CASE STUDY

3D Printing a Better Mousetrap

(or a better interplanetary heat exchanger)

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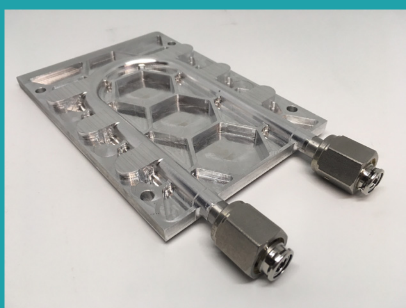


Through a multi-year endeavor, Fabrisonic has worked with NASA's Jet Propulsion Laboratory (JPL) to qualify Ultrasonic Additive Manufacturing (UAM) to print high performance thermal management devices. Fabrisonic heat exchangers (HX) have passed stringent NASA tests to surpass vibration, thermal, hermeticity and burst requirements. The use of UAM enables higher performance with both reduced weight and shorter lead times.

Current State of the Art

NASA constantly makes headlines with its interplanetary missions such as having landed several rovers on Mars. Among these missions is the Mars Science Laboratory that brought Curiosity rover into headlines around the world. For every mission going past Earth's atmosphere, numerous critical thermal systems are required to keep the sensitive electronics from getting too hot or too cold. JPL builds heat exchangers, like that used on the Mars Curiosity Rover, to circulate refrigerants through tubes to protect electronics from dangerously cold situations like when night temperatures on Mars drop to -140 degrees Fahrenheit and to reject excess heat from Radioisotope Power Sources during the day.

For decades, thermal management systems on these satellites and rovers have been limited to bent metal tubes glued along the outside of the vehicle's structure. This current production method at JPL starts with a CNC milled structural orthogrid (thin ribs on a thin plate) to which aluminum tubing is epoxied. In this design, fluid is pumped through the tubing to heat and cool critical components. This design has been the method of choice for decades because it is robust and has long standing flight heritage. However, the epoxy is a poor conductor of heat, the solution is heavy, and production can take up to nine months for a single system.

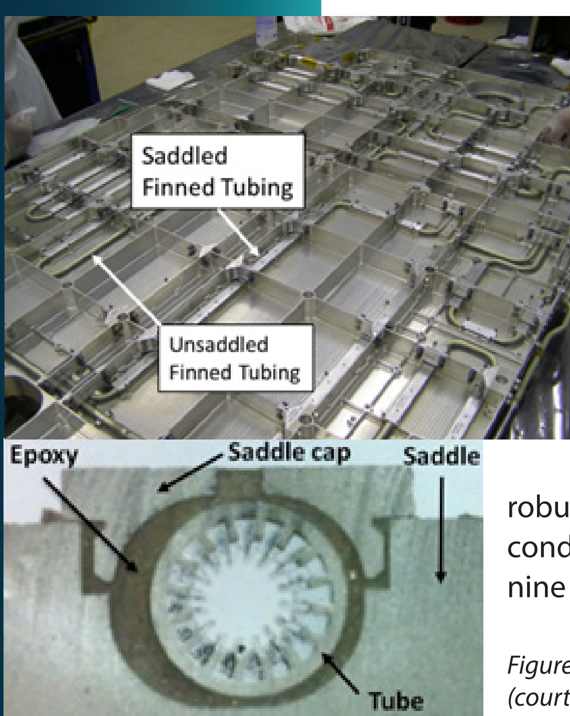


Figure 1 - Traditional HX production using bent aluminum tubing and epoxied saddles (courtesy of AJ Mastropietro, NASA JPL).

The Project

In January 2014, in search of a better solution, NASA JPL awarded Fabrisonic initial seed funding to 3D metal print a proof of concept for a better solution. Subsequently, as the viability of a 3D metal printed heat exchanger was established, follow-on funding was awarded in June of 2015 and June of 2016 (PHI and PHII SBIR). Through these programs, Fabrisonic developed pumped fluid loop heat exchangers for NASA JPL where 3D metal printing enabled the piping to be printed integrally into structural panels.

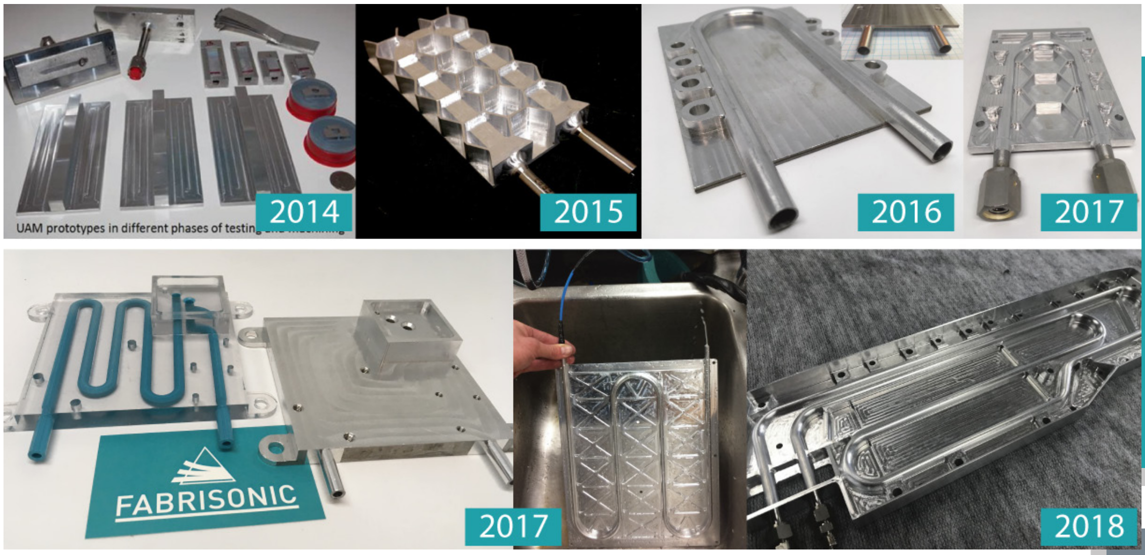


Figure 2 - Evolution of 3d printed HX's with NASA JPL.

Ultrasonic Additive Manufacturing

Ultrasonic Additive Manufacturing (UAM) is a hybrid 3D metal printing technology that uses high frequency ultrasonic vibrations to scrub metal foils together to build up metal layer-by-layer to a net shape that is selectively machined. UAM print heads are integrated into a standard CNC machining center—together forming a hybrid additive manufacturing process. With both additive and subtractive processes, UAM can produce complex internal geometries considered impossible to replicate with conventional manufacturing alone. Additionally, Ultrasonic joining is a solid-state process, which enables directly printing 'difficult' aluminum alloys such as 6061 and 7075. Since the process does not heat the metal past 250°F (much lower than melting) the chemistry, grain structure, and material properties of the incoming feedstock are retained.

1. The process can begin with either a billet plate or printed layers. To optimize build time, UAM typically begins with the largest substrate possible thereby only printing part of the final structure.
2. A wide assortment of tools are used to mill and shape channels into the substrate thereby generating both a CNC surface finish and as well as CNC accuracy. Since the channels are milled from the top, any pattern that can be imagined can be created. If the channels need to vary in three dimensions, milling and welding can be alternated to produce

complex three-dimensional flow paths.

3. To assure a strong bond over the void, channels are filled with a water-soluble support material that matches the modulus of the surrounding metal.
4. Any excess support material is milled off and a small slot is milled to facilitate support removal.
5. UAM is used to weld layers of metal (typically 0.006"/layer) over top of the billet and channels. UAM has been used to cap as thin as 0.020" and up to several inches above the flow paths.
6. Tap water is used to dissolve the support material, leaving a clean and smooth channel surface.
7. As with other additive technologies, Hot Isostatic Pressing allows consolidation of any porosity left during 3D printing.
8. If required, standard heat treat schedules can be applied.
9. NASA heat exchangers require stainless steel fittings. Fabrisonic utilizes another solid-state welding process, friction welding, to integrate fittings directly to the 3D printed structure.
10. The last step is final machining to achieve thin tube walls and structural elements from the design.

The graphic below describes the steps used to UAM a typical heat exchanger

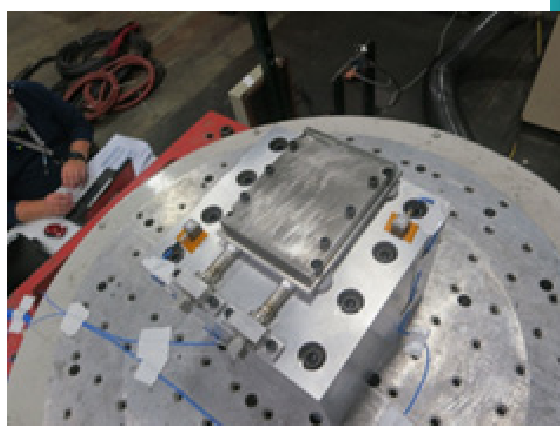
Figure 3 - Process steps for JPL test heat exchangers.

Results

Over the course of the program, dozens of different heat exchangers were built and tested. The program culminated with ground-based qualification of three identical, 3D printed heat exchangers. Testing including:

- Thermal cycling from -184°F to 248°F
- Proof pressure testing to 330 PSI
- Thermal shock testing by submersion in liquid nitrogen
- Vibe testing to simulate a Saturn V launch in x, y, and z orientations while bolted to a dummy mass to mimic a typical hosted electronics package
- Burst testing greater that 2500 PSI with a 0.030" wall thickness
- Full 3D Computed Tomography (CT) scans of each specimen before and after mechanical testing
- Helium leak testing to less than 1x10-8 GHe scc/sec

All three heat exchangers passed all tests with flying colors.



The team did a case study of a current production specimen versus an equivalent UAM design and the results were quite encouraging:

	Epoxy Tube Specimen	**Equivalent UAM Specimen**
Thermal Design:	Epoxy tube (poor thermal)	Tube integral to structure
Part Count:	40+	1
Total Mass:	1.82 Kg	1.26 Kg
Lead Time:	2-months	2-weeks (no tooling)

Thermal conductance improvement between working fluid and electronics package bolted joint interface is estimated to be about 25%-30% higher due to the complete elimination of epoxy.

Technology Outlook

The methods developed under the NASA JPL funding has been quickly extended to numerous commercial production applications. Channel widths range from 0.020" to greater than one inch with parts sized up to four feet in length. To help with technology adoption, the team is working to explore other key areas. For instance, the solid-state nature of UAM allows integrating multiple metals into one build. Thus, copper may be integrated as a heat spreader in critical locations improving thermal performance with a small weight penalty. UAM also has the capability of embedding sensors into solid metal thanks to its low temperature nature. For HX's, this means that sensors can be integrated in critical locations to improve control and to monitor system health.

Acknowledgements

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References

Mastropietro, A. J., Pauken, Michael, Hofmann, Douglas, D'Agostino, Saverio, "Ultrasonic Additive Manufacturing (UAM) of Heat Rejection System (HRS) Heat Exchangers," Innovative Spontaneous Concept R&TD, Annual Report to JPL's R&TD Program Office, 2014.

Sunada, Eric, and Rodriguez, Jose, "JPL Advanced Thermal Control Technology Roadmap," Spacecraft Thermal Control Workshop, El Segundo, CA 2017.

Maghsoudi, Elham, Mastropietro, A. J., Roberts, Scott, and Kinter, Bradley, "Experimental Thermal Performance Comparison of 3D Printed Aluminum Heat Exchangers vs Traditionally Manufactured Heat Exchangers," Spacecraft Thermal Control Workshop (STCW), El Segundo, CA, March 2017.

Mastropietro, A. J., Roberts, Scott, Hofmann, Douglas, Maghsoudi, Elham, and Luong, Simon, "NASA Development of Complex Heat Exchangers Leveraging Additive Manufacturing," Propulsion Safety and Sustainment Conference, Phoenix, AZ, May 2017.

Anderson, Lucas, Swenson, Charles, Mastropietro, A. J., Maghsoudi, Elham, Luong, Simon, Hofmann, Douglas, and Roberts, Scott, "Active CryoCubeSat Project: Design and Status," Small Satellite Conference, Logan, UT, August 2017.