Evaluation of Additively Manufactured Metals for Use on Oxygen Systems

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Aerospace Fire History

- **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

- SLM IN718 with/without HIP vs Wrought
- All materials had AMS 5664 HT
Various Nb Precipitate Formation

As-Printed/HT

HIP/HT

Wrought/HT

Void
Axial Burning Interface of HIP Sample
Composite Energy-Dispersive Spectroscopy (EDS)
• 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)
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

Mounting Material

SLM IN718

1000 μm
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
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