Evaluation of Additively Manufactured Metals for Use on Oxygen Systems

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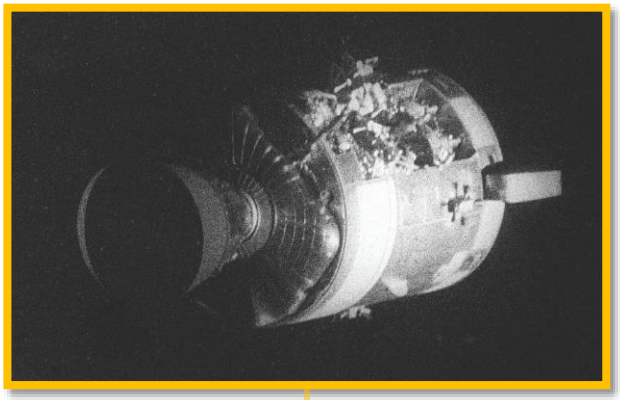
NASA Johnson Space Center

White Sands Test Facility

Aerospace Fire History



1965 | 1975 | 1985 | 1995 | 2005 | 2015

Apollo 1
1/27/1967

Apollo 13
4/14/1970

The EMU Fire
9/15/1980

MIR Fire
2/24/1997

Cygnus CRS Orb-3
10/28/2014

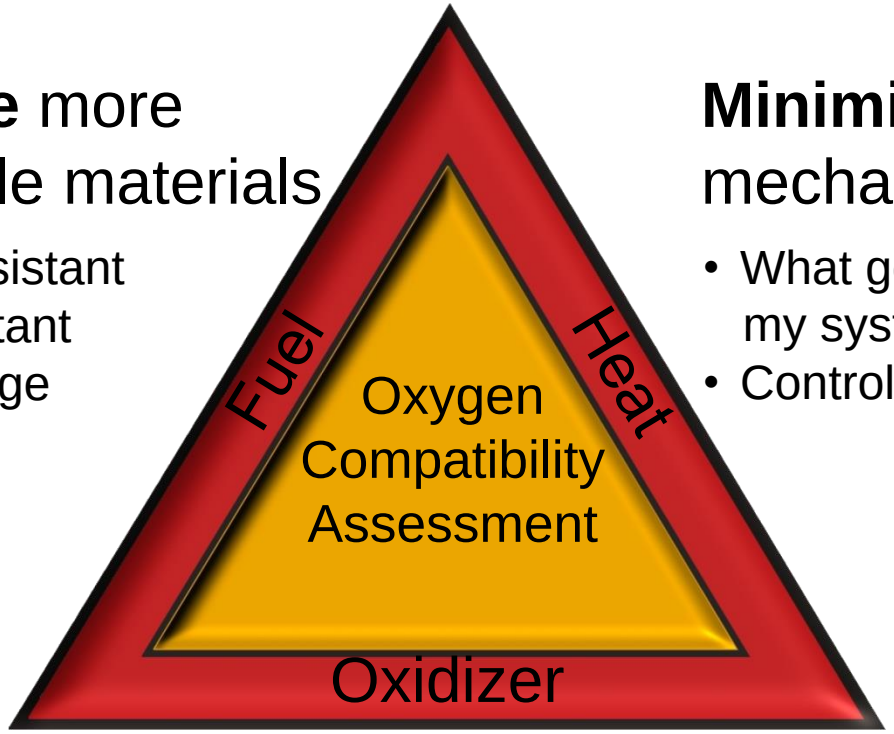
Oxygen Compatibility

- Additive Manufacturing (AM) has been, and will continue to be, used in oxygen systems
- Compatibility studies are a necessity
- Risks if not pursued
  - Equipment Damage, Loss of Mission, Loss of Life
- NASA Centers of Excellence leading efforts
  - White Sands Test Facility (WSTF)
    - Oxygen Compatibility Testing
  - Marshall Space Flight Center (MSFC)
    - Additive Manufacturing
  - NASA Engineering Safety Center (NESC)
    - Statistical Design of Experiments

We must manage the risks…

Maximize more compatible materials

- Ignition resistant
- Burn resistant
- Low damage potential



Minimize ignition mechanisms

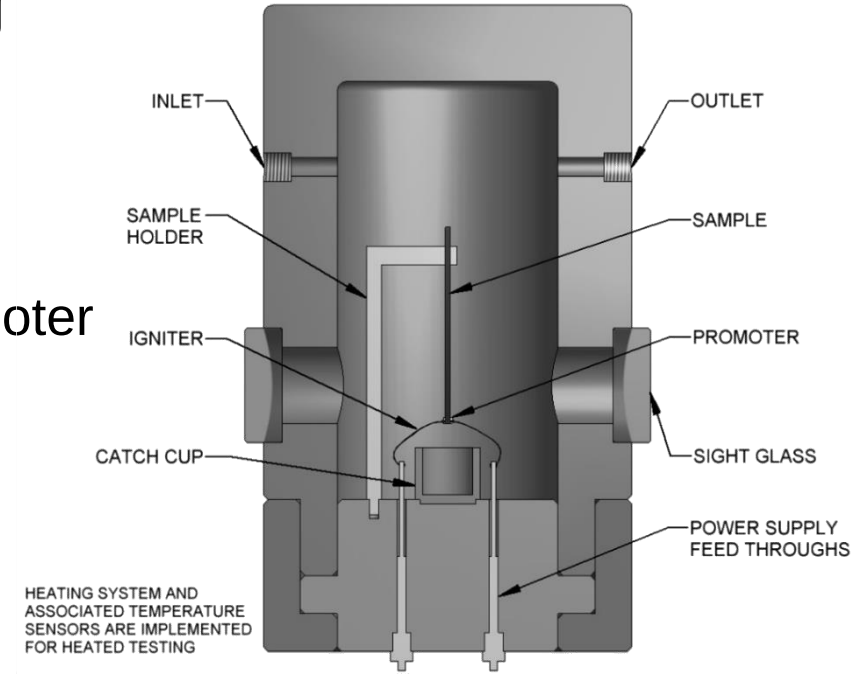
- What generates heat in my system?
- Control or eliminate

Utilize good practices

- Implement all aspects of oxygen system safety

Maximize

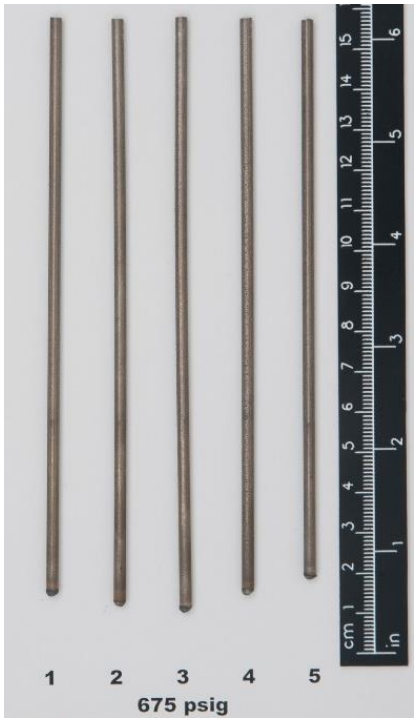
- Testing determines AM flammability performance
- NASA-STD-6001B Test 17/ ASTM G124
  - Upward flammability test
  - 1/8-in. diameter x 6-in. long
  - Unheated
  - Static Pressure
  - >99.5% Oxygen
  - Magnesium/Pyrofuse Promoter



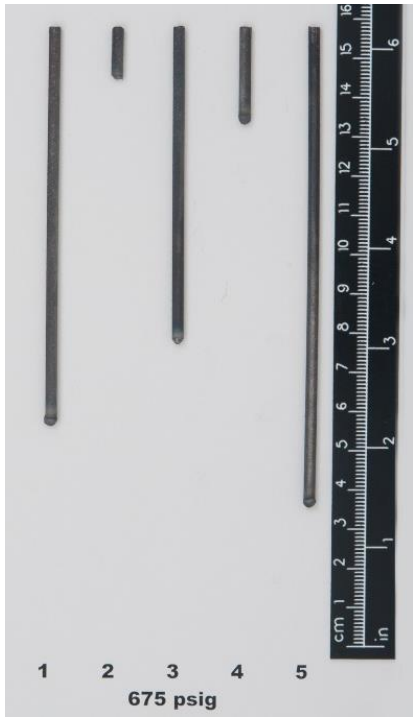
Preliminary Flammability Testing

- Experiment conducted between:
  - Wrought Inconel 718
  - Selective Laser Melting (SLM) Inconel 718 (IN718)
- Statistically designed, efficient, and randomized
- Test specimens manufactured at MSFC
- Material flammability differences noted
  - Result statistically significant but counterintuitive
- SLM IN718 post-build processes need investigation
  - Stress relief (SR)
  - Hot isostatic pressing (HIP)
  - Solutionizing and aging heat treatments (HT)

Preliminary Flammability Results



Printed, HT, no HIP



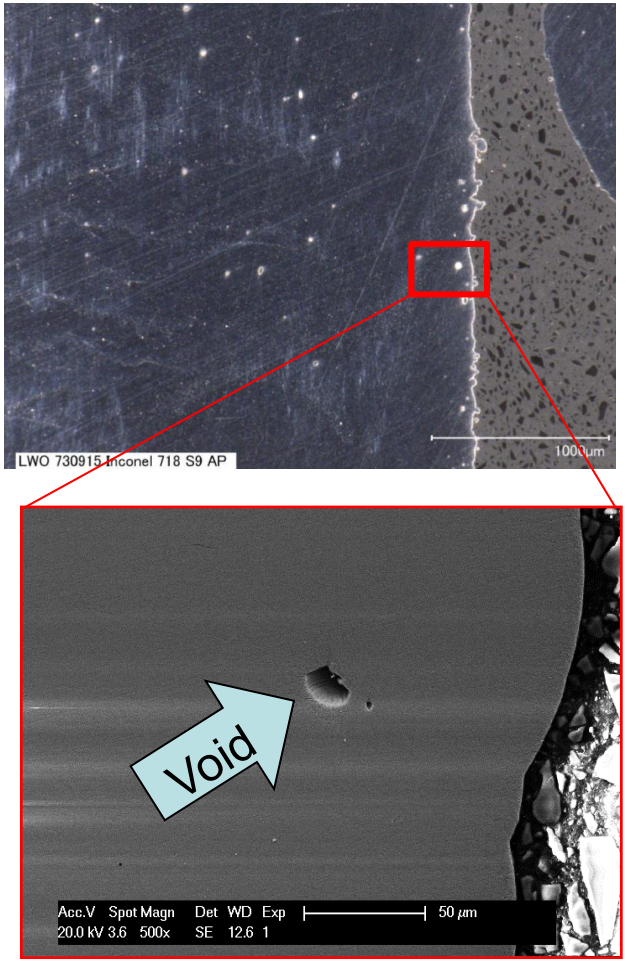
Printed, HIP, and HT

Wrought and HT

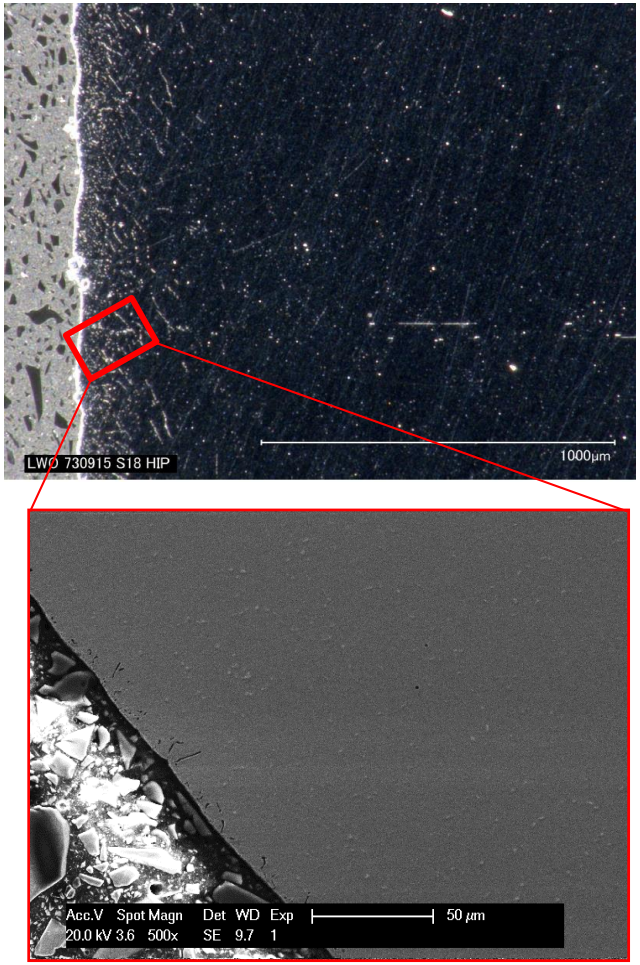
- SLM IN718 with/without HIP vs Wrought
- All materials had AMS 5664 HT

Various Nb Precipitate Formation

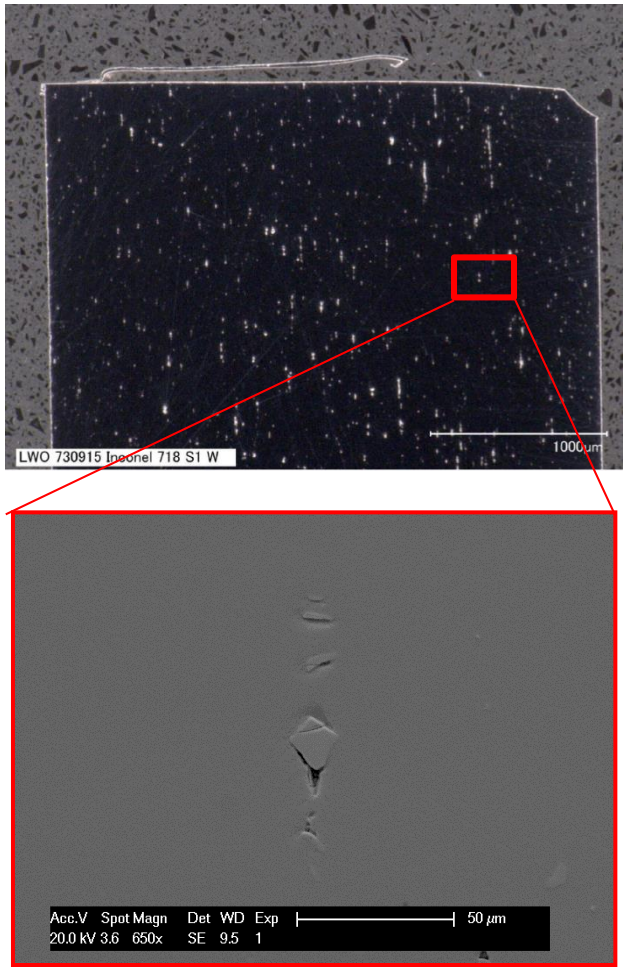
As-Printed/HT



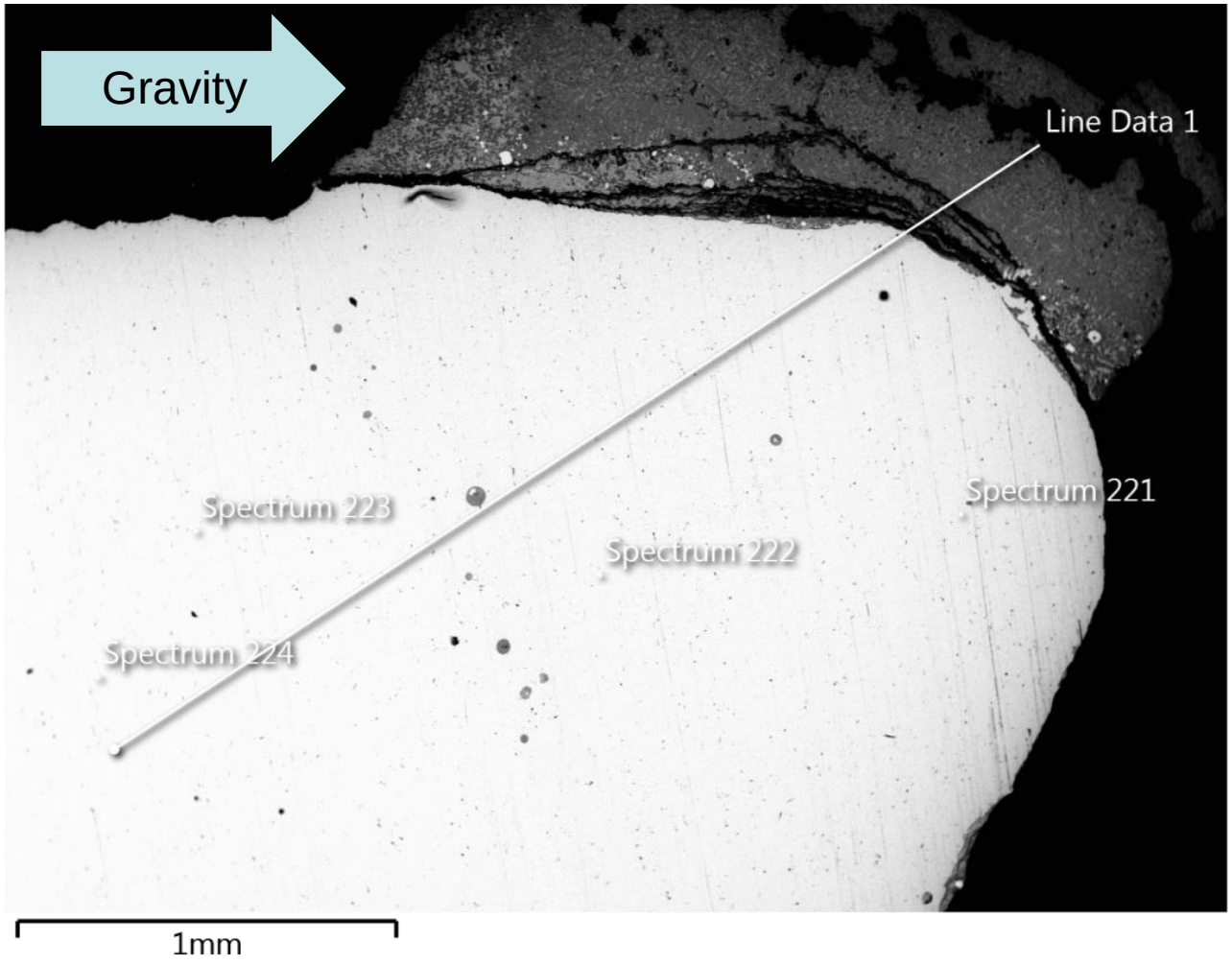
HIP/HT



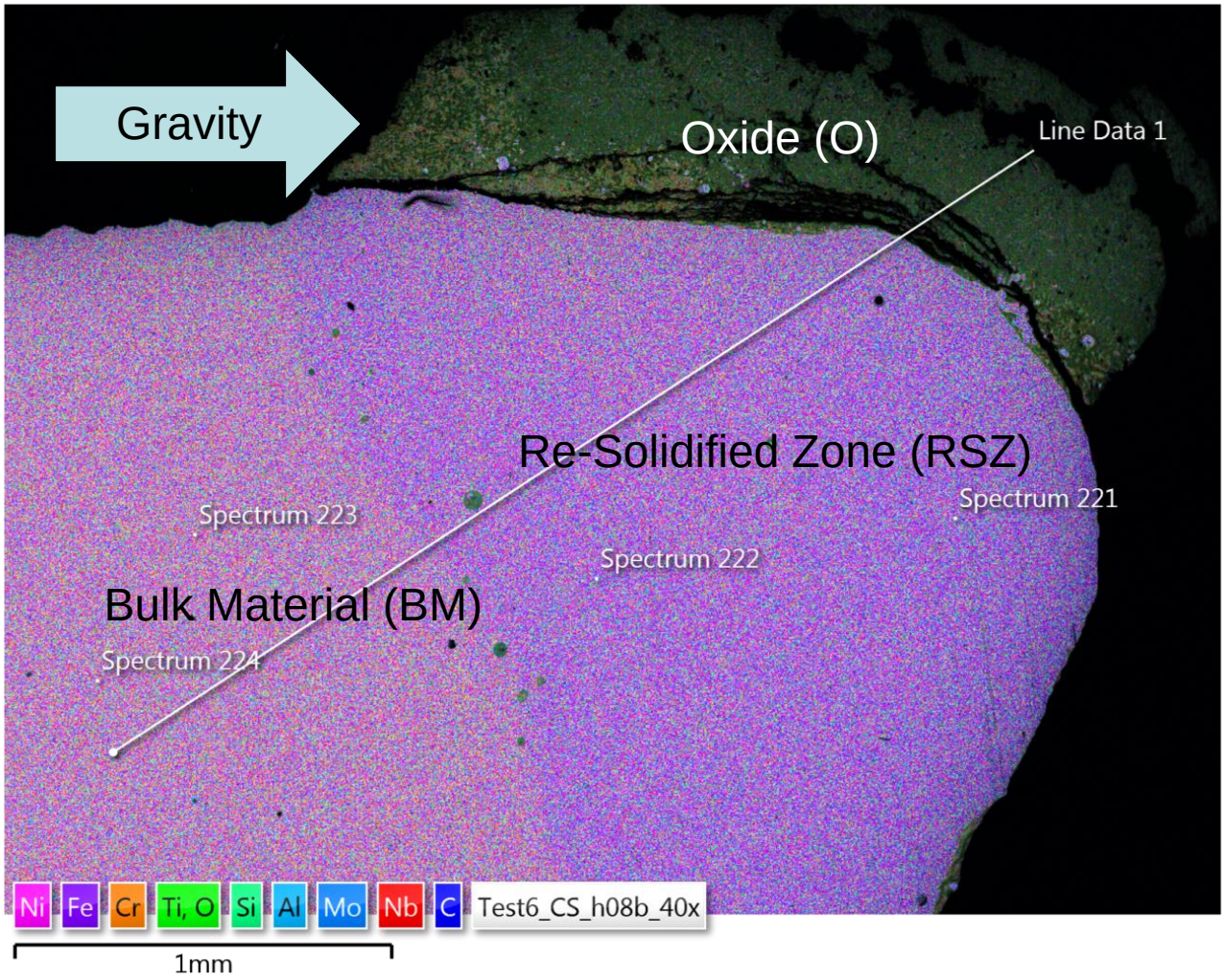
Wrought/HT



Axial Burning Interface of HIP Sample

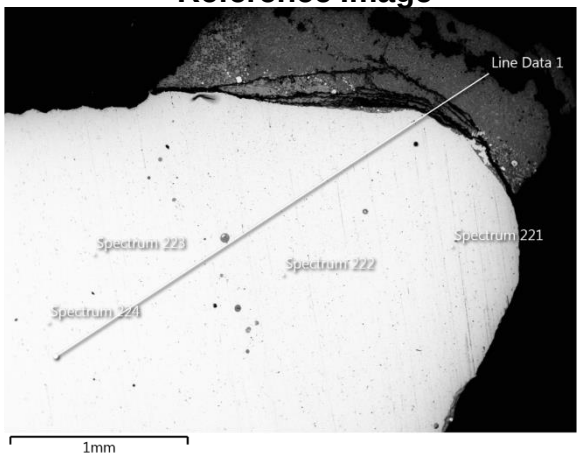


Composite Energy-Dispersive Spectroscopy (EDS)

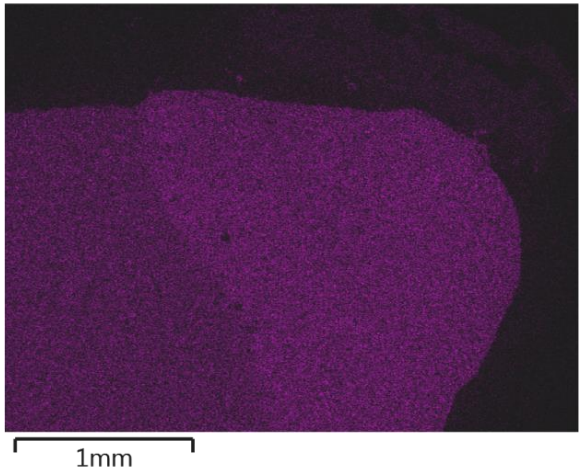


EDS Mapping of Individual Elements

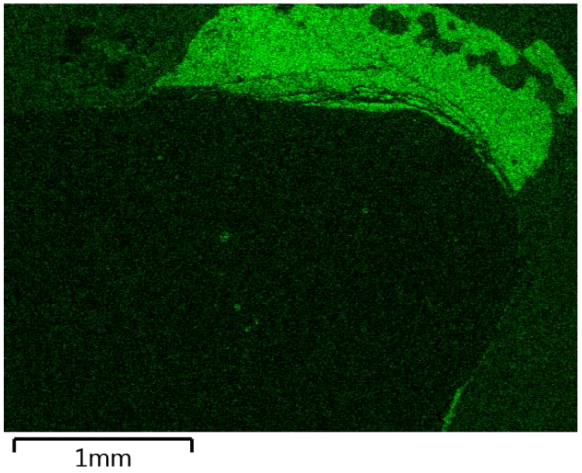
Reference Image



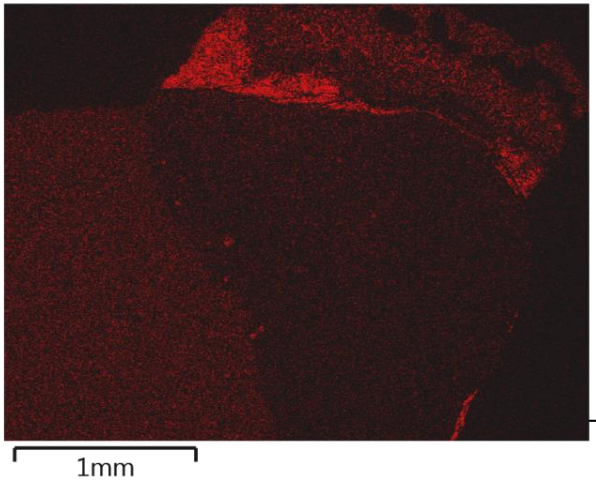
Ni K series



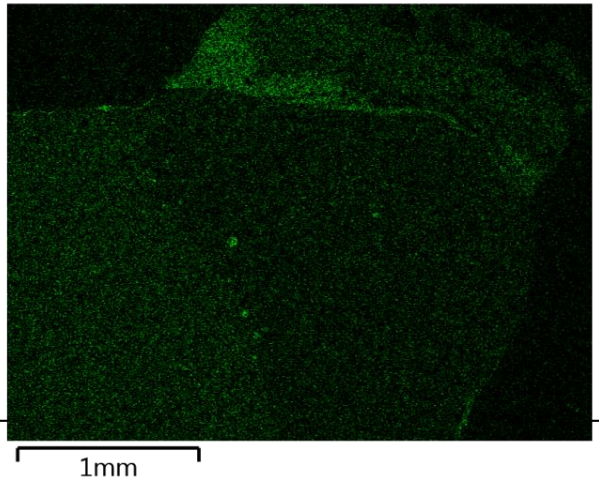
O K series



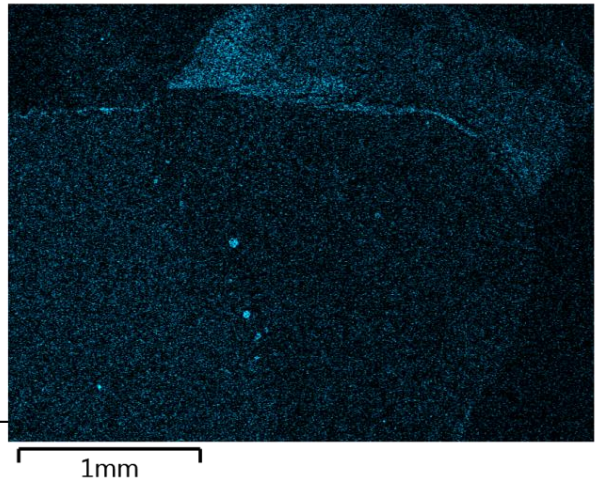
Nb L series



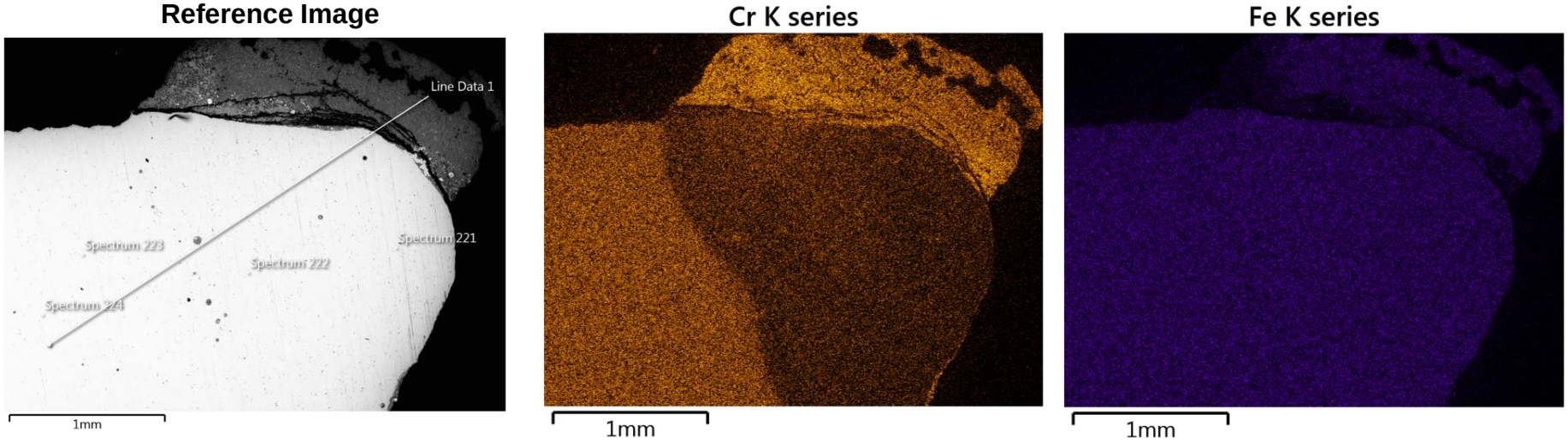
Ti K series



Al K series



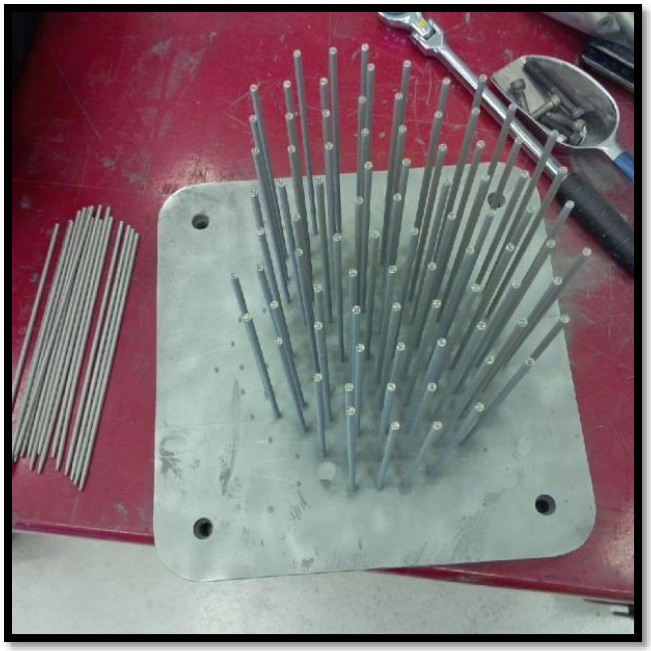
EDS Mapping of Individual Elements



- Scavenging of flammable constituents in RSZ
  - Cr, Al, Ti, Nb
- Concentration of non/less flammable constituents in RSZ
  - Ni
- Fe remained distributed in BM, RSZ, and O Zones

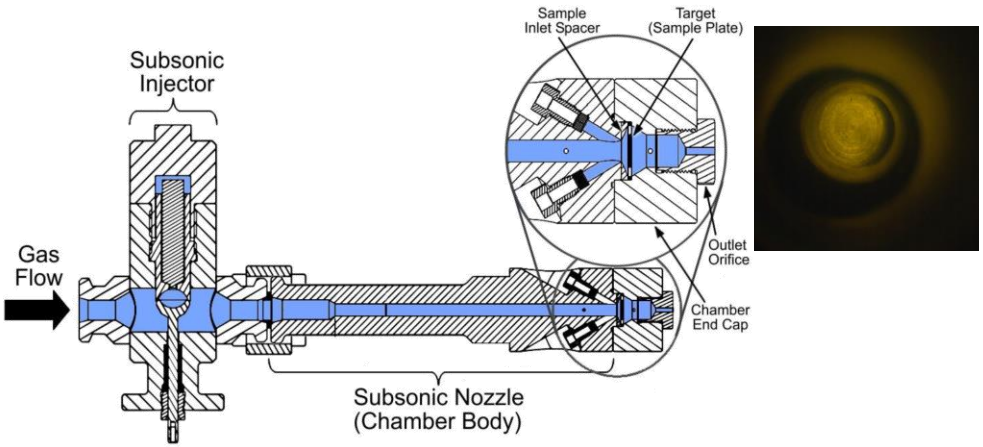
Flammability Study - Ongoing

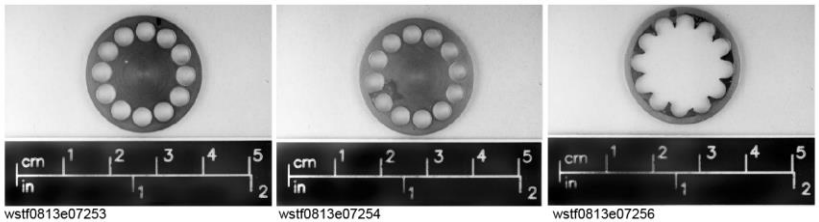
- SLM IN718
- Replicate and expand experiment
- Print parts in same build
- Synchronously SR and HT
- Factors
  - HIP (with/without)
  - Effect of HIP temperature excursion
    - Performed in vacuum furnace
    - Furnace cool vs. quench
  - AMS 5664 HT (with/without)
  - Location on build plate



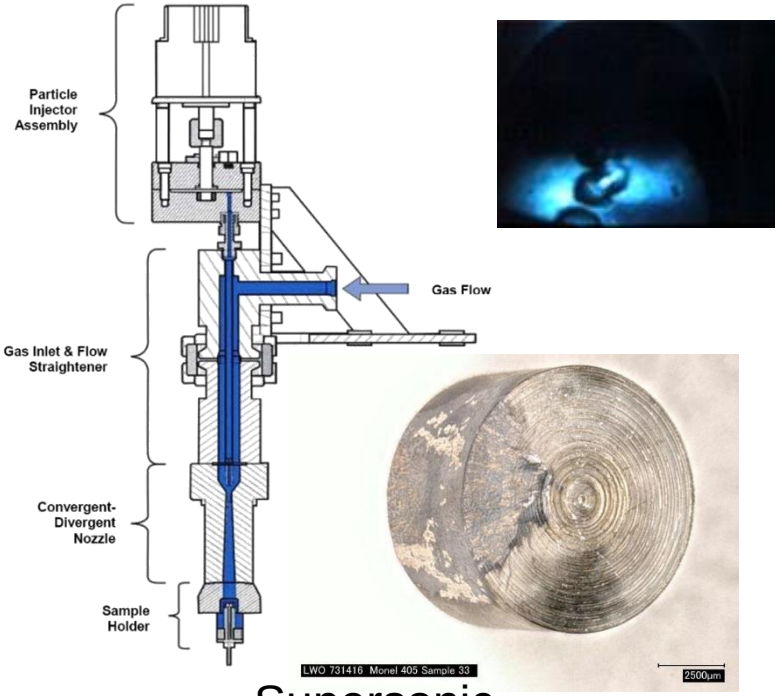
Minimize

- Particle Impact
  - Most common direct igniter of metals
  - Hazards increase with:
    - Pressure, temperature, velocity, flammable particles
  - SLM Components shed metal particles (Lowrey 2016)





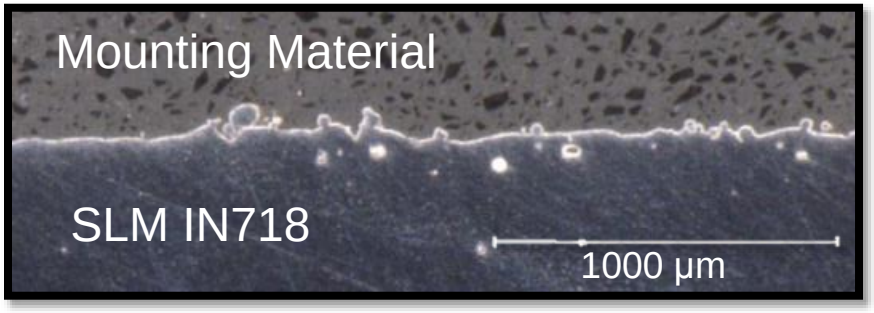
Subsonic



Supersonic

Planned Ignition Study

- Subsonic & Supersonic Impacts on SLM IN718
  - Pressures, temperatures, velocities
- Study effect of AM characteristics on ignition sensitivity
- Factors
  - Print direction
  - Surface treatment
  - Post-manufacturing processes (pending flammability results)
  - Particle types



Utilize

- AM production
  - Dedicated machine(s) for each material
- Precision cleaning
- AM component/system design recommendations
- Assembly
- Operations
- Maintenance

Long-Term Goals

- Draw additional commercial and government partners
- Test full-scale AM components
- Develop guide for the use of AM in oxygen systems
  - Design
  - Manufacturing
  - Cleaning
  - Assembly
  - Operations
  - Maintenance

Acknowledgements

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