Reactive Additive Manufacturing for Fourth Industrial Revolution Exploration Systems (RAMFIRE) Aluminum 6061-RAM2 Nozzle Testing

The NASA Marshall Space Flight Center (MSFC) has applied various forms of metallic additive manufacturing (AM) in liquid rocket engine component design, development, and testing since 2010. These AM techniques reduce hardware cost, shorten fabrication schedules, increase reliability by reducing the number of joints, and improve hardware performance by allowing unconventional design. The RAMFIRE project, funded under Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program, has furthered the use of novel AM liquid rocket nozzles in collaboration with Elementum 3D. The project advanced novel large-scale AM aluminum material technology for significant weight savings in rocket engines and launch vehicles. Previously, aluminum alloys were difficult to weld and print using additive manufacturing. Elementum 3D's patented Aluminum 6061-RAM2 alloy allows for aluminum alloys to be printed using various AM techniques and at various scales. The alloy can be leveraged for welding wire, showing drastic improvements in aluminum weldability. The RAMFIRE project focuses on five key areas: 1) Laser Powder Directed Energy Deposition (LP-DED) AL6061-RAM2 feedstock specification and verification, 2) LP-DED process development and validation, 3) LP-DED printed AL6061-RAM2 microstructural and mechanical property characterization, 4) Hot-fire test a 5.4k-lbf thrust class regeneratively cooled nozzle, 5) Print large scale regeneratively cooled nozzle. Hot-fire testing demonstrates potential of advanced space technologies to NASA and potential users by providing the relevant environments to advance TRL levels to the 5/6 range.

ALUMINUM 6061-RAM2 MATERIAL

Aluminum 6061-RAM2 is an additively manufactured alloy that provides excellent ductility, high strength, and good thermal conductivity. This alloy utilizes a Reactive Additive Manufacturing (RAM) process, patented by Elementum 3D, that mixes gas-atomized aluminum alloy materials with ceramic particulates. Traditional wrought aluminum alloys are susceptible to solidification related cracking during additive manufacturing and traditional fusion welding processes. The RAM process enables alloys with improved thermal stability, increased strength at low and high temperatures, greater fatigue resistance, and high thermal conductivity.

MANUFACTURE

The 5.4k lbf thrust class regeneratively cooled nozzle was Laser Powder Directed Energy Deposition (LP-DED) printed with Al6061-RAM2 powder. The forward and aft manifold were traditionally manufactured out of Al6061-T6. The forward manifold was Electron Beam (EB) welded to the nozzle. The aft manifold was TIG welded with Al6061-RAM2 welding wire to the nozzle. The fluid fitting ports on the manifolds are explosively bonded Al6061-T6 to Inconel 625. The Al6061-T6 section is threaded and welded to the manifolds and the 316L stainless steel fluid fittings are threaded into the Inconel 625 section. Using this design, the risk of differences in coefficients of thermal expansion between the aluminum and stainless steel during hot fire testing are mitigated. The hotwall of the nozzle is chemical mechanical polished to reduce surface roughness and heat flux. A material and component overview of what was tested under RAMFIRE is shown in Figure 2. Select process steps of the nozzle manufacturing previously mentioned is shown in Figure 2.

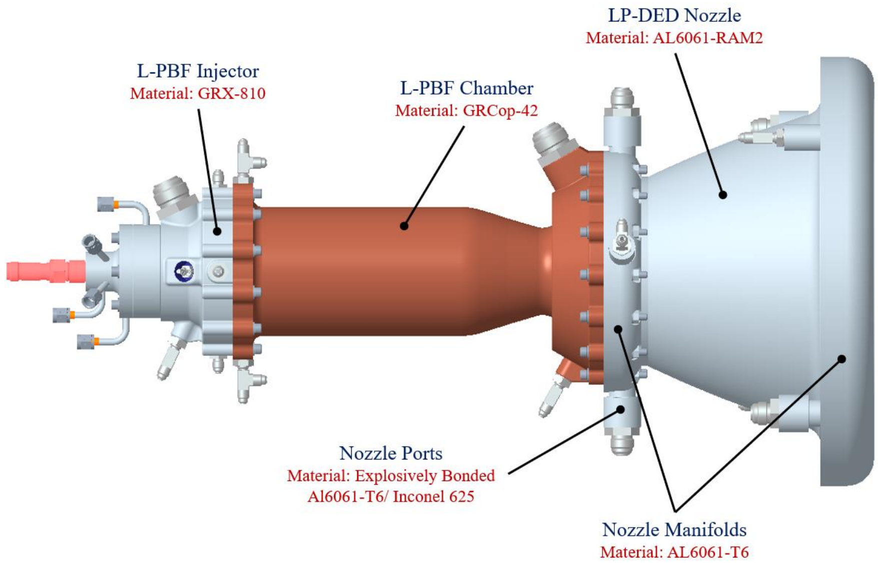

Figure 1. RAMFIRE Technology Elements.

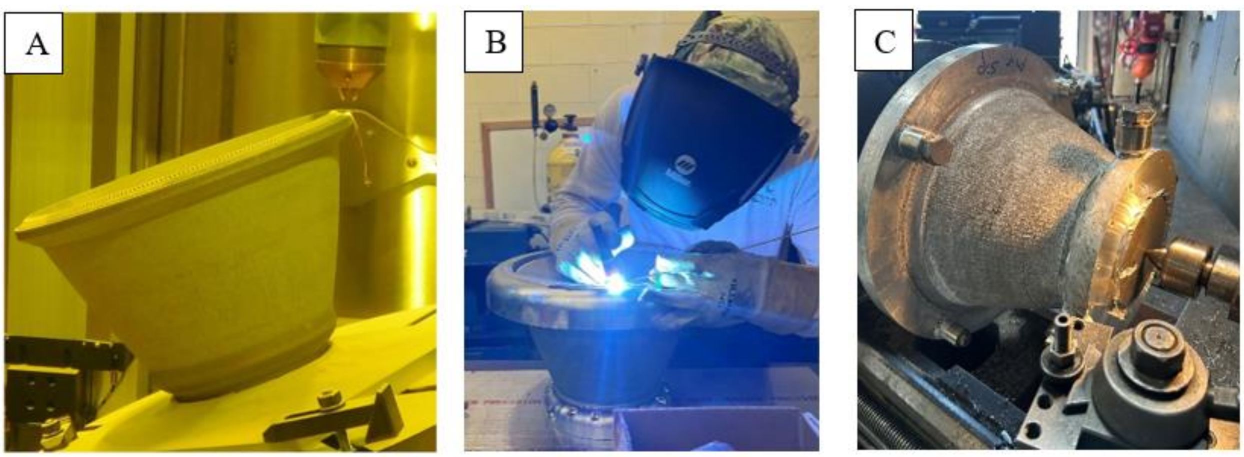

Figure 2. Select Nozzle Manufacturing Process Steps. (A) LP-DED Printing of RAMFIRE Nozzle, (B) TIG Welding the Aft Manifold to Nozzle, (C) Final Machining of the Nozzle.

Fabrication of a demonstrative large scale regeneratively cooled nozzle has been completed. The nozzle is approximately 36 inches in diameter. The nozzle was LP-DED printed with Al6061-RAM2. The demonstrative nozzle is shown in Figure 3.

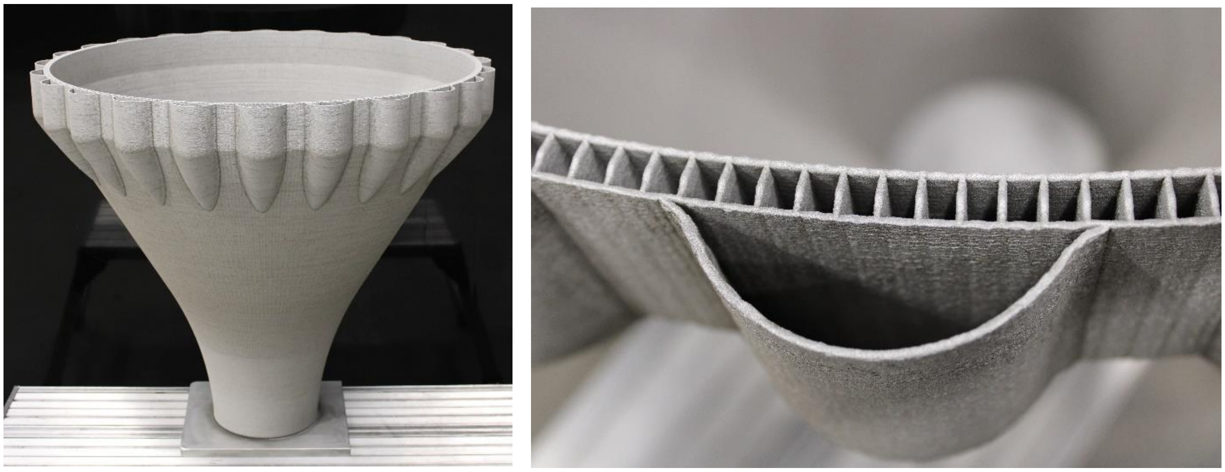

Figure 3. Demonstrative Large-Scale Regeneratively Cooled Nozzle.

WELDING DEVELOPMENT

The RAMFIRE nozzle uses two different types of welding for attaching the forward and aft manifolds. The forward manifold was mated to the AM nozzle using electron beam welding (EBW). The aft manifold was attached using Gas Tungsten Arc Welding (GTAW aka TIG), which requires use of a filler wire.

Typically, EBW of aluminum alloys requires the addition of filler material to avoid cracks in the weld. However, with the introduction of the novel Al6061-RAM2 material, filler was not required, no gross defects were recorded, and all welds appeared nominal. This indicates that the RAM additions in the nozzle powder mixed into the fusion zone of the EBW, reducing cracking susceptibility.

All GTAW work was conducted by MSFC's EM32 team who carried out base development on flat plate coupons and on a demonstration nozzle component. Because GTAW requires a filler material, the Al6061-RAM2 technology was leveraged to make filler wire. The focus of the early development was to investigate this filler metal, which had previously never been investigated by MSFC. The weld team was able to demonstrate high quality welds with these new filler metals and made a few key observations about the novel 6061-RAM2 material. These observations included that the new filler wire with RAM additions exhibited noticeable grain refinement in the weld fusion zone. Secondly, the RAM filler metal exhibited higher mechanical properties compared to a traditional 4043 filler metal. Finally, the addition of RAM particles to the solid wire reduced fusion zone cracking when compared to a 6061 wire with no RAM particle additions shown in Figure 4. These findings gave confidence in printing final test hardware.

During final test article welding, both the EBW vendor and MSFC's EM32 weld team reported no weld fusion zone cracking and each weld passed visual inspection prior to testing. After the initial hot fire test, no issues were observed with the final welds. This indicated the welds conducted on 6061-RAM2 material were in good condition for their load requirements and offered a good indication for welding this class of aluminum alloy for future projects.

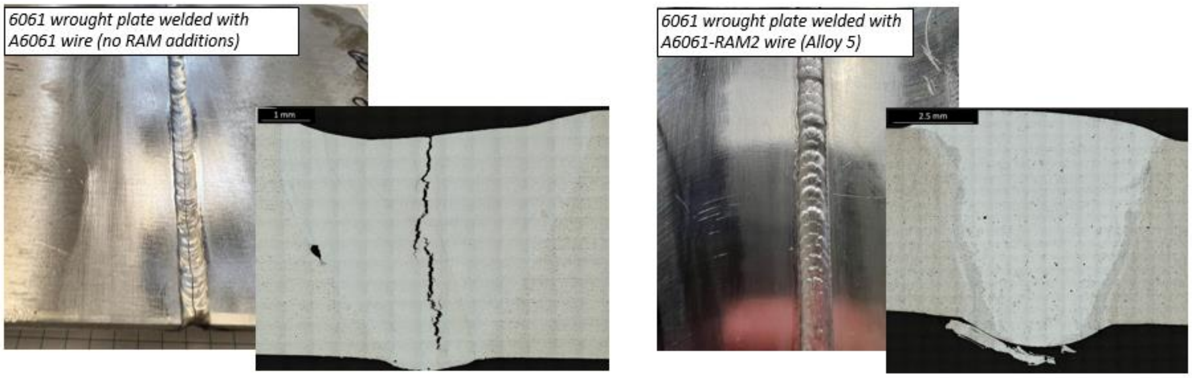

Figure 4. 6061 Wrought Plate Welded with Al6061 Wire (No RAM Additions) (Left), 6061 Wrought Plate Welded with Al6061-RAM2 Wire (Right).

PORT TESTING

The RAMFIRE nozzle uses fuel, either liquid hydrogen or methane, to regeneratively cool the hardware. The coolant enters through two fluid fittings in the forward manifold and exits from the aft manifold. One challenge was mounting the stainless-steel fluid fittings to the aluminum manifolds. There was risk of hardware damage due to the differences in coefficients of thermal expansion of the two materials at cryogenic temperatures. Additionally, there is little to no data on using aluminum at cryogenic temperatures and high pressures. In order to mitigate this risk, four fixtures were designed to be pressure cycled flowing liquid nitrogen at MSFC. The first two fixtures had the stainless-steel fluid fittings directly threaded into aluminum threads, the third fixture used a flange design that bolted stainless steel to the aluminum, and the fourth fixture was explosively bonded the AL6061-T6 to an Inconel 625 port. Two of these fixtures have been pressure cycled and burst tested and the other two are waiting for testing. The port testing overview is shown in Figure 5.

Figure 5. Port Testing Overview. (A) Four Test Fixtures Tested, (B) Testing Setup, (C) Burst Testing of the Port Samples.

HOT-FIRE TESTING

MSFC completed hot-fire testing of the Al6061-RAM2 channel-cooled nozzles to evaluate performance metrics of the nozzle and demonstrate viability of technologies in relevant environments. MSFC successfully used the Al6061-RAM2 nozzle at TS115 under the PL154 test program. The lander-scale hardware has been hot-fire tested at 5,400 lbf thrust using liquid hydrogen/liquid oxygen and liquid methane/liquid oxygen. The hardware was tested using liquid hydrogen/LOX for a total duration of 313 seconds during 9 hot-fire tests with the longest single duration of 60 seconds. The hardware was tested using liquid methane/LOX for a total duration of 275 seconds during 11 hot-fire tests. An image of the nozzle setup and hot-fire testing is shown in Figure 6.

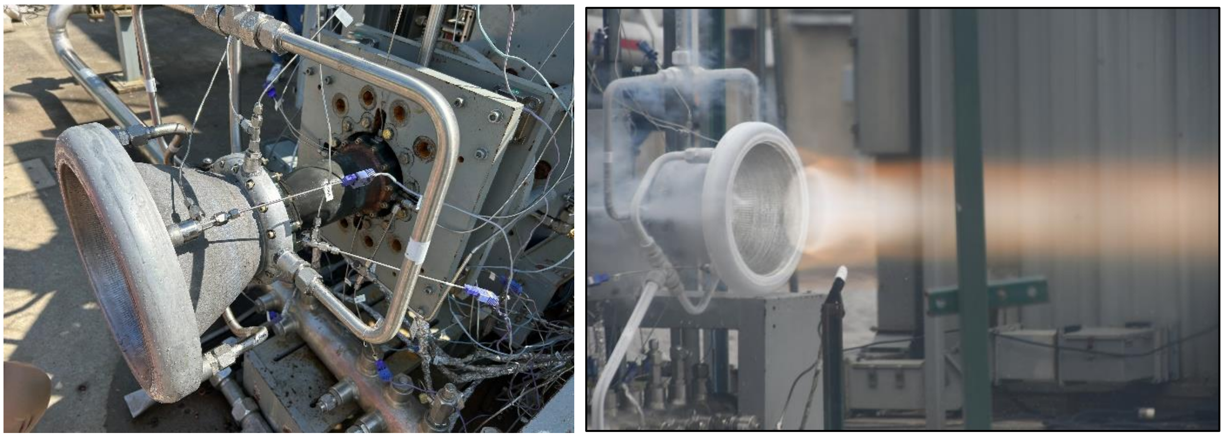

Figure 6. RAFMIRE Test Assembly with LP-DED Al6061-RAM2 Nozzle (Left), Hot Fire Test of Al6061-RAM2 Nozzle at MSFC TS115(Right).