy developments for harsh environment



LLAMA Project Overview

- **L**ong **L**ife **A**dditive **M**anufacturing **A**ssembly (LLAMA) project goals
  - Fabrication and testing of additively manufactured high duty cycle (>50 starts) lander engine hardware (highly instrumented).
  - Determine performance of GRCop-42 alloy used for the thrust chamber.
  - Disseminate data to industry partners.
- GRCop-42
  - Copper-based (Cu-Cr-Nb) alloy w/ Cr2Nb precipitates for dispersion strengthening.
  - Developed for high heat flux environments such as combustion chambers.
- LLAMA hardware and test program
  - Laser Powder Bed Fusion (L-PBF) GRCop-42 chambers.
  - Carbon-Carbon (C-C) and Direct Energy Deposition (DED) NASA HR-1 nozzles.
  - Additively manufactured L-PBF injectors (Alloy 625 and 718).
  - Two separate test phases completed in February 2021.



LLAMA Hardware Overview

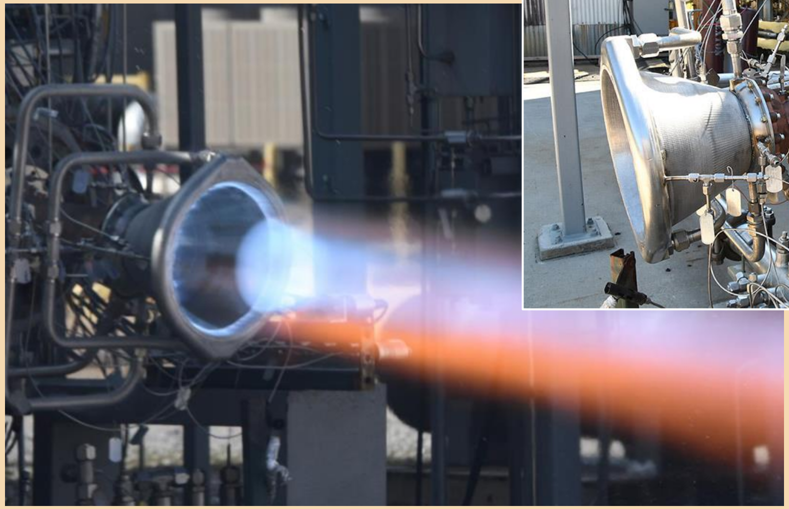
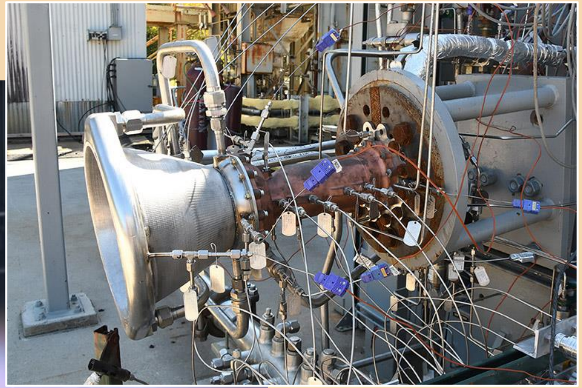
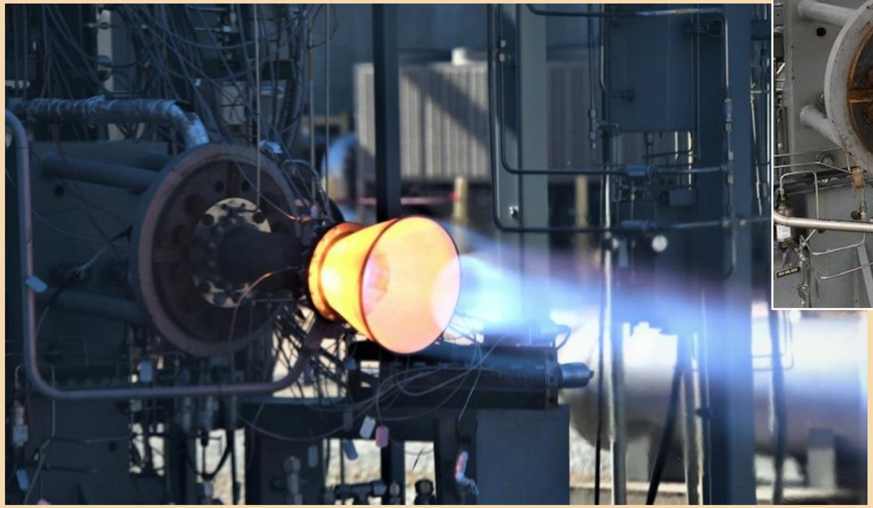
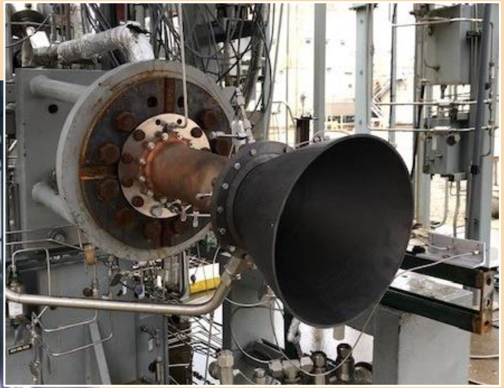

L-PBF GRCop-42 Chambers

DED of Integral Channels

Final DED Regen Nozzle


Carbon-Carbon Nozzles


Additive Injectors

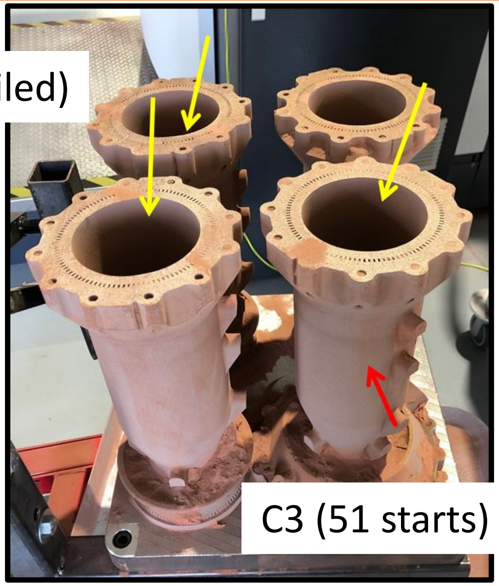
7k-lb$_f$ GRCop-42 chamber and Composite Nozzle

Anomaly Background

- Tested in early 2021
- Location: MSFC Test Stand 115
- L-PBF GRCop-42 chamber
  - 9 starts and 83.3 seconds total before separation.
  - No issues observed in prior chamber test data.
- Carbon-Composite experimental nozzle
  - Untested and possessed a noticeable crack.
  - Deemed an acceptable risk.

Multiple L-PBF Chambers Built and Tested

- EOS M400 L-PBF printer
  - Certified GRCop-42 powder lot
  - 4 chambers on the build
    - 3 w/ identical designs for LLAMA
- Computed Tomography Scans
  - No observations from data prior to HIP
  - Did not specifically look for witness lines – focused on powder removal verification
- Post-processing
  - C1 – HIP, EB weld manifold, exterior polishing
  - C2 – HIP, EB weld manifold
  - C3 – HIP, EB weld manifold, chemically milled

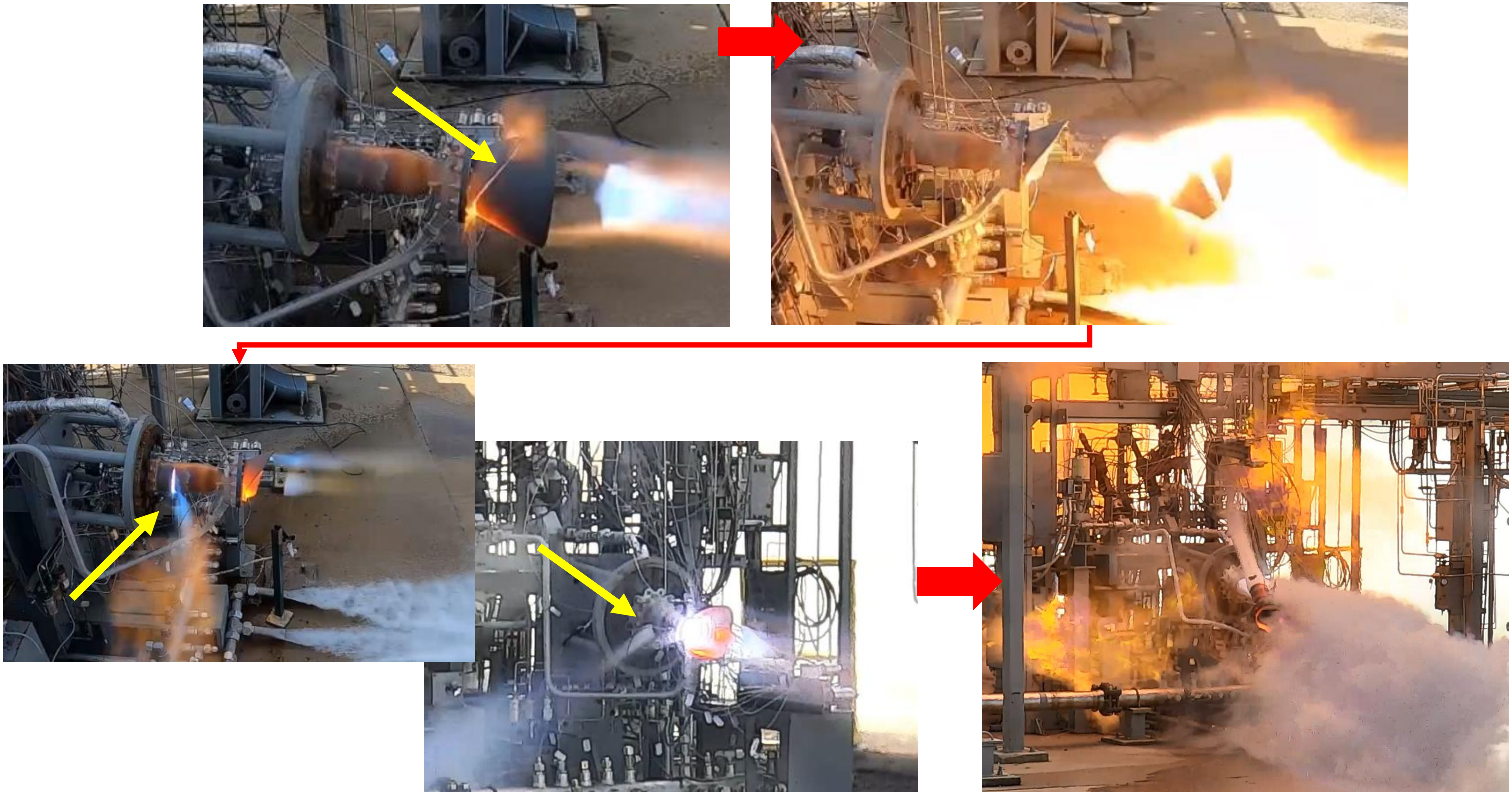


C1 - Untested

C3 - 51 Starts

C2- Separated

Anomaly Timeline



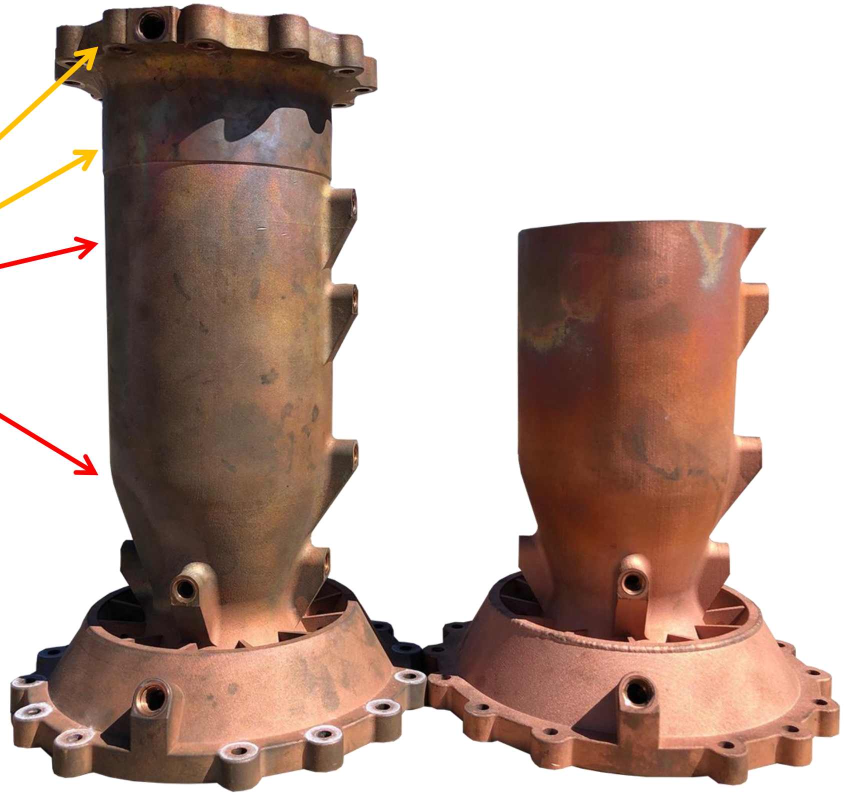
Chamber Process Investigation

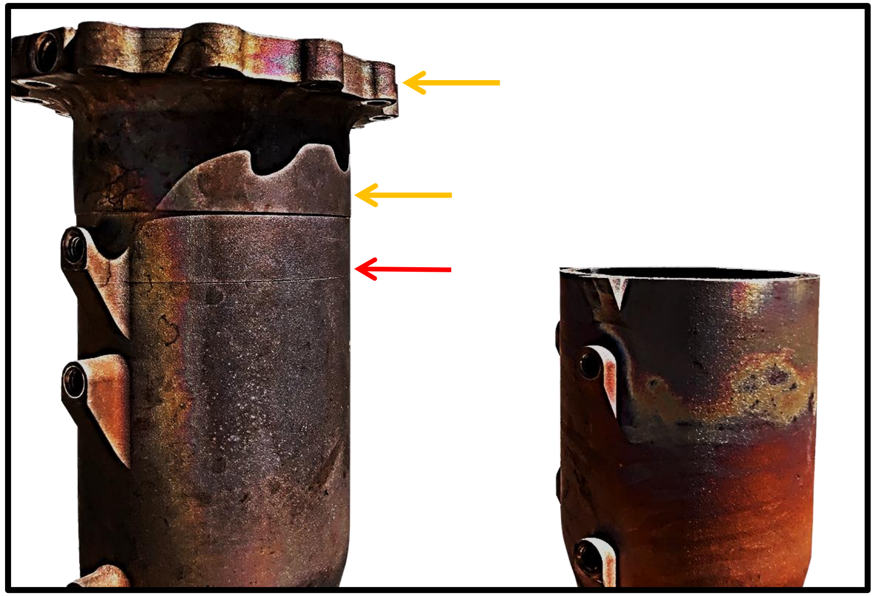
<u>Goal:</u> Determine the root cause and impacts of build interruptions that occur following stop and start during the chamber build process. Areas of concern were at witness lines (chamber with 51 cycles) and separation (back-up chamber) during testing.

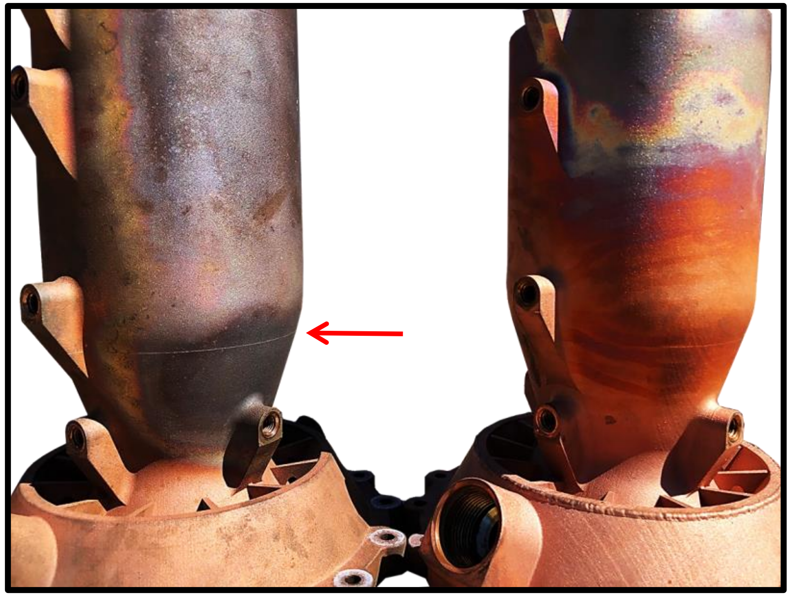
1. Created a plan to evaluate this process issue.
2. Evaluated fabrication process and build records of the chambers.
3. Completed NDE and evaluations of chambers.
   - Digital images, microscopic images, and measurements for **witness line** reference locations.
   - Fracture surface of chamber C2 examined for any noticeable defects or fracture points.
   - MSFC NDE team completed CT scan of all three chambers.
4. Sectioned chambers for metallography.
5. Completed metallography to understand region of concern and “good” regions.
   - Fabricated tensile and fatigue specimens with **representative witness lines.** *(full length specimens from original build not available)*
6. Completed tensile and fatigue testing of material from chambers (micro) and witness specimens.
7. Completed fractography and microstructural characterization of (sectioned) chambers and samples.
8. Reporting of lessons learned and recommendations.

Witness Lines Matched to Build Timeline

Date	Time	Event	Slice Number	Height (in)	Restart	Exposed to Air?
1/16/2020		Build Completion	8889	14		
1/14/2020	5:10	Power Outage	8764	13.805	7:01	No active purge, chamber sealed
1/11/2020	14:13	Brownout	8084	12.731	14:25	No active purge, chamber sealed
1/8/2020	17:41	Empty Overflow	6562	10.332	18:47	Exposed to air
1/4/2020	12:48	Empty Overflow	2968	4.674	13:14	Exposed to air
12/30/2019		Build Start	0	0		



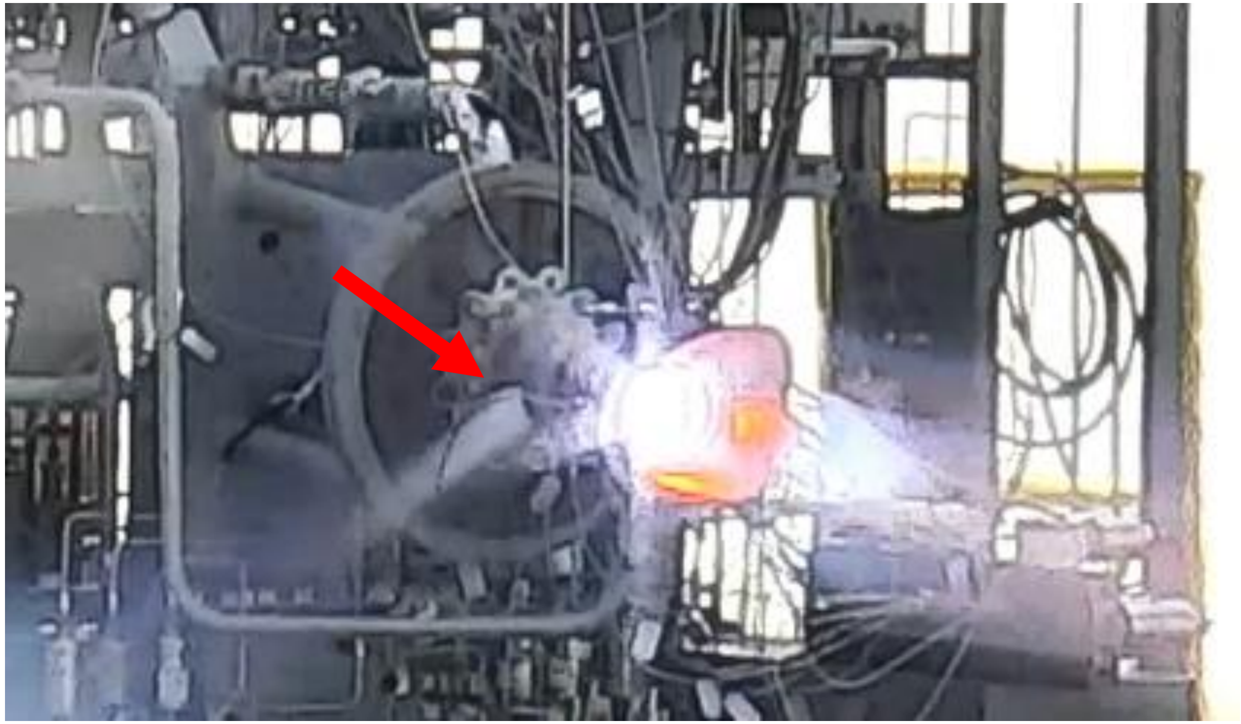




Color adjusted in photos to highlight witness lines

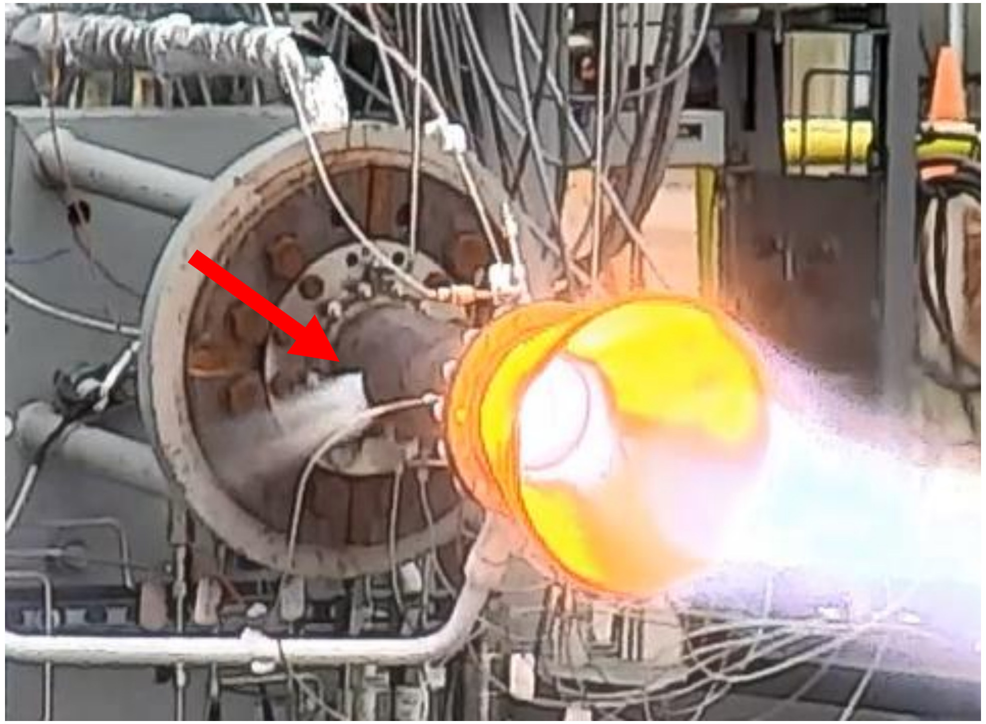
C3 & C2 Separation Comparison

PK129 Test 18



C2 - separated chamber (9 starts)

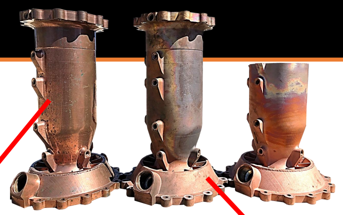
PK129 Test 13



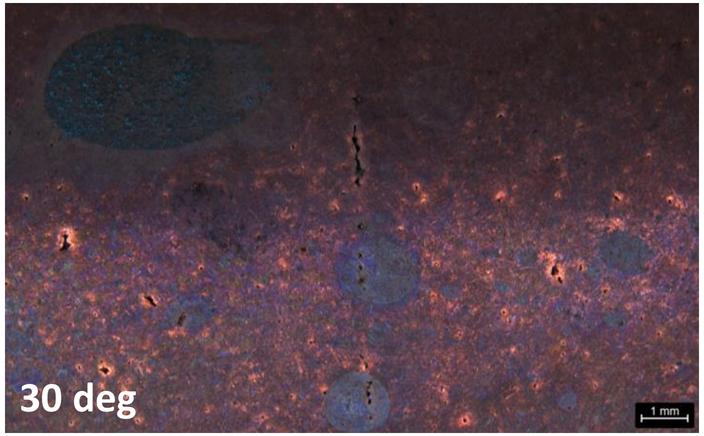
C3 - 51 start chamber (full life cycle)

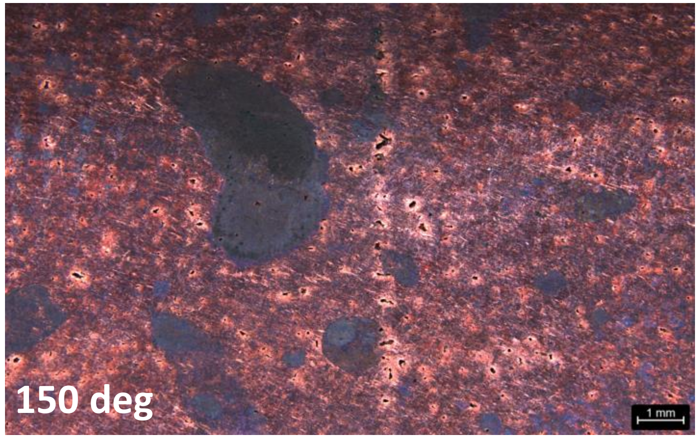
Optical Images of Chambers Post-Test

- Unpolished external surfaces.
- Top (power outage) and bottom (powder overflow) witness lines did not appear to have many detrimental defects.
- Middle witness line on chamber 1, there were some large lack of fusion defects that appeared to line up with the restart line.
- Chamber 3 – no defects visible at the surface beyond the crack that had already developed after test.

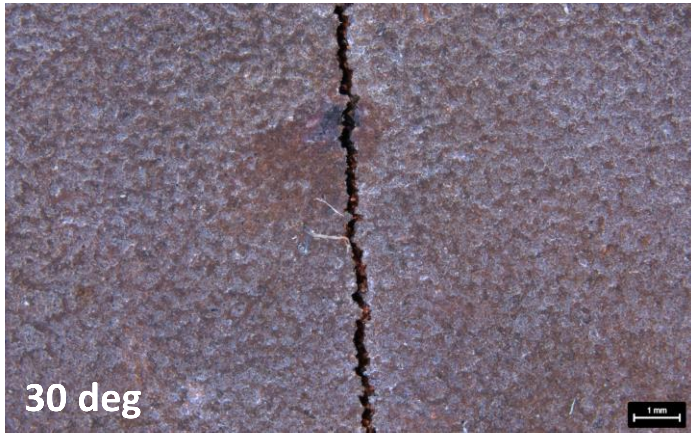


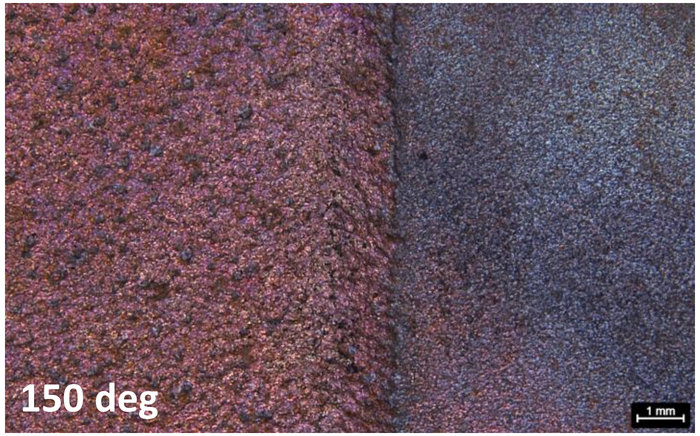
Middle witness line: C1 (untested)
Surface was polished using CMP



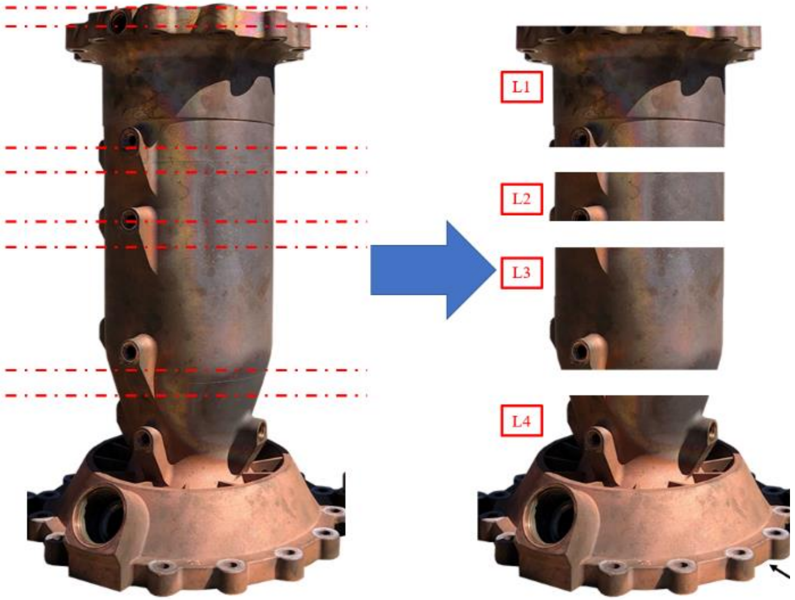


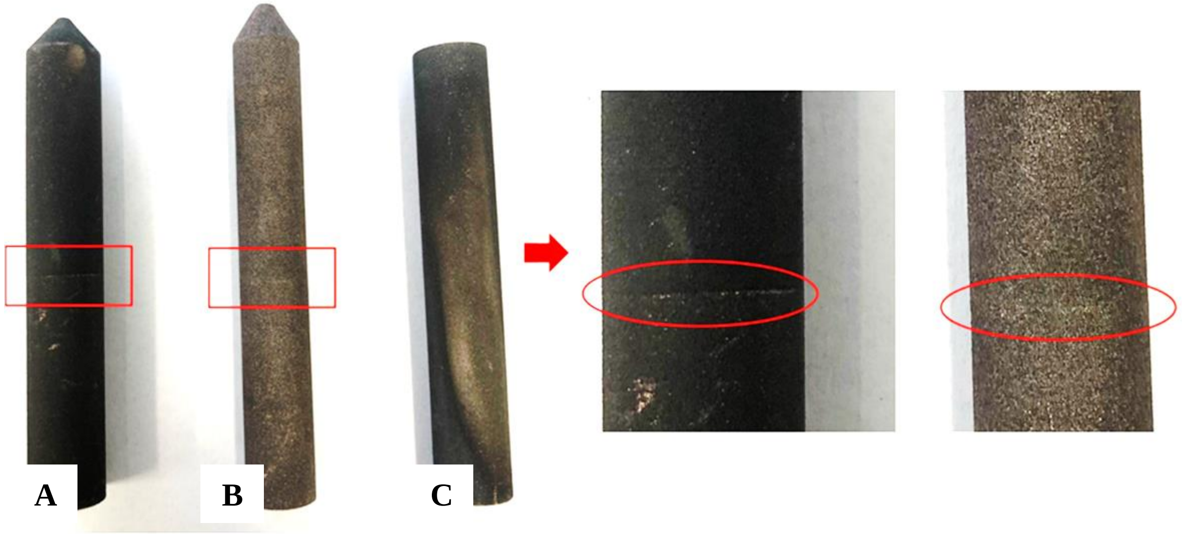
Middle witness line: C3 (51 starts)





Test Specimens: Chamber Sectioning, Test Bars

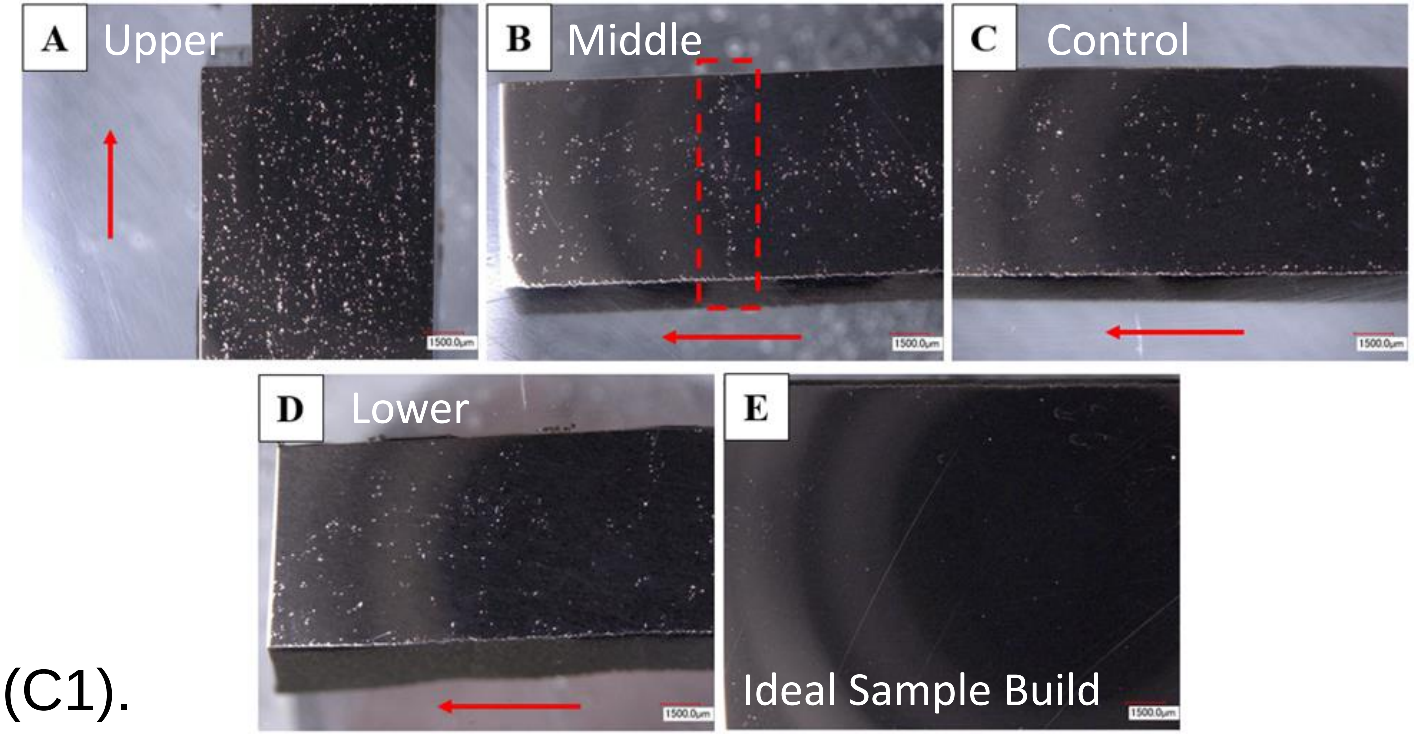




Bar	Chamber Restart Replicated	Witness Line Replicated	Restart
A	None	Control Section	None
B	Empty Overflow	Middle and Lower	Chamber Open
C	Power Outage	Upper	Chamber Closed

Optical Images of Chamber Sections

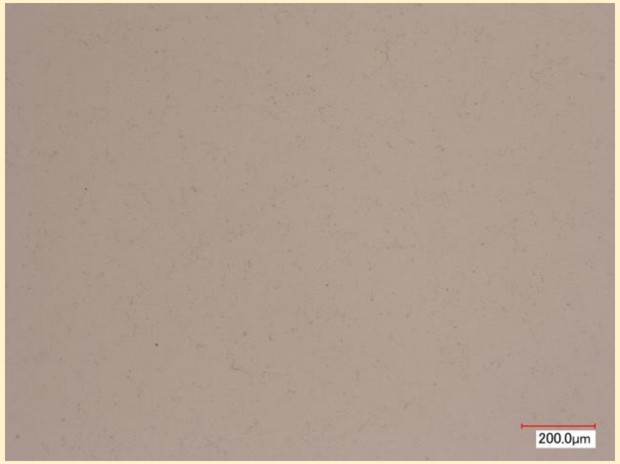
Label	Section	Porosity
A	Upper Witness Line	0.748%
B	Middle Witness Line	1.906%
C	Control Section	0.511%
D	Lower Witness Line	1.743%
E	Tensile Bar	0.006%



- Samples taken from un-tested chamber (C1).
- Tensile bar built separately as part of investigation.
- Proper HIP of chambers was confirmed.
- Porosity is evident throughout samples.
- Clear congregation of porosity around witness lines.
- Porosity reduces load bearing capacity (reduced area) and can act as stress concentrators/crack initiators.

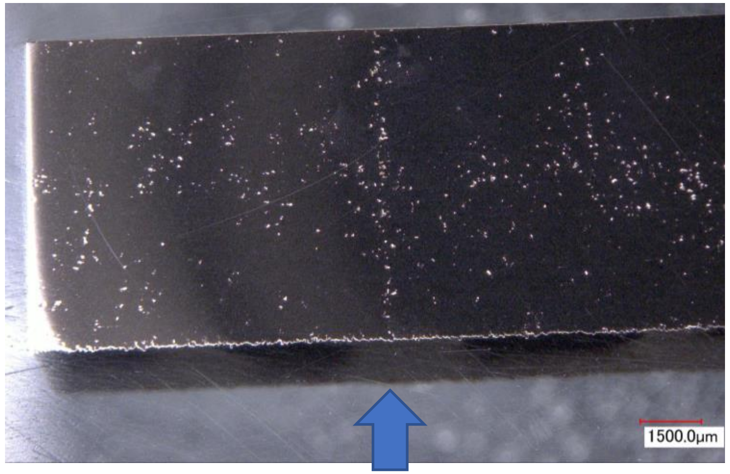
Optical Images of Section

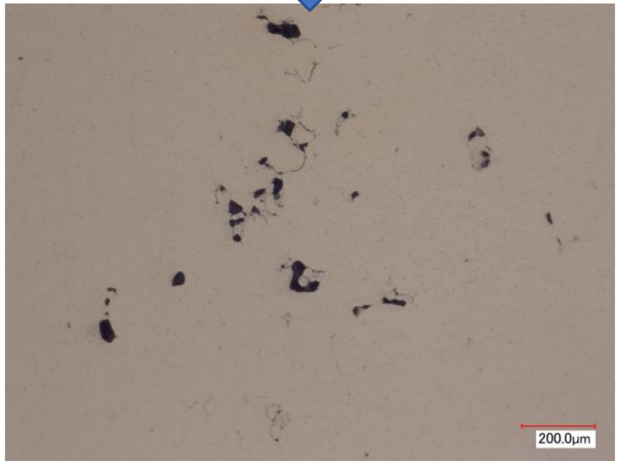
Witness Bar Control with identical restart



200x

C1 (Leaked), Middle Witness Line





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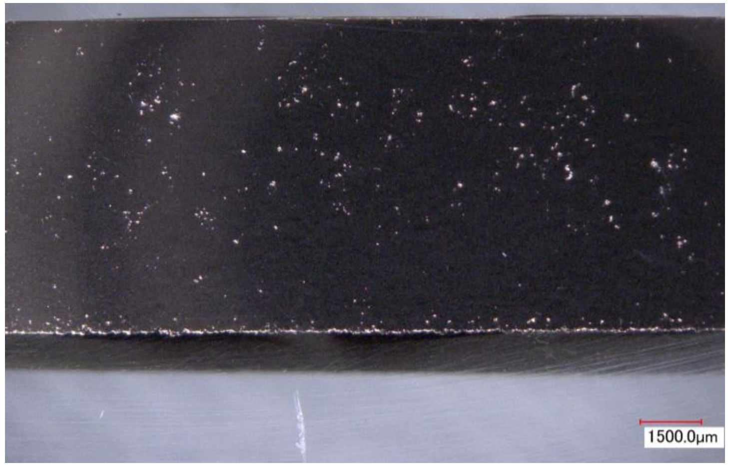
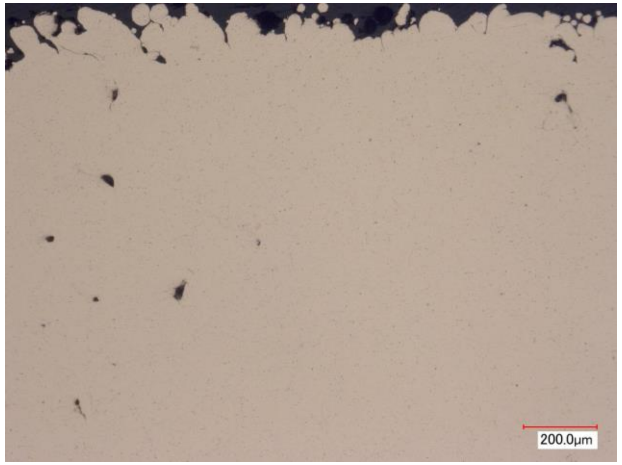
C1 (Leaked), Chamber Control





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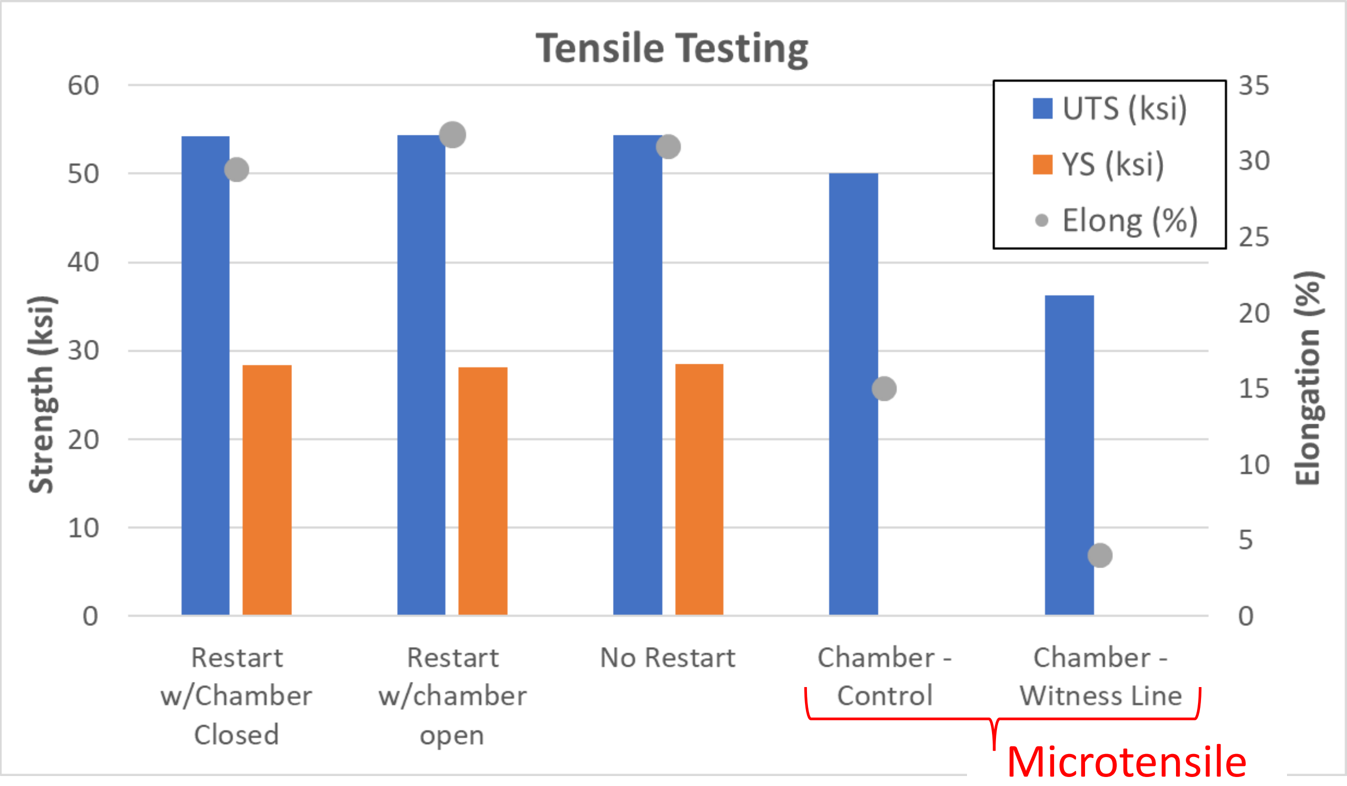
Build Direction

Combined Microtensile & Tensile Results

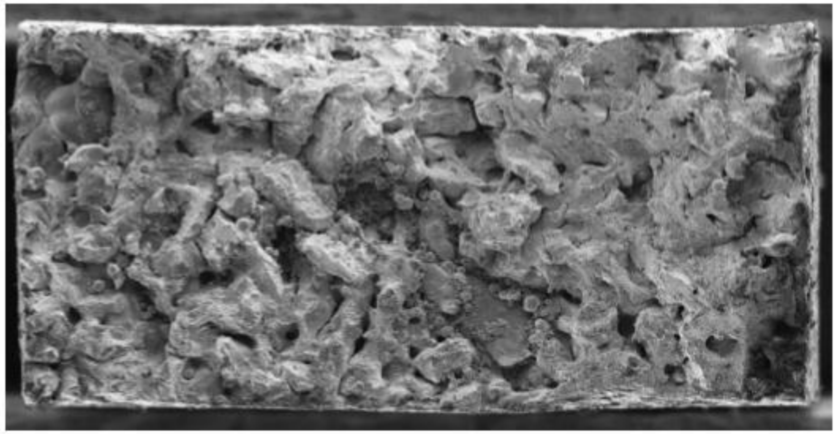
- Room temp tensile testing conducted on ASTM E8 specimens (0.25” dia gage) from witness bars with various restarts
  - Testing at 1200F for ASTM E8 round bars showed similar trends
  - Fracture surfaces appeared similar
- Microtensile testing conducted at room temp on section from chamber (C1 and C3) at witness line and non-witness



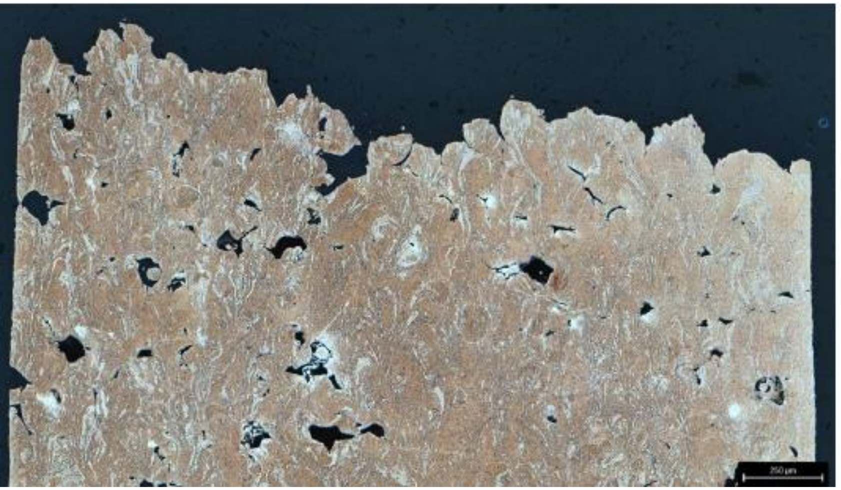
Fractography of Samples after Mechanical Testing

Microtensile

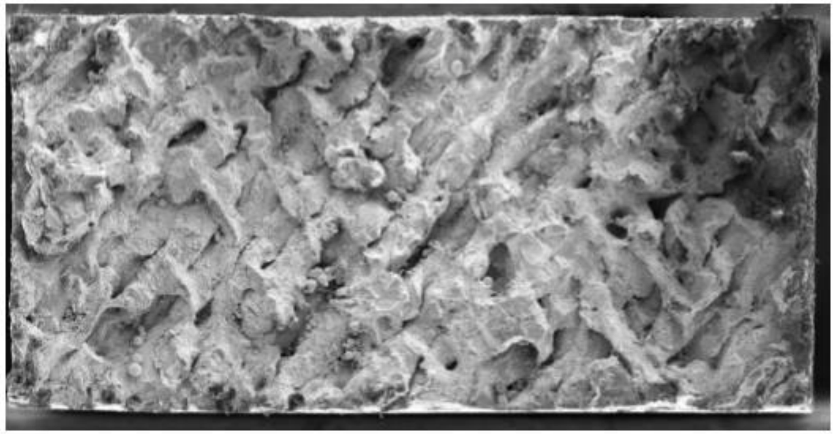
1T1B



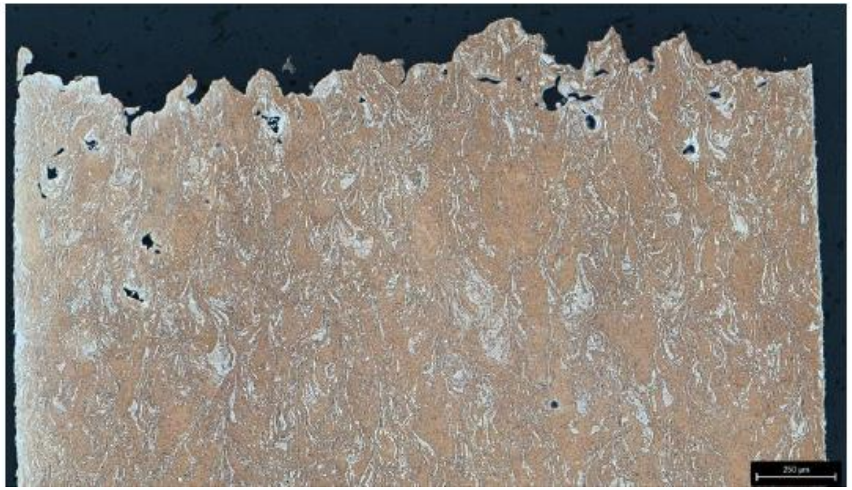
- Granular fracture surface, indicating a brittle fracture
- Irregular shape porosity, indicating lack of fusion



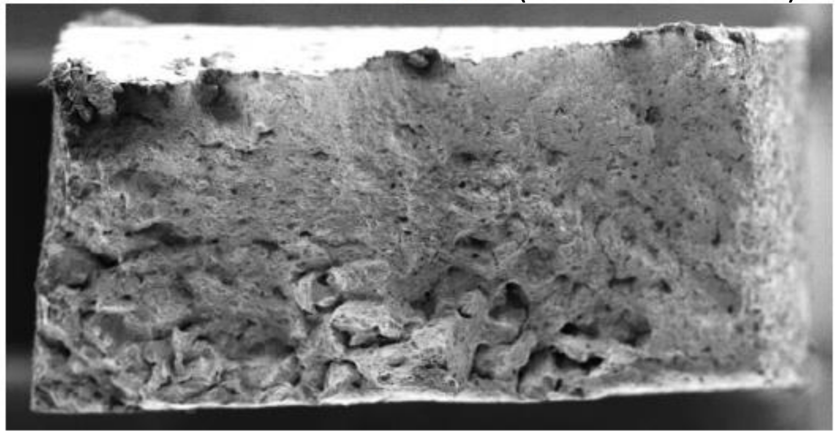
1T2B



- Granular fracture surface, indicating a brittle fracture
- Laser scan pattern clearly visible



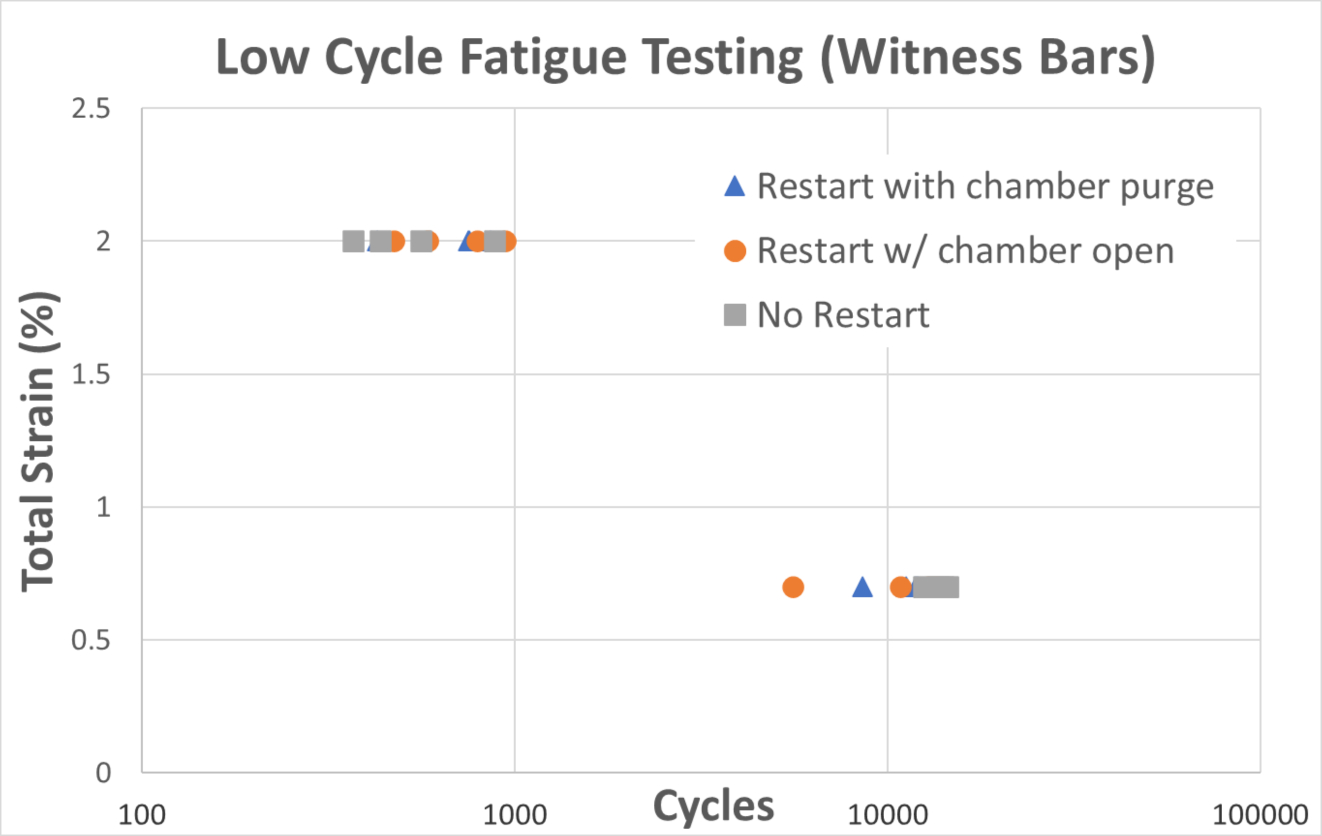
1T3B (Chamber Control)



- Overloaded fracture surface and necking, indicating a more ductile fracture
- Less porosity compared to witness lines

Low Cycle Fatigue of Post-build Witness Specimens

- LCF conducted at room temperature, total strain of 0.7% and 2%
- R = -1, triangular



	Restart w/purge	Restart, open	No restart
2%, Avg	785	781	562
St Dev	175	182	228
0.7%, Avg	12171	10677	13669
St Dev	1657	3582	849

*4 samples per test case

Strain, %	Cycles, Nf
2	924
2	840
2	529
2	846
0.7	9,760
0.7	12,597
0.7	13,531
0.7	12,796
2	668
2	593
2	986
2	878
0.7	5,579
0.7	10,805
0.7	13,426
0.7	12,899
2	369
2	437
2	559
2	882
0.7	14,038
0.7	12,514
0.7	14,499
0.7	13,624

Conclusions

- Chamber experienced tensile overload during hot-fire at the witness line that had a higher degree of voids.
- The L-PBF GRCop-42 chambers built under LLAMA had higher porosity (1-2%) that congregated more at witness lines causing lack of fusion.
- Granular surfaces, unmelted particles, and irregular pores were observed in microtensile specimens (sectioned) from chambers.
- Areas affected by build interruptions must be properly evaluated and dispositioned. AM machine restarts represent a risk, and appropriate restart procedures should be developed and followed to maintain material quality.
  - Witness specimens using different types of restarts showed similar tensile strengths and LCF results.
- Build log indicated no issues with parameters, but *an issue* (parameters, lens, etc) caused the porosity and HIP did not fully close these voids.
- Demonstrates the process sensitive nature of AM parts and build interruptions need to be properly documented, fully evaluated, and properly dispositioned.

Conclusions and Recommendations

- Build interruptions in GRCop-42 components do not inherently possess weakened material properties if a restart procedure is properly executed.
- Full height specimens should be built with all components to characterize the material.

- While not subject to NASA-STD-6030, this chamber provides a good case study on why it is important that AM materials used in critical applications adhere to NASA-STD-6030 standards and the need for robust process development, in-depth material evaluation, and process controls.

Backup

Acknowledgements

- David Myers / MSFC EM21
- Scott Ragasa / MSFC EM21
- Sturbridge Metallurgical Services
- Product Evaluation Systems
- IMR Test Labs
- Robert Amaro / AMTT
- Oneda

ICP & IGF Chemical Analysis

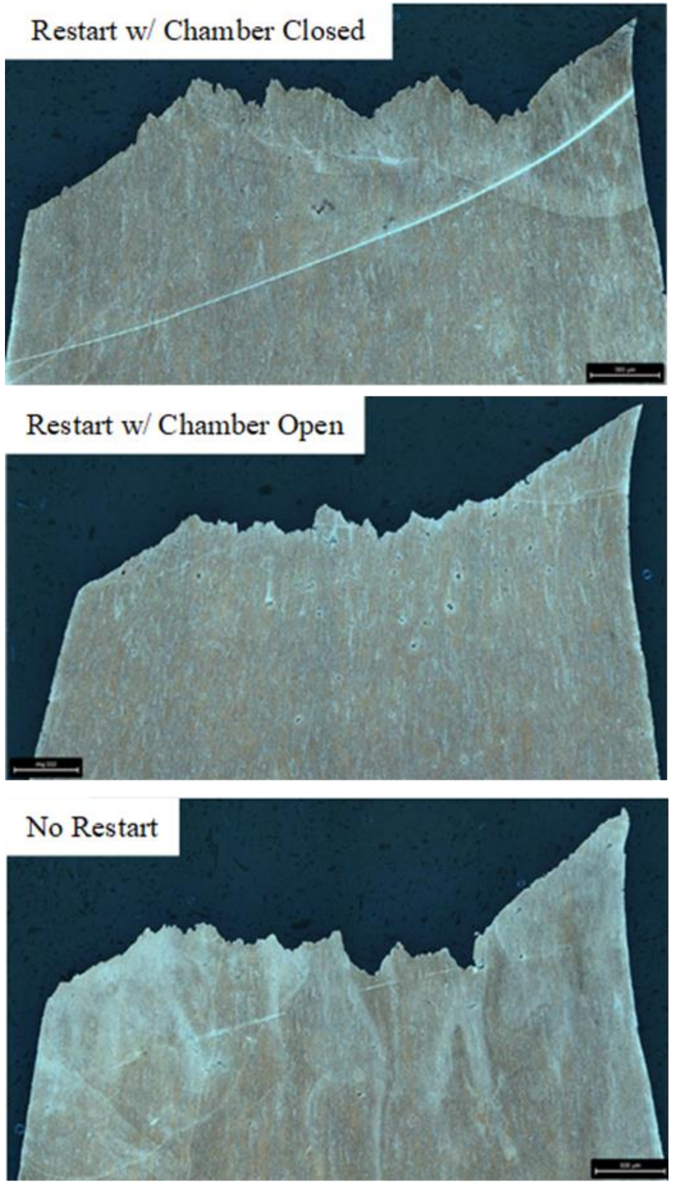
- 7 pieces from entire length of chamber C1
- Observations:
  - Composition did not vary throughout length of chamber
  - Al, Si higher than expected – crucible fluxing potentially
  - Ni, Co, Fe within detection limits
  - O notably high – can reduce conductivity and produce Al-Nb-O particles that create fatigue cracking
- Cr/Nb ratio is strong indicator of GRCop's effectiveness (precipitates for dispersion strengthening)
  - High ratio in chamber pieces
  - Results in excess chromium precipitates
  - Reduces high temp strength and creep resistance
- Important for AM GRCop parts to have consistent compositions

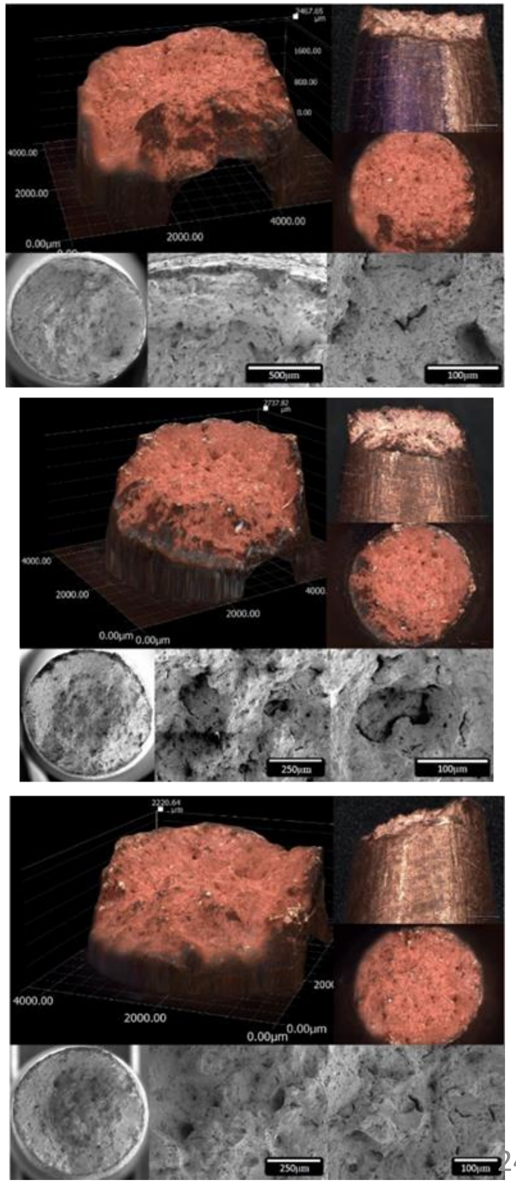
Element	Chamber Avg.	Spec Target	PC Results
Copper	93.88	-	-
Chromium	3.37	3.27	3.10
Niobium	2.57	2.92	2.70
Oxygen	0.06	0.025	0.033
Iron	0.02	0.005	0.007
Aluminum	0.05	0.04	-
Silicon	0.02	0.01	-
Nickel	0.02	-	-
Cobalt	0.01	-	-
Phosphorus	0.01	-	-
Silver	0.01	-	-

Documentation	Cr/NB Ratio
Chamber Average	1.31
Specification Target	1.13 - 1.18
PC Results	1.15

Fractography – Tensile Fracture

- 3 witness test bars from tensile simulating build stoppages
- Observations:
  - No major differences between fractures
  - Typical cup-cone fracture surfaces common for ductile metals
  - Fracture surfaces had elongated grains
- Conclusions:
  - Similar fractures track with similar properties observed in bars previously





Fractography – LCF Fracture

- 3 test bars from LCF
  - Fracture surfaces smeared b/c LCF had fully reversible cycles
  - Closed chamber restart bar never fully fractured
- Observations:
  - Open restart: flat surface before overload failure transition, secondary crack below primary crack
  - No restart: three separate cracks jogged together