Welding of Crack Sensitive Aluminum Alloys for Liquid Rocket Propulsion Applications

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1. NASA / Marshall Space Flight Center

2. Fortius Metals

Introduction – William Evans

- Welding Engineer at NASA Marshall Space Flight Center
  - Huntsville, AL
  - Working in M&P for 4 years
- MS/BS Welding Engineering – 2019
  - The Ohio State University
- Programs Supported:
  - SLS Production
  - Human Landing Systems
  - Large Scale AM Dev
    - DED
    - Welding AM
  - Industry Weld Consultations
  - Various Partnership Programs
    - Space Act Agreements
    - Cooperative Agreements

Agenda

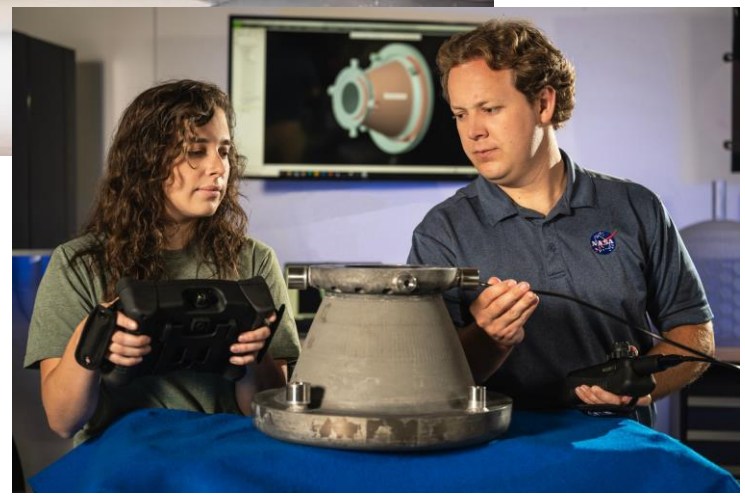
- **Program Background**
  - Development at NASA
  - Aluminum Rocket Nozzle Test Program
- **6061 material overview**
- **Initial Welding Development**
  - Wire Fabrication
  - Weld Testing at MSFC
  - Metallography
  - Mechanical Testing
- **RAMFIRE Hardware Welding**
- **Hot Fire Test Results**
- **Conclusions**

Program Background

- **This welding development program was designed to support the fabrication of rocket engine hardware for hot-fire testing purposes**
- **The goal of this program was to develop welding procedures with a newly developed Aluminum filler metal**
  - Reduction in weld cracking
  - Improvement in overall weld performance
- **This new welding wire offers numerous benefits for traditional welding processes but also holds far reaching implications for wire based additive manufacturing process (LW-DED, WA-DED)**
- **New aluminum materials offers large improvements for the Aerospace/Space industry**

RAMFIRE Background

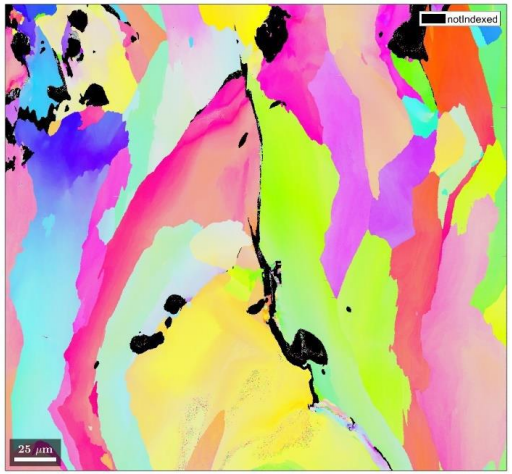
- **NASA Announcement of Collaborative Opportunity (ACO) Partnering with Elementum 3D**
- **LP-DED built aluminum liquid rocket engine nozzle**
  - LOx/Methane
  - LOx/LH2
- **Successful hot fire test campaign at MSFC 2023**
- **Chamber pressures more than 825 psi**
- **22 total starts, 579 s of run time (almost 10 minutes)**



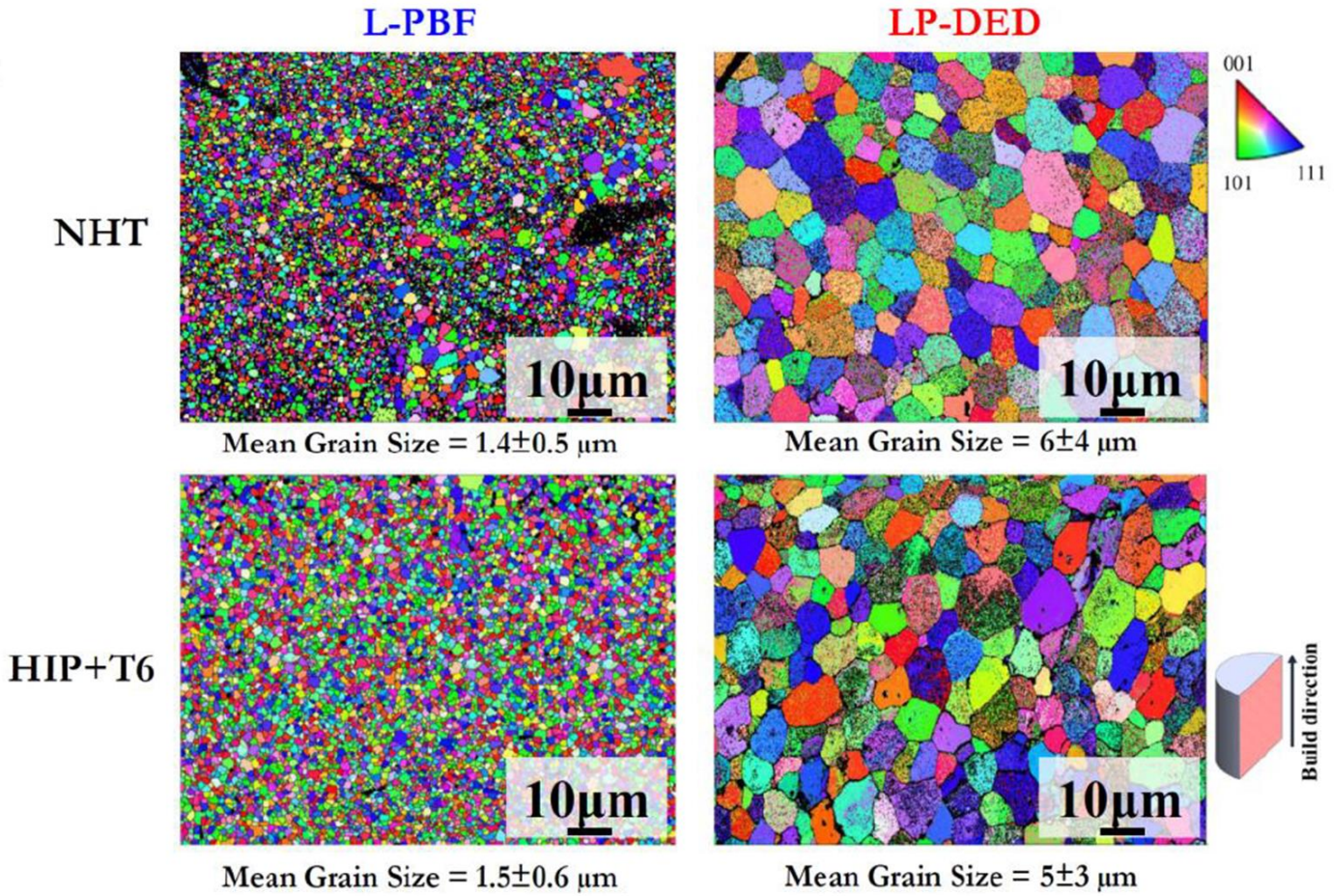
https://www.nasa.gov/centers-and-facilities/marshall/nasas-innovative-rocket-nozzle-paves-way-for-deep-space-missions/

Aluminum 6061-RAM2 – Material Background

Element	AA6061 Matweb	AA6061-RAM2 (LP-DED)	AA6061-RAM2 (L-PBF)
Al	95.8 - 98.6	94.61	94.67
Mg	0.8 - 1.2	0.83	0.84
Si	0.4 - 0.8	0.56	0.54
Mn	Max. 0.15	0.01	0.00
Cr	0.4 - 0.35	0.07	0.10
Cu	0.15 - 0.4	0.26	0.28
Fe	Max. 0.7	0.17	0.09
Ti	Max. 0.15	2.45	2.44
Zn	Max. 0.25	0.00	0.01
B	-	0.74	0.74
Others, each	Max. 0.05	Max. 0.05	Max. 0.05
Other, Total	Max. 0.15	Max. 0.16	Max. 0.16

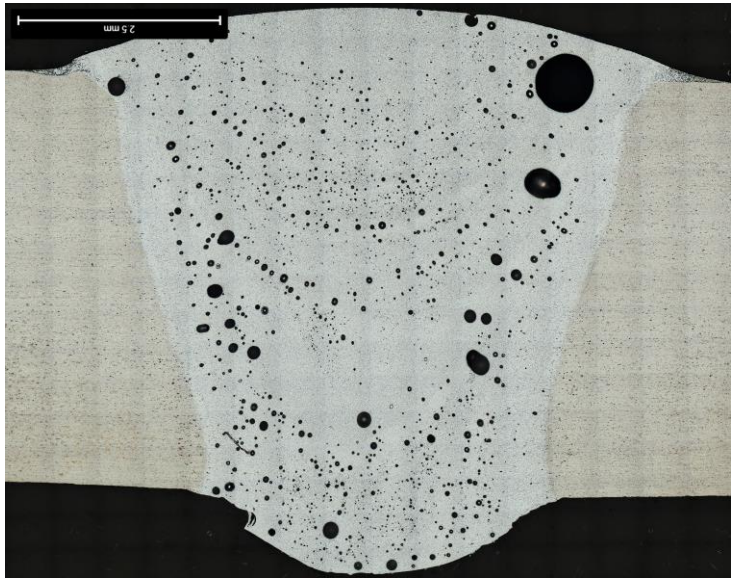


ESBD Image of Traditional AA6061 processed with L-PBF

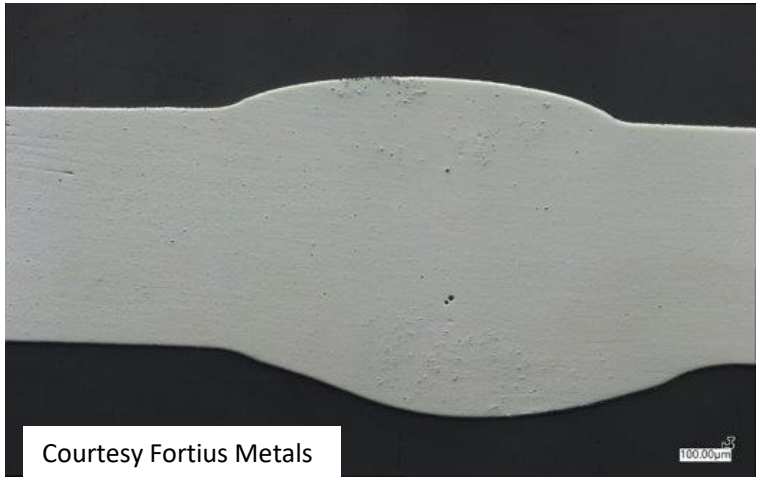


ESBD Image of AA6061-RAM2 processed with different AM Techniques

RAM Wire Fabrication Developments



External vendor wire, poor cleanliness.

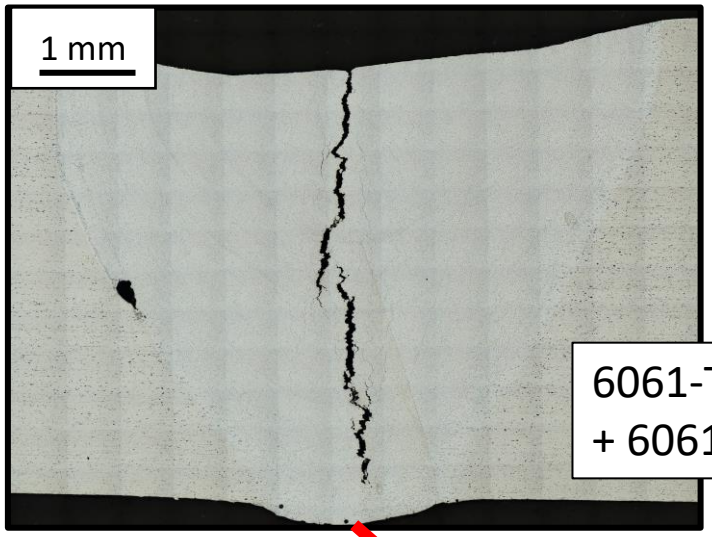


Internally produced RAM2 wire.
Acceptable porosity.

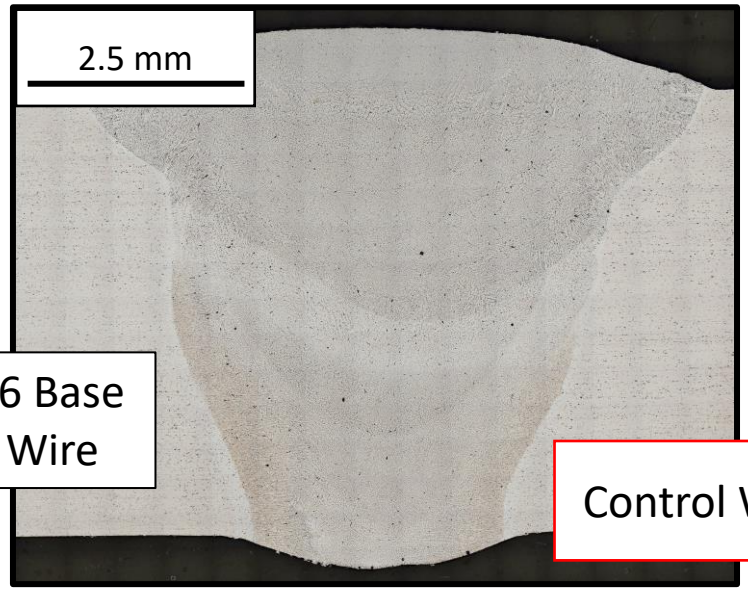
Increasing wire cleanliness

Wire Produced internally by Fortius Metals resulted in defect free welds suitable for welding applications on RAMFIRE

6061 – RAM2 Weld Wire Testing at MSFC



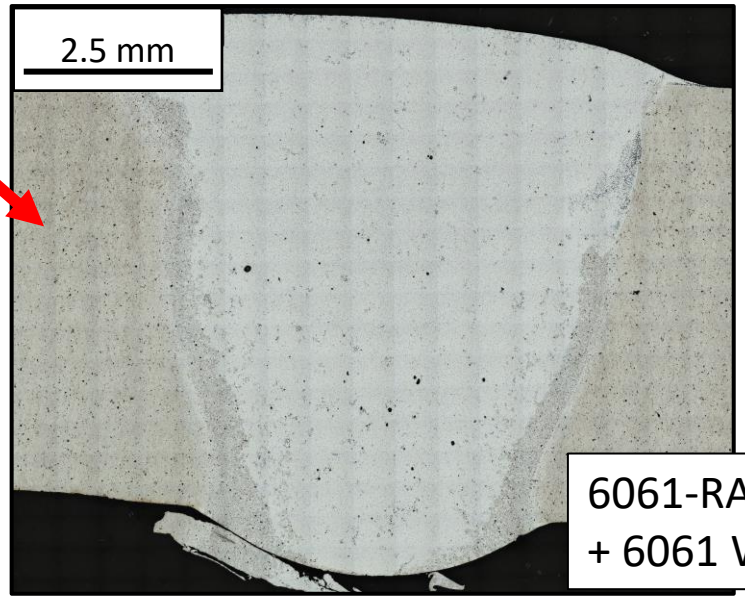
6061-T6 Base
+ 6061 Wire



6061-T6 Base
+ 4043 Wire

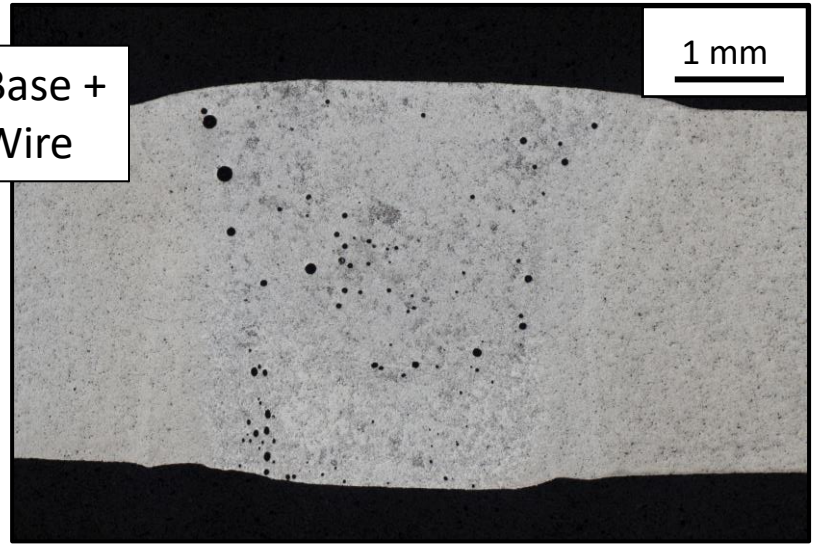
Control Weld

Same Wire, RAM
added to Base Metal

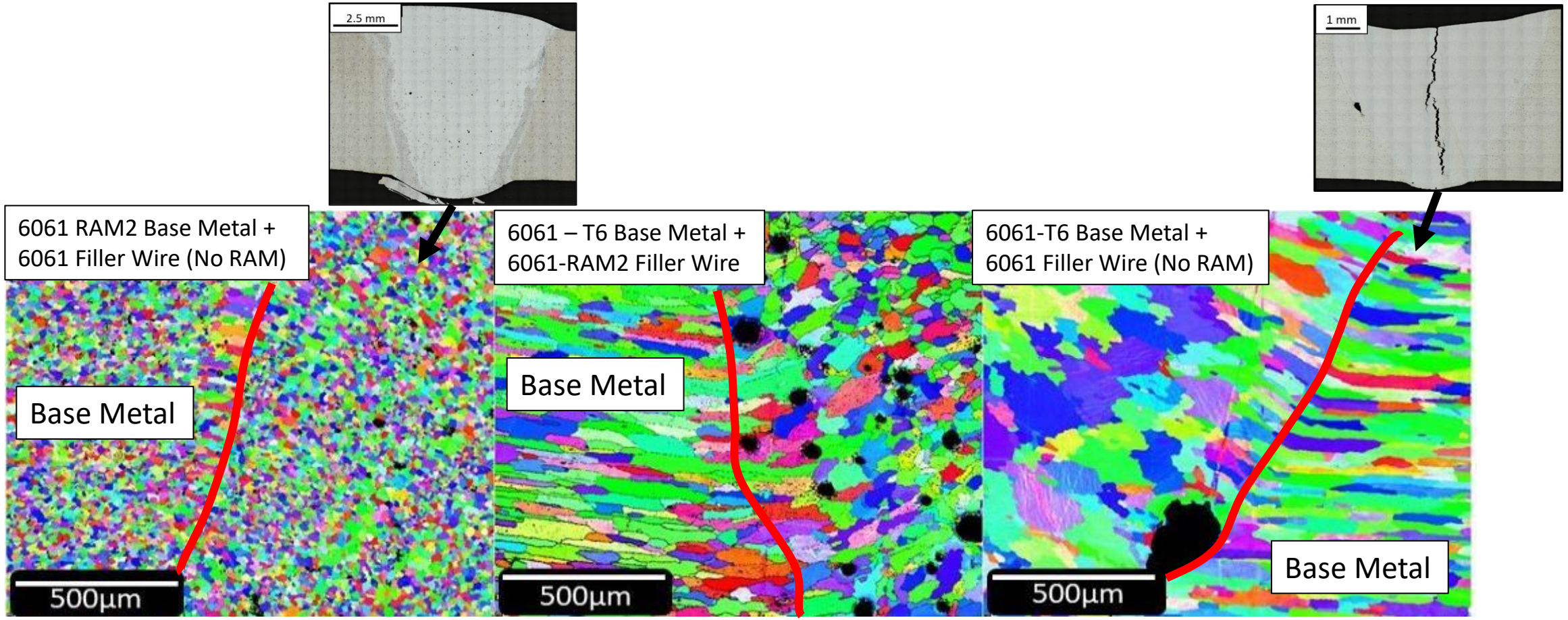


6061-RAM2 Base
+ 6061 Wire

6061-RAM2 Base +
6061-RAM2 Wire

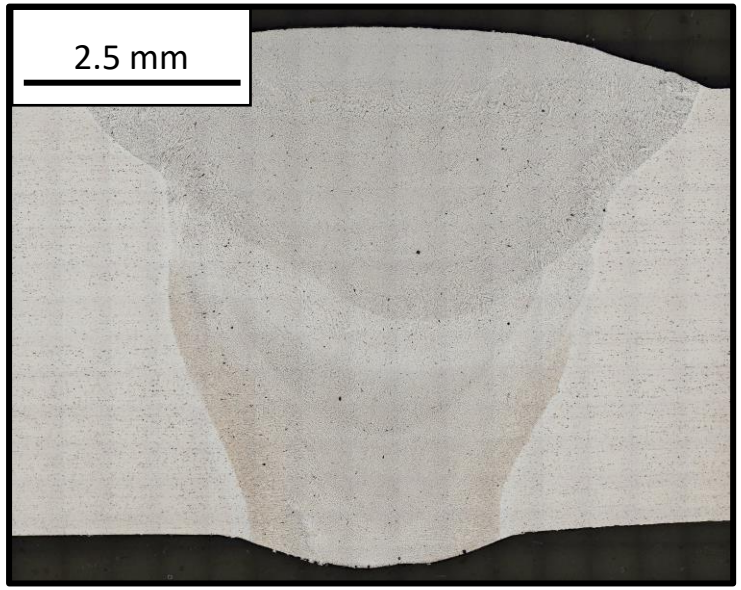


EBSD Scans (MSFC GTA Welds)



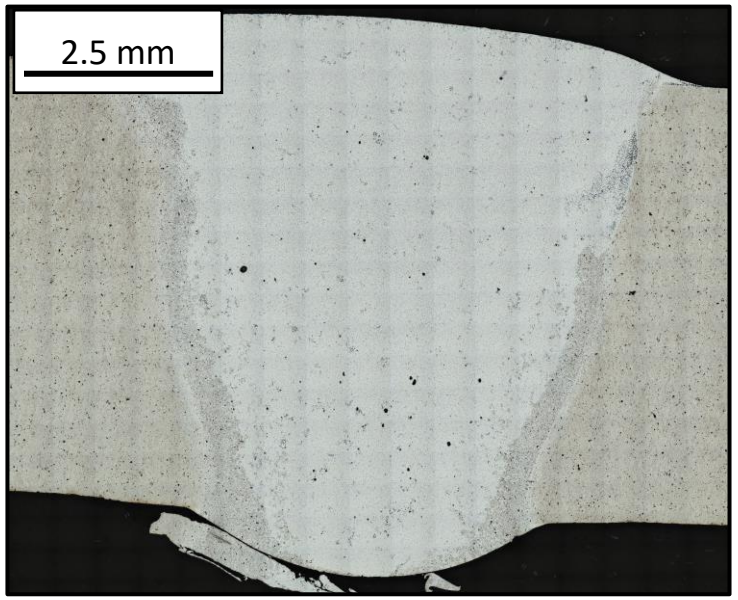
SEM imaging shows a reduction in grain size in the fusion zone of welds conducted using material with RAM additions

RAM Wire Mechanical Testing



6061-T6 Base + 4043 Wire

Ultimate Tensile Strength: 29.7 ksi
Yield Strength: 17.83 ksi
Elongation: 8.8%



6061-RAM2 Base + 6061 Wire

Ultimate Tensile Strength: 37.26 ksi
Yield Strength: 25.65 ksi
Elongation: 10.85%

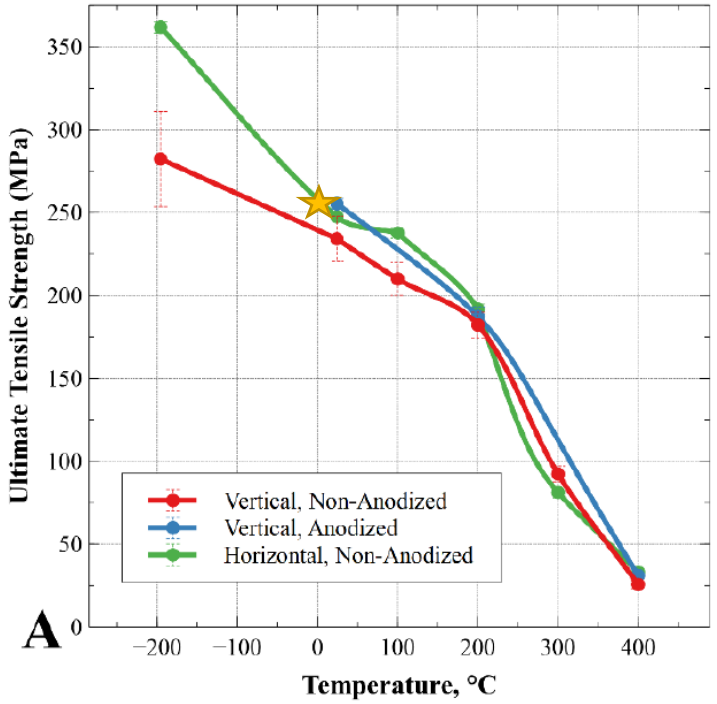
- Both samples tested in the as welded condition
- Specimens were flat strip tensile specimens
- RAM particles were observed to be swept into the weld fusion zone
  - Distance of mixing was not measured

Additions of RAM in the base plate improved weld cracking susceptibility of the 6061 wire and allowed for an overall improvement of the weld performance.

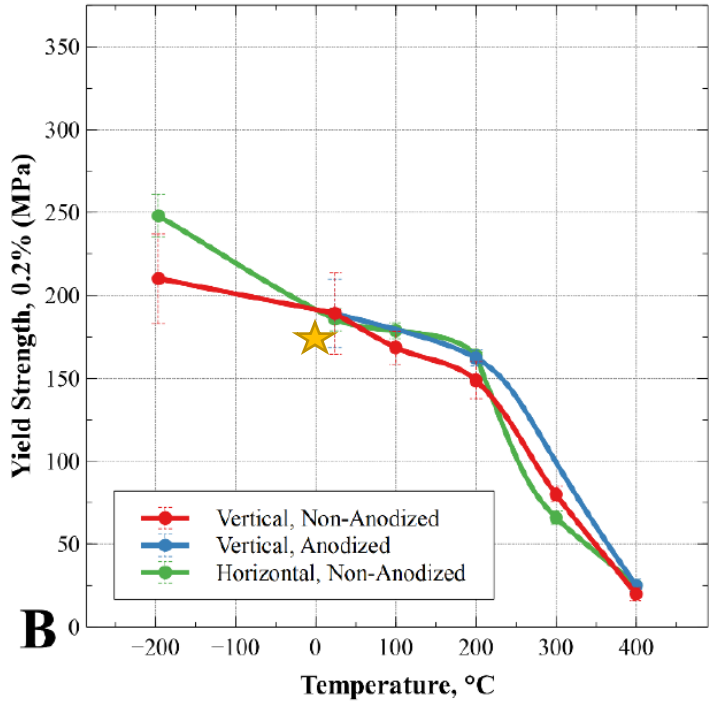
Mechanical Properties Comparison

Tensile Properties of 6061-RAM2 L-DED vs. Temperature

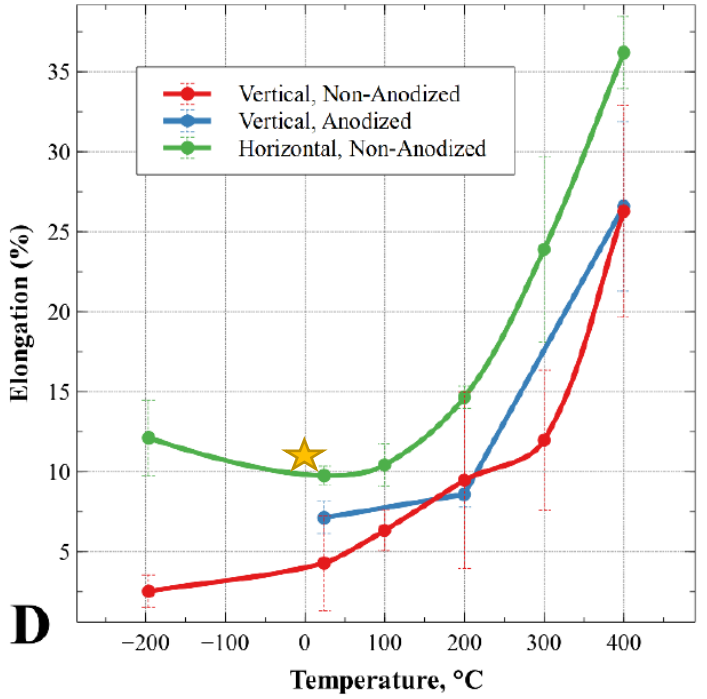
UTS



YS



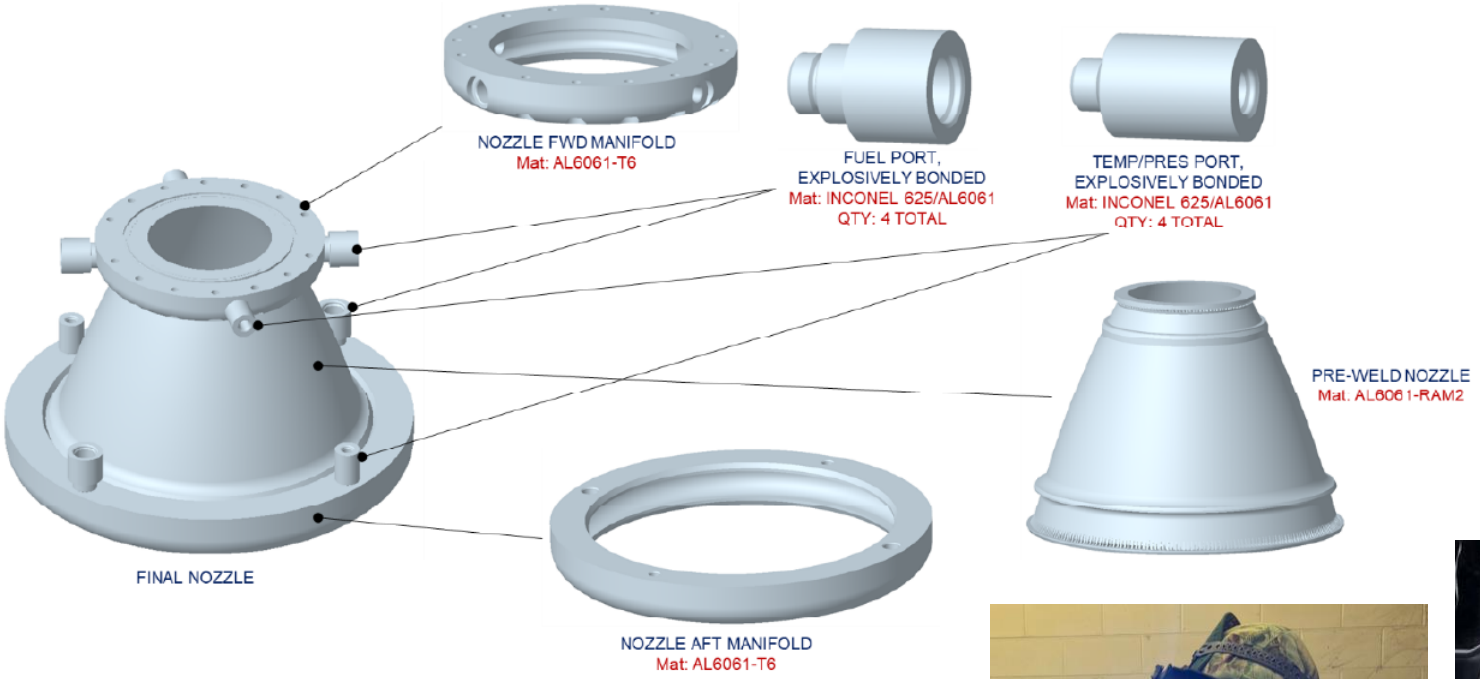
Elongation



Denotes performance of 6061-RAM2 plate welded with 6061 wire

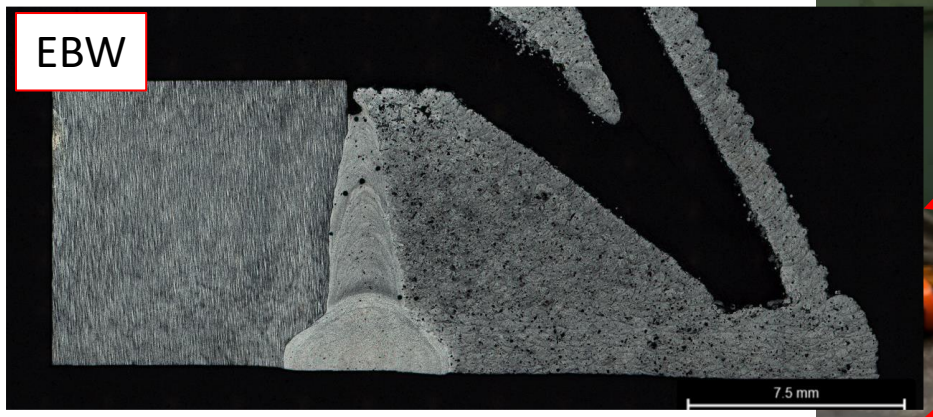
Highest performing weld condition demonstrated that the use of RAM material in GTA welding can demonstrate near T6 heat treat condition in the AA6061 L-DED system.

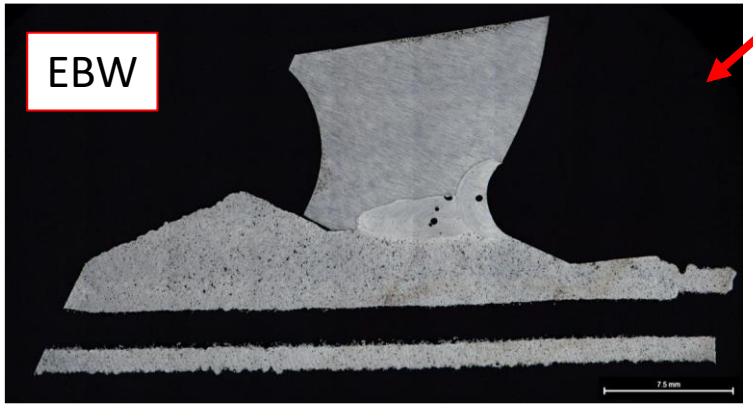
RAMFIRE Nozzle Assembly

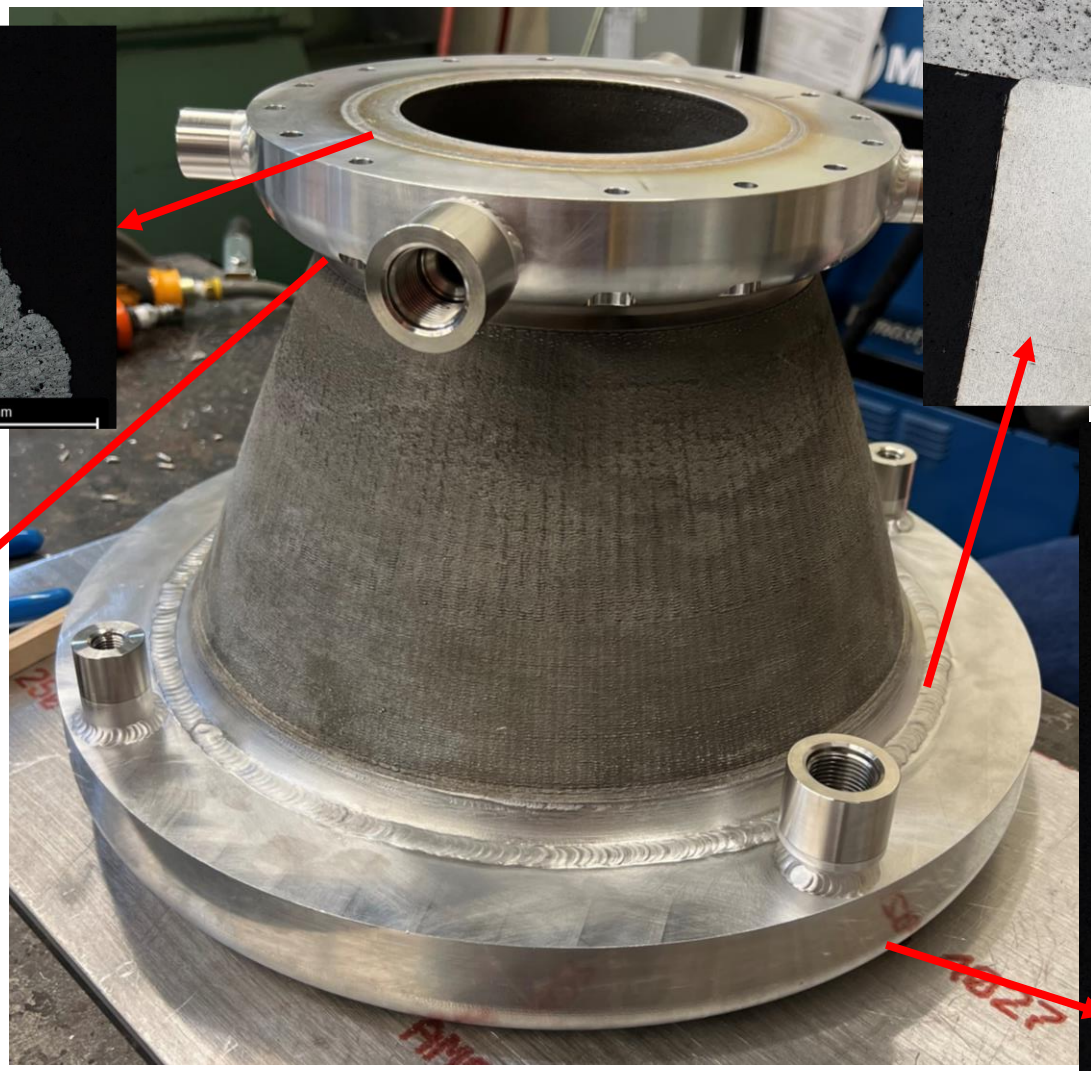


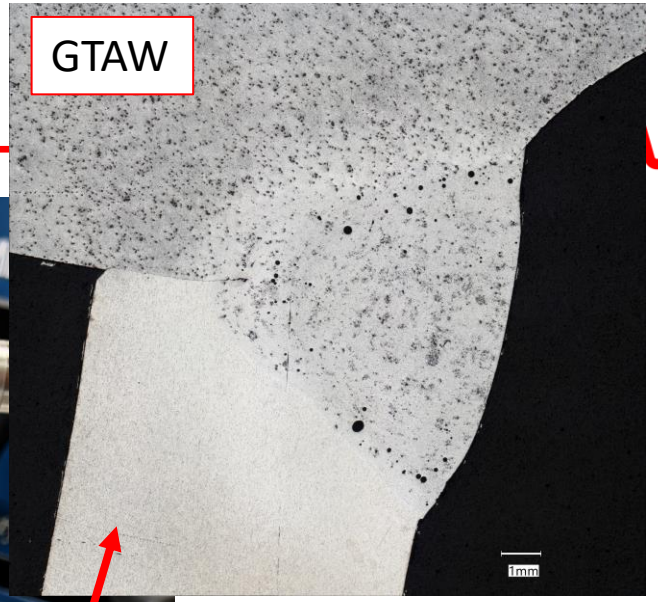
Multiple welding processes used for nozzle assembly. Electron beam welding used on the forward manifold, GTA Welding used on the aft manifold and the fuel ports, Explosion bonding was used to manufacture fuel ports.

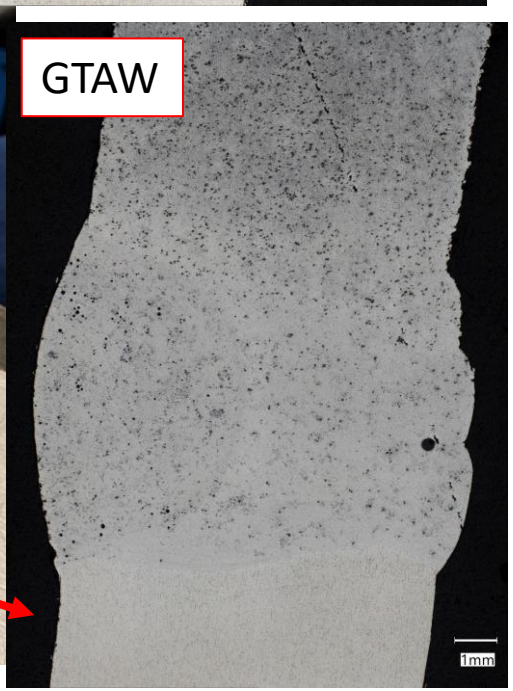
Welding Processes on RAMFIRE





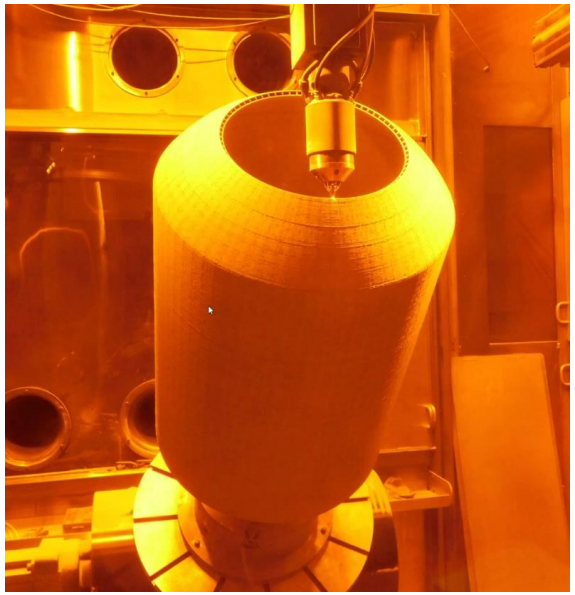






RAMFIRE Engine Test

Future Development



Continued RAM enhanced Aluminum L-DED for launch vehicle applications

Aluminum weld wire undergoing WA-DED/WAAM testing and development

Aluminum with RAM began as metal powder of PBF applications but has grown to be used for large scale additive manufacturing technologies. Welding wire with RAM additions offers large improvements for welding and wire based additive manufacturing. Multiple Aluminum wires are in development/testing.

Conclusions

- **At the end of the test program two 6061-RAM2 liquid rocket engine nozzles we printed, welded and hot fire tested at Marshall Space Flight Center**
- **Aluminum 6061-RAM2 exhibited improved weldability results as compared to conventionally manufactured 6061-T6**
  - Weldments made on material with RAM particles did not exhibit weld cracking
- **Grain refinement was observed in the weld fusion zones in weldments made on materials which included additions of RAM particles**
  - RAM additions in the base metal were observed to have migrated into the weld fusion zone leading to refined grain structure of the fusion zone
- **Mechanical performance improvements were observed in weldments made with RAM material compared with conventionally welded material**
  - Both using RAM filler metal and using RAM enhanced base material

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Questions?

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