REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
08-09-2021	Technical Report	Sept 2021

4. TITLE AND SUBTITLE
A Multi-Disciplinary Approach to Materials Joining for Fabrication of a Prototype Stirling Engine Heat Exchanger

5a. CONTRACT NUMBER
DE-NA0003525

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Lawrence Johnson, Chuck Walker, Kenneth Armijo, James Scott, Dennis De Smet, Peter Kinney, Brad Hoff, Anthony Baros, Ender Savrun

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Sandia National Laboratories, Albuquerque NM, USA
Air Force Research Laboratory, Directed Energy Directorate, Kirtland AFB, NM, USA
Sienna Technologies, Inc., Woodinville, WA, USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory, Directed Energy Directorate, Kirtland AFB, NM, USA

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RD

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited. Public Affairs release approval # AFRL-2021-3018

13. SUPPLEMENTARY NOTES

Funding provided by the Air Force Research Laboratory and the Operational Energy Capability Improvement Fund

14. ABSTRACT
A prototype heat exchanger for a Stirling type heat engine is fabricated using multi-disciplinary joining techniques. A complex assortment of materials and geometries are joined in multiple steps producing sub-assemblies which are then consolidated into the final heat exchanger assembly. To build the heat exchanger, an array of Inconel® 718 tubes is high vacuum furnace brazed to Multimet® Alloy tube headers and Multimet header collectors using commercially available BNi-2 BFM paste. A set of vendor-fabricated electromagnetic (EM) susceptor tiles, individually comprised of cylindrical AlN:Mo ceramic matrix composite elements, a metal back-plane assembly including a Kovar® baseplate, and internal (96.4Au-3Ni-0.6Ti) Braze Filler Metal (BFM) interfaces are then high vacuum furnace brazed to the Inconel tubing array also using BNi-2 BFM paste and foil. Finally, the completed absorber/tubing array is then joined to the Stirling engine cylinders using Gas Tungsten Arc Welding (GTAW) more commonly known as Tungsten Inert Gas (TIG) welding and Multimet filler rod. The complete heat exchanger assembly is then leak checked using a Varian Helium-leak tester. Mating of the heat exchanger to the Stirling engine and performance testing is not discussed herein.

15. SUBJECT TERMS
Heat Exchanger; Stirling Engine; Material Joining; millimeter wave; RF; W-Band; power beaming; susceptor;

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Anthony Baros
U	U	U	U	7	**19b. TELEPONE NUMBER (*Include area code*)** 505-853-8186

A Multi-Disciplinary Approach to Materials Joining for Fabrication of a Prototype Stirling Engine Heat Exchanger

L. Johnson[1], C. Walker[1], K. Armijo[1], C. Andraka[1], J. Scott[1], D. De Smet[1], P. Kinney[1], B. Hoff[2], A. Baros[2], E. Savrun[3]

[1]Sandia National Laboratories, Albuquerque, NM, USA
[2]Air Force Research Laboratory, Directed Energy Directorate, Kirtland AFB, NM, USA
[3]Sienna Technologies, Inc., Woodinville, WA, USA

Abstract

A prototype heat exchanger for a Stirling type heat engine is fabricated using multi-disciplinary joining techniques. A complex assortment of materials and geometries are joined in multiple steps producing sub-assemblies which are then consolidated into the final heat exchanger assembly. To build the heat exchanger, an array of Inconel® 718 tubes is high vacuum furnace brazed to Multimet® Alloy tube headers and Multimet header collectors using commercially available BNi-2 BFM paste. A set of vendor-fabricated electromagnetic (EM) susceptor tiles, individually comprised of cylindrical AlN:Mo ceramic matrix composite elements, a metal back-plane assembly including a Kovar® baseplate, and internal (96.4Au-3Ni-0.6Ti) Braze Filler Metal (BFM) interfaces are then high vacuum furnace brazed to the Inconel tubing array also using BNi-2 BFM paste and foil. Finally, the completed absorber/tubing array is then joined to the Stirling engine cylinders using Gas Tungsten Arc Welding (GTAW) more commonly known as Tungsten Inert Gas (TIG) welding and Multimet filler rod. The complete heat exchanger assembly is then leak checked using a Varian Helium-leak tester. Mating of the heat exchanger to the Stirling engine and performance testing is not discussed herein.

Introduction

The Stirling Engine is a closed gas loop heat engine developed and patented in 1816 by Robert Stirling[1], it contains a fixed quantity of a gas and utilizes the thermal gradient driven expansion and contraction of the gas to produce mechanical force. A heat exchanger transfers heat energy from the heat source to the system gas through absorption of the source heat and conduction of that heat to the gas contained within. As the gas passes through the heat exchanger it absorbs the heat from the heat exchanger and then begins to expand in volume as it proceeds to a cylinder and piston where it completes expansion and thereby it forces the piston to the bottom of its stroke. The flow of the gas then reverses direction as it cools and it exits the cylinder as it is forced out by the rising piston. The gas passes through the heat exchanger again completing its cycle as it expands into the other cylinder and piston.

Statement of Problem; The construction of a heat exchanger must take advantage of the highest quality materials and joining processes to produce a functional, efficient, and robust Stirling Engine system. The materials must be compatible for joining by one or more methods and the joining processes utilized must at best complement each other or at least not interfere with one another. While many materials may be directly incompatible and joining processes may interfere with each other in temperature requirements or limitations, some intermediate materials can bridge compatibility gaps and processes can be performed in a deliberate order. Properly sequencing joining processes allows one to fulfill immediate temperature necessities of a higher melting point BFM while ignoring the limitations of the other lower melt point BFMs to be utilized in subsequent braze steps. Conversely; lower braze temperatures of later braze steps are carefully controlled to avoid remelting brazements of previous steps. For example the active alloy Au-Ni-Ti BFM used for the EM susceptor tile subassemblies has a brazing temperature of 1030°C[2], and the BNi-2 BFM alloy used for the brazing of the Gas Passage Assembly and later for brazing the EM susceptor tiles onto the Gas Passage Assembly has a melting point of 1000°C[3]. Note that while BNi-2 is used in a sub-assembly braze and then again in a later brazement where the initial braze at 1020°C using BNi-2 is exposed again to 1010°C the previous brazements were in little danger of re-melt due to a higher temperature diffusion hold during the first BNi-2 braze operation. Furthermore; accumulation of mass and bulk are carefully considered throughout the entire process and delayed where possible to avoid issues associated with stress and geometric bulk.

Heat Exchanger Design

The Heat Exchanger was developed to enable a ground-to-ground power beaming experiment in which a beam of millimeter-wave (mm-wave) radiation is launched from a transmitter, received at a remote location, and eventually converted to useable electrical power[4]. Components comprising the heat exchanger include sixteen EM susceptor tiles (A), sixty 0.125 inch (3.175mm) diameter Inconel tubes (B), two Multimet headers (C), two Multimet Collectors (D), and two Multimet piston cylinders (E), as illustrated in Figure 1. These components are described in further detail in the following portions of the paper.

The EM susceptor tiles (A) produced by Sienna Technologies Incorporated (STI) (Woodinville, WA, USA) are vacuum furnace brazed to the Inconel tubes (B) using BNi-2 foil and paste BFM. The Inconel tubes (B) are vacuum furnace brazed into the Multimet headers (C) using BNi-2 paste BFM. The Multimet headers (C) are vacuum furnace brazed to the

Multimet collectors (D) using BNi-2 paste BFM, and the Multimet collectors (D) are welded to the piston cylinders (E) by a TIG welding process using Multimet weld filler rod.

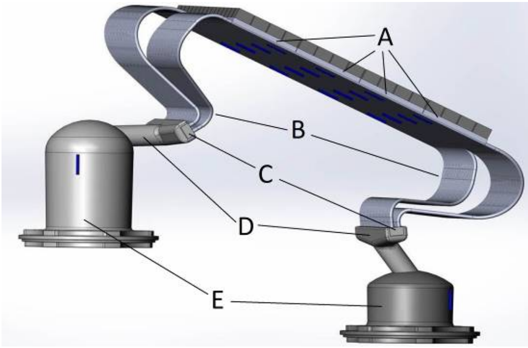

Figure 1. A computer rendering of a Stirling Engine heat exchanger. Components are: A) mm-Wave Absorbing Tile Array (16), B) Gas Tubing Array (60), C) Tubing Headers (2), D) Gas Flow Collectors (2), E) Piston Cylinders (2).

Sub-Assemblies and Components

EM Susceptor Tiles, such as those shown in Figures 2 & 3 enable absorption of an incoming beam of mm-wave EM radiation (~95 GHz), conversion of the radiation to heat, and conduction of heat to the gas tubing array which contains the working gas (H2) for the Stirling engine.

Figure 2. A EM susceptor tile. Visible are the 25 AlN Cylinders and metal baseplate.

In the present configuration, each tile contains an array of 25 electromagnetically lossy AlN:Mo ceramic matrix composite cylinders[5,6] which absorb the mm-wave EM energy within their bulk, converting it to heat[7,8]. The spacing of the ceramic cylinders is driven by a compromise between mm-wave radiation absorption efficiency[8] and manufacturability. The high thermal conductivity of the AlN matrix[5] enables efficient conduction of heat from the bulk ceramic cylinders to the metal back-plane to which they are attached.

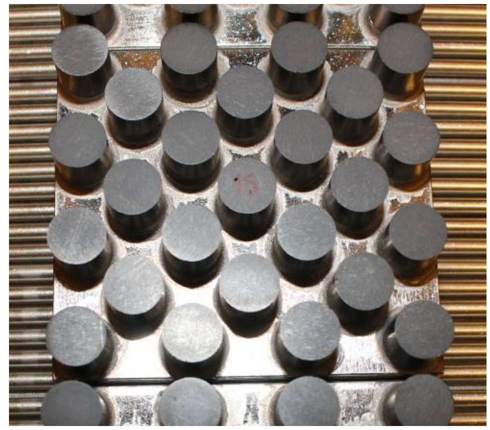

Figure 3. A top view of the AlN Absorber Tile.

The bottom portion of the EM susceptor tile back-plane consists of a Kovar baseplate with 15 parallel grooves machined to accommodate the Inconel tubes.

The Gas Tubing Array consists of the passages which carry the gas through the system to the heat transfer section are formed from sixty Inconel tubes. All sixty identical length tubes seen in Figure 4 are bent into the same shape which is arranged into two symmetrically opposite groups of 30 tubes which align into two rows at the tube headers while creating a single plane of all 60 tubes for the Absorber Tile Array.

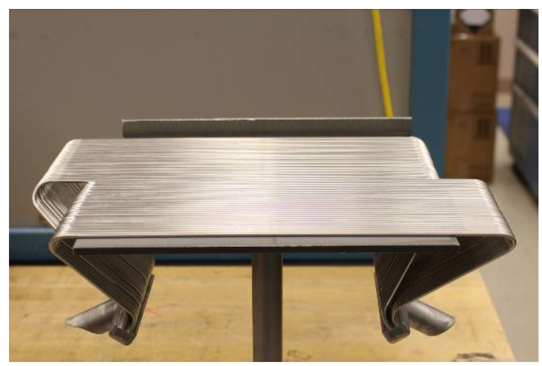

Figure 4. The Gas Tubing Array, note that all sixty tubes have the same shape and length and are divided into two opposite groups of thirty tubes.

The two groups constituting equivalent lengths with the same shape; in theory serve to produce no preferred flow path for the gas which in turn balances energy transfer equally among all tubes beneath the EM susceptor tile array.

The Tubing Headers identically machined from Multimet billet terminate the tubing array at both ends. While providing a structural anchor to support the mass of the heat transfer section, they also maintain the spatial arrangement of the gas tubes in a parallel and planar orientation that accommodates the EM susceptor tiles. Each header has two rows of thirty holes drilled through the billet.

Brazing tests (Figure 5.) are performed to determine the best possible sizes to be used for the fit-up and clearance of the Inconel tubes.

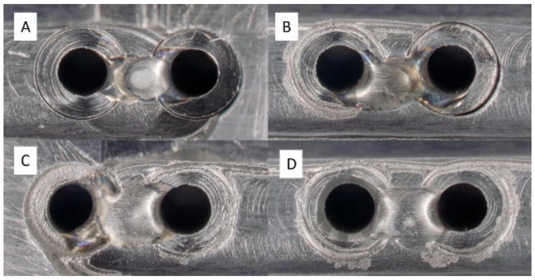

Figure 5. Tube to Header braze joint clearance test specimens: A & B indicate insufficient clearance, while C indicates the minimum braze clearance which allows complete braze flow, and D may indicate excessive clearance that could result in a brittle centerline eutectic phase.

The sixty Inconel tubes are fit by hand into the headers and each tube is autogenously spot welded to the interior face of the header using a TIG process. (Figure 6)

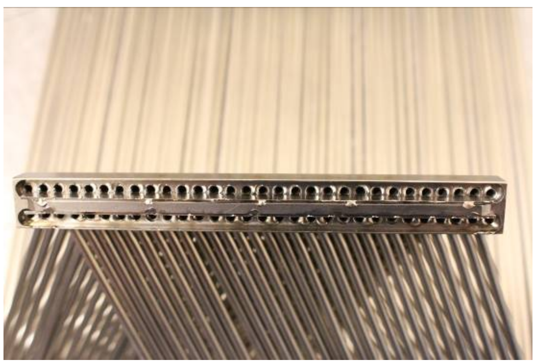

Figure 6 The gas tubes are set flush to the inside surface of the Header and TIG welded prior to brazing. The depth setting shims (TIG welded to the center divider) are removed prior to brazing.

This is done to secure the tubes during brazing in lieu of fixturing. The 120 tube brazements to the headers and the headers to the collectors is performed in a single vacuum furnace braze run, which is discussed in more detail later.

Collectors cast from Multimet alloy and having precision machined channels for the Tubing Headers (Figure 7) provide the transition from the Tubing Headers to a larger diameter pipe which is welded by TIG process the Piston Cylinders. The Collectors; with a shape similar to the capital letter "T", have a channel machined along the top to accommodate the Tubing header. As with most components of this system the Collectors are functional as well as structural. In this regard the collectors not only comprise the structural support of the heat transfer section but they also collect the gas flow from the sixty gas tubes (Figure 8) anchored in each tubing header into a single larger delivery pipe connected to each piston. It is noteworthy to point to the fact that all gas passages in this system are bidirectional and thus the collectors also serve as the divergence point for the gas to split evenly into the sixty individual gas flow paths of the tubing headers. As previously mentioned the sixty tubes, the two headers and the two collectors were all brazed in a single furnace run which is described in more detail in the section titled "Joining Operations".

Figure 7. The rectangular Header block (center) is inserted in a channel machined into each Header. Also visible are the tack weld spot and the subsequently brazed joint.

The Piston Cylinders are castings of Multimet alloy that have precision machined bores and mounting flanges. The cylinders are arranged one at each end of the heat exchanger so that the gas flows out from the first cylinder, through the whole heat exchanger and into the second cylinder. There are no valves controlling gas flow in or out of the cylinders but one cylinder does have a longer bore that accommodates a gas re-generator assembly in the bore above the piston. No details regarding the gas re-generator are provided in this discussion. The transition between the collectors and the cylinder headspace is shaped by hand using various files and rotary grinding tools so that the transition from the cylinder wall to the collector tube is smoothed to promote a laminar gas flow and minimize turbulence. The collectors are welded to the cylinders using a standard TIG welding process and 0.0625 inch (1.588 mm) diameter Multimet alloy filler rods.

Figure 8. From this orientation it can be seen that the shape of tubes allows the two groups of thirty tubes to align into two rows in the header

Joining Processes

As an assembly's geometries and materials increase in complexity; so too must the joining processes also increase in complexity. This is especially so when high quality permanent joining of pressurized systems is needed as in this case. The

EM susceptor tiles, purchased from STI, contain Active Braze interfaces (with A96.40-Ni3-Ti0.6 filler) joining AlN ceramic cylinders to a metal back-plane structure which includes a Kovar baseplate. Separately, the tubing array, the headers, and the collectors were vacuum furnace brazed by Sandia National Laboratories: Metallurgical and Materials Joining Lab of Org. 1831. Although the majority of this assembly is vacuum furnace brazed, nevertheless two key metal-to-metal joints are made using TIG welding.

The Order of Joining Operations were as follows; 1) The EM susceptor tiles were brazed by the vendor during manufacturing. 2) The Gas Tubing Array, the Tubing Headers, and Collectors were all vacuum furnace brazed into a single Gas Passage assembly. 3) The EM susceptor tiles were vacuum furnace brazed onto the Gas Passage. 4)The Piston Cylinders were TIG welded onto the Collectors.

The Gas Passage Assembly is assembled by hand with the Gas Tubing Array approximately aligned and loosely inserted into the Tubing Headers. The planar surface of the Gas Tubing Array is clamped between two Kovar plates while the tube ends are carefully tack welded using TIG weld process. Tube ends are not welded completely around their circumferences but rather only in a spot of sufficient size to hold the tube securely in place during the furnace brazing operation. Next the Collectors are positioned on the Tubing Headers and tack welded in place by autogenous TIG method. The entire Gas Passage Assembly is then solvent cleaned with acetone and rinsed with isopropanol and blown dry with a nitrogen blow gun. BNi-2 BFM paste is then dispensed onto the joints were the Gas Tubes enter the Tubing Headers and BNi-2 paste is also dispensed onto the joint between the Tubing Headers and the Collectors. The gas passage assembly with BNi-2 brazing paste applied is then set on a layer of Alumina separator sheets on top of a Molybdenum pedestal and strips of alumina are inserted between the individual tubes (Figure 9) to prevent diffusion bonding and to establish the clearance required for the tube channel fins on the bottom of the Absorber Tiles.

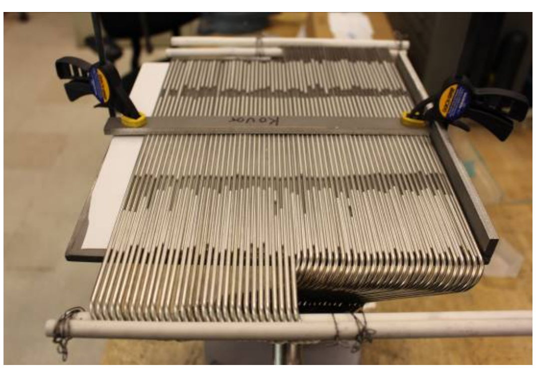

Figure 9.The Gas Tubing Array is clamped down to a Kovar setting plate with 0.020 inch thick Alumina strips separating tubes, and 0.020 inch thick Alumina plates between the Inconel tubes and the Kovar setting plate, also Alumina rods tied together with Molybdenum wire help align tube ends.

A pair of 0.375 inch (9.525 mm) diameter Alumina rods are tied together with 0.030 inch (0.762 mm) diameter Molybdenum wire to align tubing groups into the two opposite groups of 30 tubes each. Alumina sheets are then added on top of the planar surface of the Gas Tubing Array and weights are placed on top of the Alumina sheets (Figure 10) to maintain the planar surface during brazing.

Figure 10. The clamps are replaced with additional Alumina plates and stainless steel weights to keep the tubes flat in the vacuum brazing furnace.

Type K thermocouples are placed in contact with the assembly, the vacuum brazing furnace is closed and the vacuum system started. (Figure 11) The vacuum level of approximately 10^{-6} torr is achieved in approximately 30 minutes. The vacuum brazing temperature profile for the BNi-2 BFM is as follows: Heat to 65°C at 5°C/minute and hold at 65°C for 60 minutes to allow any water moisture and high vapor pressure solvents to evaporate and be removed by the vacuum system. Heat to 450°C at 5°C/minute and hold at 450°C for 120 minutes to allow the organic compounds of the brazing paste binder to be vaporized removed by the vacuum system. Heating then continues to 950°C at 5°C/minute and is held at 950°C for 45 minutes to allow any variation of temperatures within the assembly to come within 3°C of each other before continuing. Finally, the temperature is increased to 1020°C at 5°C/minute and is held at 1020°C for 30 minutes for the brazing to take place. Following brazing the temperature is allowed to cool at 5°C/minute to about 100°C under vacuum at which time Argon is introduced to the chamber to facilitate further cooling.

After brazing; the 3 component types (tubes, headers, and collectors) a total of 64 pieces are now a single part referred to as the Gas Passage Assembly. The Gas Passage Assembly is leak checked using the Pfeiffer Vacuum QualyTest™ Select HLT265 Helium leak tester. The Gas Passage Assembly is attached on one end to the leak tester by a flexible hose and the Collector on the opposite end of the Gas Passage Assembly is plugged. A vacuum is then drawn on the entire assembly including all of the brazed joints. A handheld wand with helium gas flowing from a small tube is then passed slowly near all of the braze joints and around the entire assembly. The leak tester display is monitored for any sign of a deteriorating vacuum condition that would indicate a leak. Next the Gas Passage Assembly is enclosed within a nylon bag and the bag is filled with helium gas, again the leak tester is monitored for indications of a leak. For this application no leak rate is acceptable therefore only a result of "No

Detectable Leak" (NDL) is considered to be a passing condition.

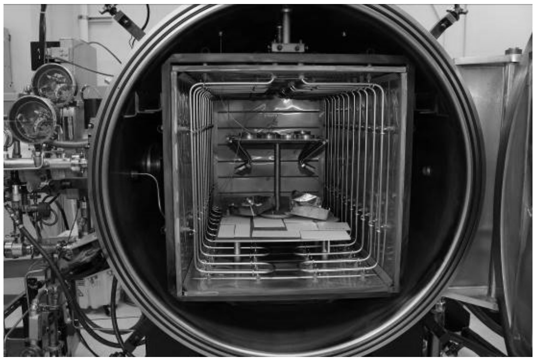

Figure 11. The Gas Tubing Array with the Tubing Headers and Collectors is loaded into the Centorr Vacuum Products vacuum furnace.

The EM Susceptor Tiles are cleaned using acetone and isopropanol rinses and Boron Nitride stop-off is then applied to the sides of the tiles to prevent the flow of braze filler between tiles. BNi-2 brazing foil with 0.002 inch (0.0508 mm) thickness is resistance welded into each tube channel on the bottom of the tile. (Figure 12) A build plate is fashioned from an Aluminum plate with paper card stock and masking tape covering the build area. The tiles are then arranged on the build plate in a 'Tiles on Bottom' orientation with Alumina separator strips between them and with the gas tubing channels facing up for access to insert the Gas Tubing Array.

Figure 12. The sixteen EM susceptor tiles have 0.002 inch thick BNi-2 foil spot welded into the Gas Tube braze channels.

As the gas tubes are inserted into the slots, 0.010 inch diameter 304L stainless steel spheres are resistance welded to the interface between the tube and channel wall. Each sphere is tack welded twice; once to the channel wall and once to the tube. Each tile is tack welded in 4 to 6 places; in the corners first, then in central spots if needed to maintain the tubes in the channels of the tiles. A 1 inch (25.4 mm) length of the same Inconel tube is also tack welded to the center of each tile (Figure 13) on the back of the Gas Tubing Array. With one end of each 1 inch (25.4 mm) long tube pinched a thermowell is prepared for later placement of thermocouples to monitor system operating temperatures.

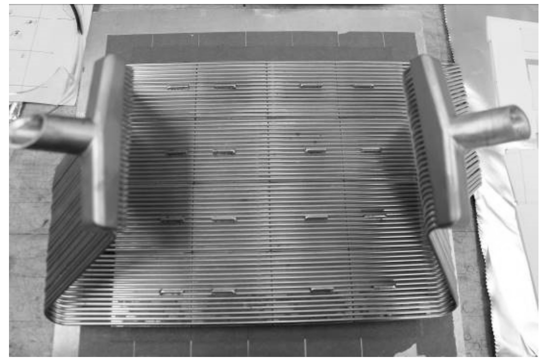

Figure 13. The back side of the Gas Tubing Array after fixing the EM susceptor tiles to the front (underneath), a short piece of Inconel tubing is tack welded to the back of each tile for placement of thermocouples after brazing.

Following completion of all resistance tack welding, BNi-2 paste is then applied to each tube/channel joint. The preplaced BFM foil ensures that the filler is present in the joint; however, the thin foil is insufficient in quantity to fill the entire joint. The additional paste BFM applied to the joint exterior provides the volume of filler required by the joint[9] With the Absorber Tile Array and the Gas Passage Assembly still on the build plate; Alumina strips are arranged around the Thermowells in several cross directional flat layers until a continuous layer of Alumina sheets can be laid across the entire underside of the Gas Tubing Array to fully support the weights to be placed on top of each tile during brazing. The layers of inter-woven Alumina strips do not allow any weight to be supported on the Thermowells tack welded to the underside of the tubes which could produce a poor brazement between any given tile and its associated gas tubes. A poor brazement would result in low mechanical strength of the system as well as reduced thermal conductivity; both of which are severely detrimental results to be avoided at all cost. After the Alumina support system is constructed, then the Kovar furnace setting plate is placed on top and clamped in place to the build plate at each corner using conventional C-clamps. This is done to maintain the arrangement of all components while the whole setup is inverted to obtain an orientation of 'Tiles on Top'. The inverted assembly is placed on the Molybdenum pedestal to remove the C-clamps and the Aluminum/Paper/Tape build-up plate. (Figures 14 & 15) The assembly is then transferred to the vacuum furnace hearth plate which has had a support structure (Figure 16) built upon it and the hearth plate partially reinserted into the furnace to limit the distance of movement required to close the furnace door.

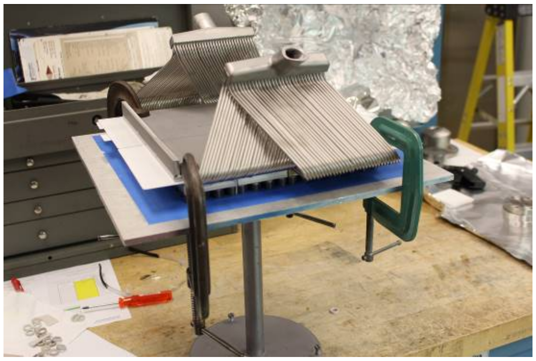

Figure 14. The entire assembly is moved from the table top to a molybdenum pedestal where it is inverted for removal of the clamps and the aluminum build surface.

Due to this extreme amount of weight; adequate support is needed below and is provided in the form of 1(25.4 mm) inch by 1 inch (25.4 mm) molybdenum bars running under each row of tiles for four bars in total. The four Molybdenum bars are supported by four Kovar cylinders of 10 inch (254 mm) diameter and 6 inch (152.4mm) height and 0.25 inch (6.35 mm) thick walls and with one end closed. The Kovar cylinders are arranged on the furnace hearth plate with the closed end up to form another sort of pedestal where the Molybdenum bars can be shimmed to achieve full and even support of the Kovar setting plate from underneath. The Kovar alloy is chosen for this application due to its attribute of high strength at high temperatures which insures adequate support of the assembly during brazing at 1010°C.

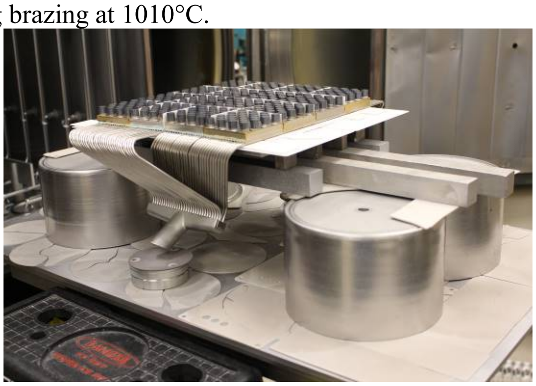

Figure 15. After removing the clamps and the aluminum build plate the assembly is then moved to the raised setting arrangement constructed from Kovar cylinders and Molybdenum bars with Alumina shims and blocks.

Type K thermocouples are placed in contact with the assembly, the vacuum brazing furnace is closed and the vacuum system started. The vacuum level of approximately 10^{-6} torr is achieved in approximately 30 minutes. Again the vacuum brazing temperature profile for BNi-2 is as follows: Heat to 65°C at 5°C/minute, hold at 65°C for 60 minutes to allow any water moisture and high vapor pressure solvents to evaporate and be removed by the vacuum system. Heat to 450°C at 5°C/minute, hold at 450°C for 120 minutes to allow the organic compounds of the brazing paste binder to be vaporized removed by the vacuum system. Heating then continues to 950°C at 5°C/minute and holds at 950°C for 45 minutes to allow any variation of temperatures within the assembly to come within 3°C of each other before continuing. Finally, the temperature is increased to 1010°C at 5°C/minute and holds at 1010°C for 30 minutes for the brazing to take place. Following brazing the temperature is allowed to cool at 5°C/minute to about 100°C under vacuum at which time Argon is introduced to the chamber to facilitate further cooling.

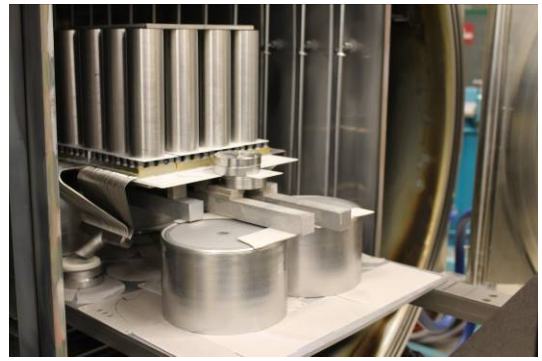

Figure 16. To place the sixteen weights onto the individual EM susceptor tiles; the furnace hearth plate is inserted partially into the hot-zone and then the weights are placed before inserting the hearth plate fully into the furnace.

Once again after brazing; the assembly is leak checked using the Pfeiffer Vacuum QualyTest™ Select HLT265 Helium leak tester. One Collector end is attached to the leak tester by a flexible hose and the Collector on the opposite end of the Gas Passage Assembly is plugged. A vacuum is then drawn on the entire assembly including on all of the braze joints. A handheld wand with helium gas flowing from a small tube is then passed slowly near the braze joints and around the entire assembly. The leak tester display is monitored for any sign of a leak indicated. Next the Gas Passage Assembly is again enclosed within a nylon bag and the bag is filled with helium gas, and again the leak tester is monitored for leak indications.

The Two Piston Cylinders are bolted onto a fixture having the proper spatial arrangement to match that of the Stirling Engine to which this Heat Exchanger is to be mounted to. The Piston Cylinders as well as the Collectors are shaped to match one another by machining, grinding, and hand filing so that the joints between these components will be net shape or near net shape upon completion of the TIG welding operation. (Figure 17) The welding machine used is a Miller Dynasty 700 with a Weldtec-20F torch and ultra-high purity Argon gas. The filler rod used for the welding is Multimet alloy: 0.035” diameter rod for the root pass followed by 0.062” diameter rod for the fill passes as well as for the reinforcement cap and face. Temperature is monitored using a K-type thermocouple contact probe and the part temperature is maintained below 200°C by allowing long cool-down periods between short welding durations.

Next the entire completed Heat Exchanger is again connected to the HLT265 Helium leak tester by means of the same welding fixture used to set the Piston Cylinder positions as described above and again the leak tester is monitored for leak indications.

Figure 17. TIG welded joint between a Collector and a Piston Cylinder

Conclusion

The Heat Exchanger assembly's gas passages were tested following each of the two vacuum furnace brazing operations and again following the completion of the two piston/collector TIG weld operations. No leaks were detected within the detection limits of the helium MSLD (<5E-12 atm-cc/sec (4.9E-11 Pa-M^3/s) following each of the joining operations. Leak checking the assembly following each joining process step served to indicate that each step was successful, or indicate any leak that could have developed following the later joining operations.

No delamination or cracks of the AlN:Mo cylinders were found following any of the joining processes. Using sufficiently low temperature ramp rates ensures that ceramic materials susceptible to thermal shock remain intact.

Complex assemblies and sub-assemblies with conflicting joining conditions and temperature requirements are successfully fabricated by sequencing the joining operations in the proper order. Generally performing higher temperature operations before lower temperature ones. Considerations of fixturing or setting arrangements is extremely important for vacuum furnace operations to maintain ideal positions of all components at temperature. By delaying the accumulation of mass and geometry until as late as possible in the assembly process, difficulties with furnace fixturing and supports are avoided.

Acknowledgements

This work was funded by the Air Force Research Laboratory and by the Operational Energy Capability Improvement Fund. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. Approved for public release; distribution is unlimited. Public Affairs release approval #AFRL-2021-3018.

References

[1] Specification of Stirling's Patent No 4081 of 1916, The Engineer, Editor: Loughnan St. Lawrence Pendred (Morgan Brothers Publishing Dec. 1917) p. 516

[2] Wesgo Product Data Card, Morgan Advanced Materials, Wesgo Metals Company (Datalizer 2013), Side 2

[3] Brazing Filler Metal Selector Chart v 2.2c, Wall Colmonoy Corporation, Wall Colmonoy Corporation 2012, p.1

[4] B. W. Hoff, et al., "Millimeter Wave Interactions with High Temperature Materials and Their Application to Power Beaming," International Microwave Power Institute 52nd Annual Microwave Power Symposium, Long Beach, CA, 2018.

[5] B. W. Hoff, F. W. Dynys, S. C. Hayden, R. O. Grudt, M. S. Hilario, A. E. Baros, M. L. Ostraat, "Characterization of AlN-based Ceramic Composites for Use as Millimeter Wave Susceptor Materials at High Temperature: High Temperature Thermal Properties of AlN:Mo with 0.25% to 4.0% Mo by Volume," MRS Advances, Vol. 4, No. 27, 1531-1542 (2019).

[6] B. W. Hoff, S. C. Hayden, M. S. Hilario, R. O. Grudt, F. W. Dynys, A. E. Baros, I. M. Rittersdorf, M. W. Ostraat, "Characterization of AlN-based Ceramic Composites for Use as Millimeter Wave Susceptor Materials at High Temperature: Dielectric Properties of AlN:Mo with 0.25 v% to 4.0 v% Mo at Temperatures from 25-550 °C," MRS Journal of Mat. Res., Vol. 34, No. 15 (2019), 2573-2581.

[7] I. M. Rittersdorf, B. W. Hoff, A. S. Richardson, S. A. Martin, V. V. Yakovlev, P. S. Kim, J. W. Schumer, "A 1-D Model for the Millimeter-Wave Absorption and Heating of Dielectric Materials in Power Beaming Applications," IEEE Trans. Plasma Sci., Early Access (2021).

[8] P. Kumi, S. A. Martin, V. V. Yakovlev, M. S. Hilario, B. W. Hoff, and I. M. Rittersdorf, "Electromagnetic-thermal model of a millimeter-wave heat exchanger based on an AlN:Mo susceptor," COMPEL - The international journal for computation and mathematics in electrical and electronic engineering, Vol. 39, No. 2, pp. 481-496 (2020).

[9] American Welding Society Committee on Brazing and Soldering, Brazing Handbook, Fourth Edition, (American Welding Society 1991), p. 13