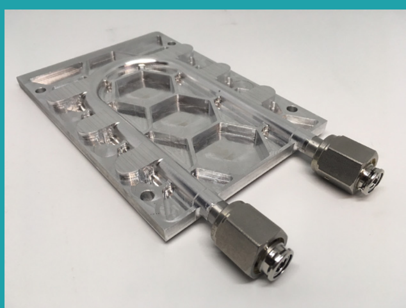
Space-grade 3D Metal Printed Heat Exchangers

Justin Wenning, Production Engineer
Fabrisonic LLC



Why 3D Printed Heat Exchangers?

NASA's Jet Propulsion Laboratory (JPL) constantly makes headlines with its interplanetary missions around our galaxy such as landing several rovers on Mars. For every interplanetary mission that JPL oversees, numerous critical heat exchanger devices are required to regulate the sensitive, on-board electronic systems from temperature extremes experienced in space. These devices can be small (3 in. x 3 in.) or large (3 ft. x 3 ft.).

For decades, the construction of these heat exchanger devices has been limited to bent metal tubes glued along and fastened to the outside of the vehicle's structure, see Figure 1. This approach has long been the method of choice over the years within NASA. However, the method is heavy and underperforms thermally. In addition, production of the devices can take up to nine months because they are assembled and quality-checked by hand. Applying 3D-printing technology to make these structures shows the potential to remedy these limitations and greatly improve interplanetary heat exchanger device design. Through a multi-year endeavor, Fabrisonic has been working with NASA JPL to develop and qualify ultrasonic additive manufacturing (UAM) heat exchanger devices. The concept is to incorporate the pumped-fluid loop tubing directly into the structure through UAM for robustness,efficiency, and multi-functionality such as acting as a structural member.

Ultrasonic Additive Manufacturing and Heat Exchangers

UAM is a hybrid 3D metal-printing technology that uses high frequency ultrasonic vibrations to scrub metal foils together layer by layer as opposed to using a directed energy heat source (e.g., laser, e-beam, etc.). UAM systems are integrated into computer numerical control (CNC) frameworks to enable subtractive operations interchangeably with the additive ultrasonic process — a form of hybrid additive manufacturing. Because there are no controlled atmospheres in the process, UAM system design and part size can range drastically in size. Ultrasonic joining is a solid-state (no melting) process, which enables joining alloys that have been historically difficult to weld. Examples include 1000, 2000, 6000, and 7000 series aluminums, coppers,

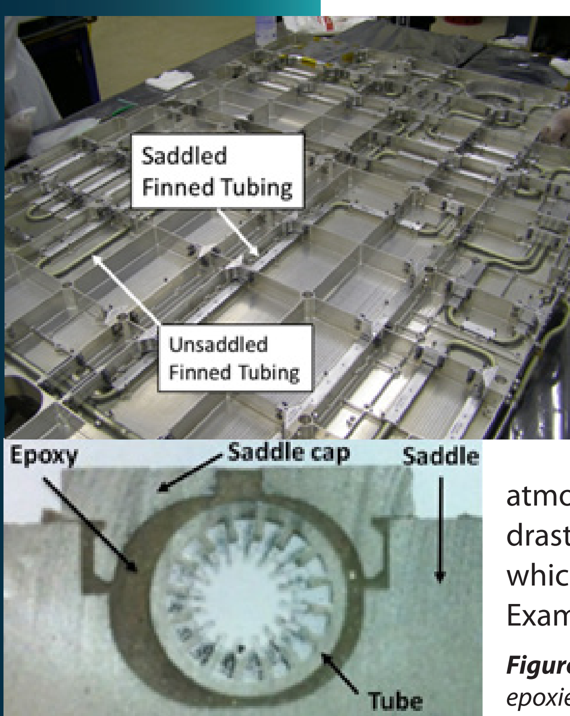


Figure 1 *- Traditional heat exchanger device production at NASA JPL using bent tubing and epoxied saddles (courtesy of AJ Mastropietro, NASA JPL). This approach involves a long lead time, touch-labor, extra weight, and poor thermal performance.*

stainless steels, and exotic refractory metals. These metals are commonly used in JPL heat management systems.

Fabrisonic began collaborating with NASA JPL to investigate simple, small-size UAM heat exchangers in 2014 through a JPL Spontaneous R&TD grant [1]. The team then moved onto larger more representative structures in 2015-2017 through NASA's SBIR/STTR program [2-5]. The culmination of this effort was the construction of a full-size, functioning heat exchanger prototype for the Mars 2020 rover mission that was 30% lighter in mass and made in a fraction of the time. The heat exchanger technology progression is shown in Figure 2. All of Fabrisonic's heat exchanger devices involve building the pumped-fluid loop directly into the surrounding structure, an unprecedented task for NASA JPL.

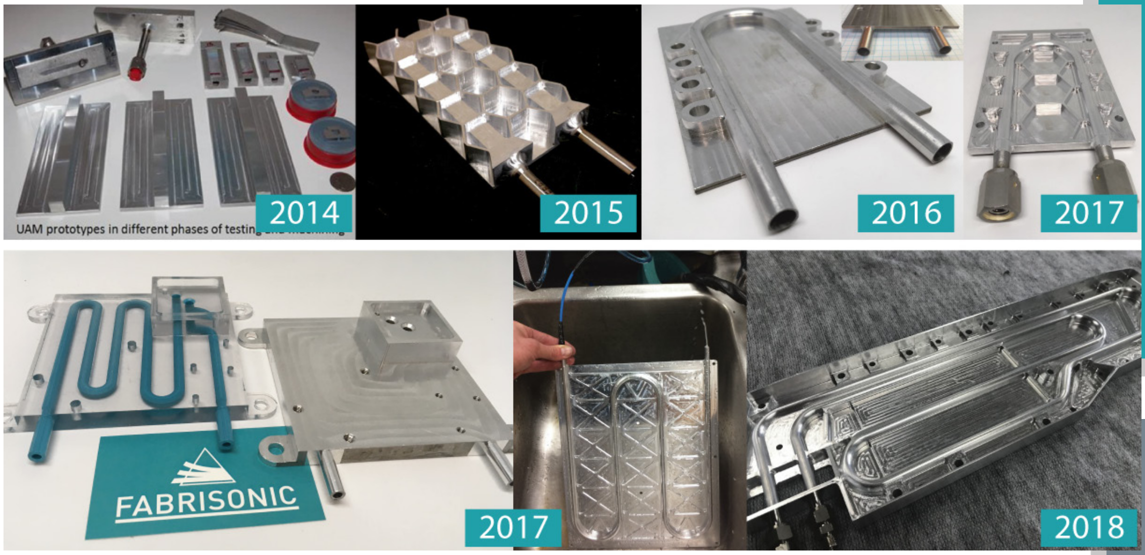


Figure 2 *- Evolution of UAM 3D printed heat exchanger with NASA JPL. Samples began small to evaluate benchmark burst and helium leak performance in 2014. The team then began focusing on technology scale-up and system integration. The culmination is a full-size functioning.*

UAM heat exchanger devices are made following the steps outlined in Figure 3. The process begins with a metal substrate, like all 3D metal-printing. Material is then added and removed from the structure for the internal passageways. A proprietary water-soluble support structure is then added to help with additional material deposition. Finally, optional heat-treating and final CNC machining is carried out to add strength and features, respectively. Friction welding was used on NASA JPL development parts to add SS tubing to the aluminum structure. SS tubing is desirable for fitting attachment since hermetic aluminum welds are challenging and cannot always be achieved.

Raising the Technology Readiness Level

A big component of UAM heat exchanger evaluation and scale-up for NASA JPL was elevating the technology readiness level (TRL) from 3 to near 6. Over the course of the program, dozens of different heat exchangers were built and tested by Fabrisonic and affiliate, EWI, to work toward a prototype which would undergo stringent ground-based qualification standards based-off current NASA JPL heat exchanger devices.

This NASA JPL TRL 6 qualification included:

- Proof pressure testing to 330 PSI
- Controlled thermal cycling from -184°F to 248°F in an environmental chamber for two days
- Vibration testing on an electrodynamic shaker to simulate a common day rocket launch (1-10 G) in all orientations while bolted to a dummy mass to mimic a typical hosted electronics package
- Helium leak testing to less than 1x10-8 cc/s GHe between thermal and vibration testing
- Burst testing greater that 2500 PSI with a 0.030-in. wall thickness
- Full 3D computed tomography (CT) scans of each specimen before and after mechanical testing to evaluate void density and any accumulated damage from testing.

All three of the UAM heat exchanger components passed the testing qualifications to elevate the technology to near TRL 6. Further helium leak and burst testing was then conducted at NASA JPL to corroborate results. Thermal shock testing was carried out on certain heat exchangers by submersion in liquid nitrogen (-320°F) to test the bi-metallic friction welded stainless steel aluminum joint. The joint was found to be robust and helium leak tight after submersion.

Figure 3 - UAM process steps for fabricating NASA JPL heat exchangers.

Technology Outlook

UAM heat exchanger technology developed under NASA JPL funding has been quickly extended to numerous commercial production applications. Channel widths range from 0.020 inch 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 lack of melting in UAM enables the integration of multiple metals into one build since high temperature chemistry is avoided. 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 heat exchanger devices, this means that sensors can be integrated in critical locations to improve control and to monitor system health.

CT Scan　　　　Vibration Testing

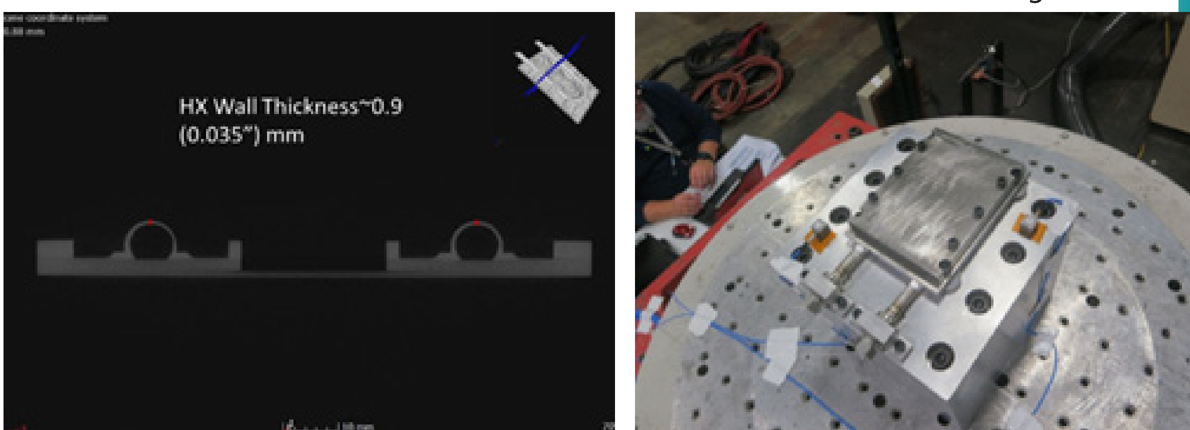


Figure 4 *- Stringent ground-based space-grade qualification testing of UAM heat exchanger devices. EWI helped Fabrisonic complete CT Scanning and helium leak testing of UAM heat exchangers throughout development.*

Acknowledgements

The authors would like to acknowledge NASA's Space Technology Mission Directorate SBIR Project Management Office (Reference Contract NNX16CP13C) and its Small Spacecraft Technology Project Management Office for enabling this work. Part of the research was also carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

1. 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.

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

3. 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.

4. 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.

5. 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.

***Justin Wenning** is a production engineer at Fabrisonic LLC, an EWI affiliate. His expertise is in developing UAM capabilities for advanced heat exchangers, structural health monitoring components, and dissimilar metal parts. Justin graduated from The Ohio State University with a degree in welding engineering with a focus on ultrasonic joining. Justin was awarded as a member of the prestigious Forbes Magazine 30-Under-30 in Manufacturing & Industry in 2017 as well as the Society of Manufacturing Engineers (SME) 30-Under-30 Award in 2016.*