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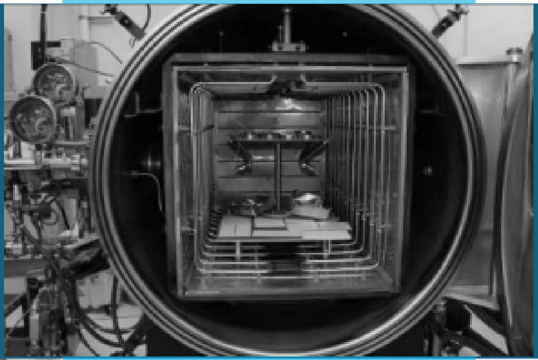
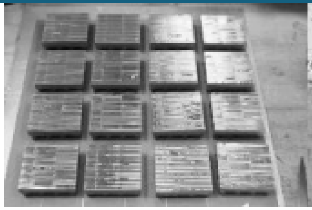
A Summary of the Fabrication of a Prototype Stirling Engine Heat Exchanger





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

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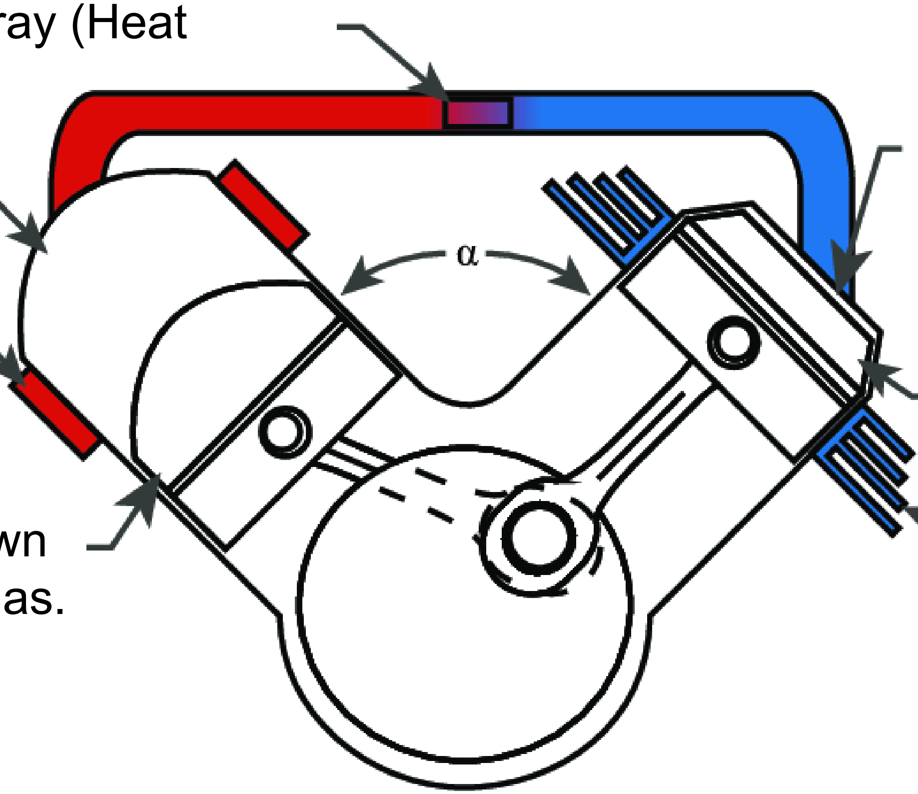
Application

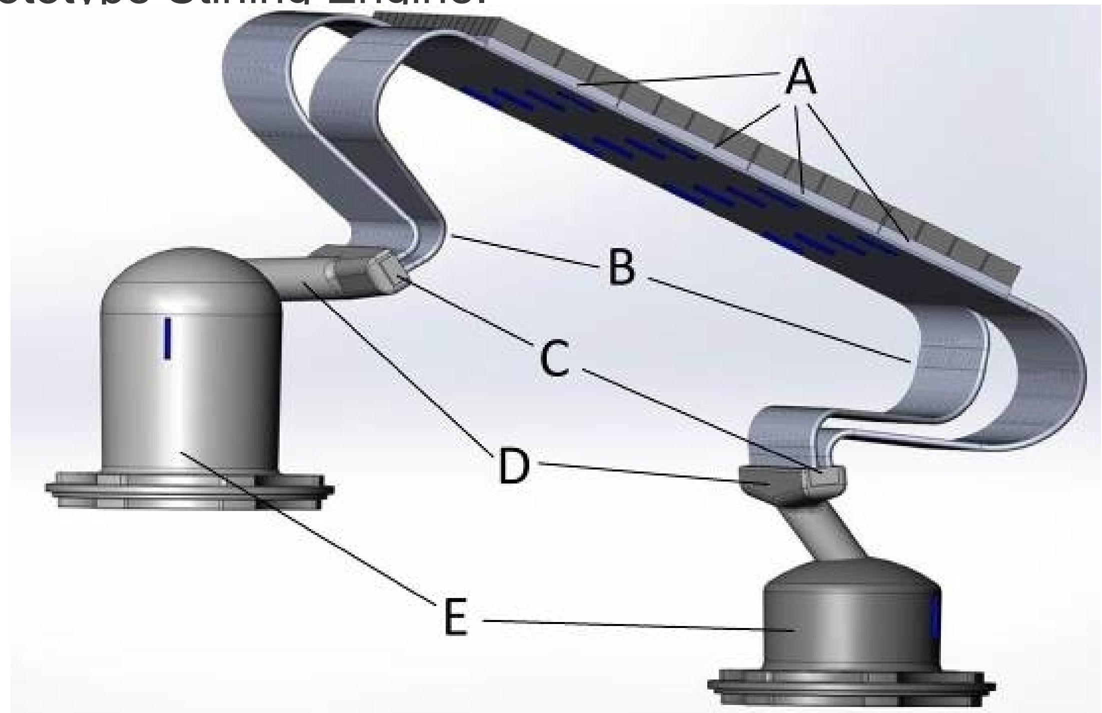
This integrated unit comprised of the EM Susceptor Array, Gas Passage Assembly, & Piston Cylinders is the main heat exchanger as well as a single piece gas containment vessel for an Alpha Type Stirling heat engine prototype. In this case the system gas is heated by the EM Susceptor Array, cycled through the Gas Passage Assembly into the Piston Cylinders where it acts upon the two pistons to produce mechanical force by rotating the crankshaft.



Ranieri, Salvatore & Prado, Gilberto & Macdonald, Brendan. (2018). Efficiency Reduction in Stirling Engines Resulting from Sinusoidal Motion. Energies. 11. 2887. 10.3390/en11112887.

Challenge

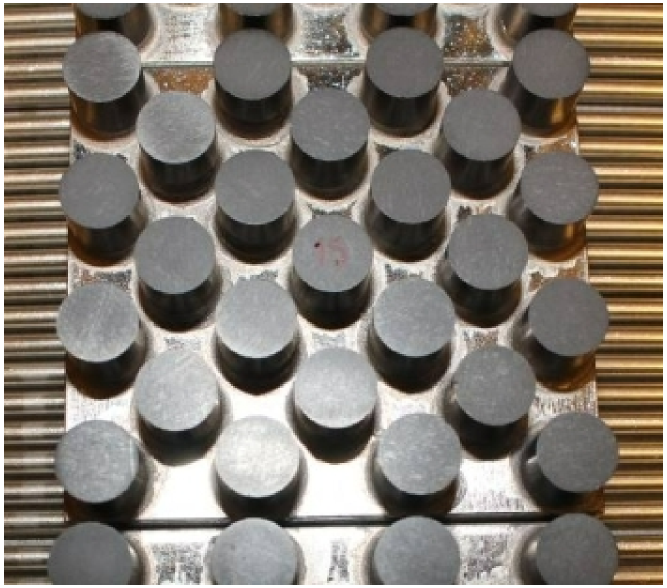
Perform joining operations in deliberate order such that each subsequent step respects the limitations of the previous step with regards to brazing temperature, braze alloy remelt temperature, and geometric constraints to produce a fully integrated, metallurgically bonded, leak free part (Top End) for a prototype Stirling Engine.

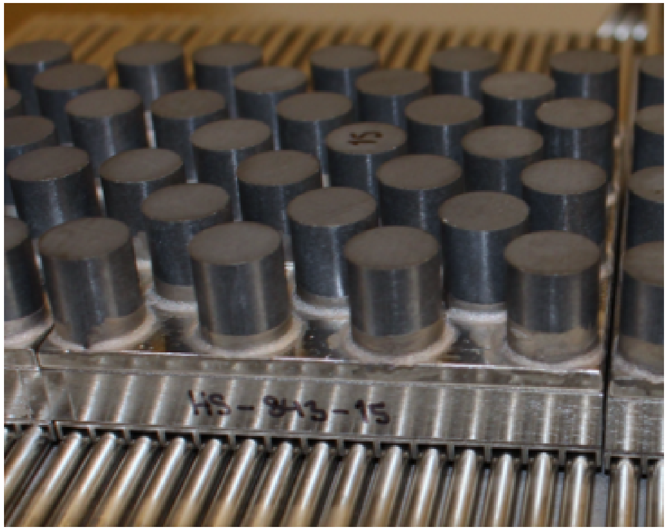


A computer rendering of a Stirling Engine heat exchanger. Components are: A) mm-Wave Absorbing Tile Array (16), B) Gas Tubing Array (60), C) Tubing Headers (2), D) Gas Flow Collectors (2), E) Piston Cylinders (2).

Electro Magnetic Susceptor Tiles

BFM: Au96.40-Ni3-Ti0.6 (1030°C)





EM Susceptor tiles are constructed by :

Sienna Technologies, Inc.® in Woodinville, WA, USA

25 Aluminum Nitride Composite cylinders brazed to Kovar baseplates using Au96.40-Ni3-Ti0.6.

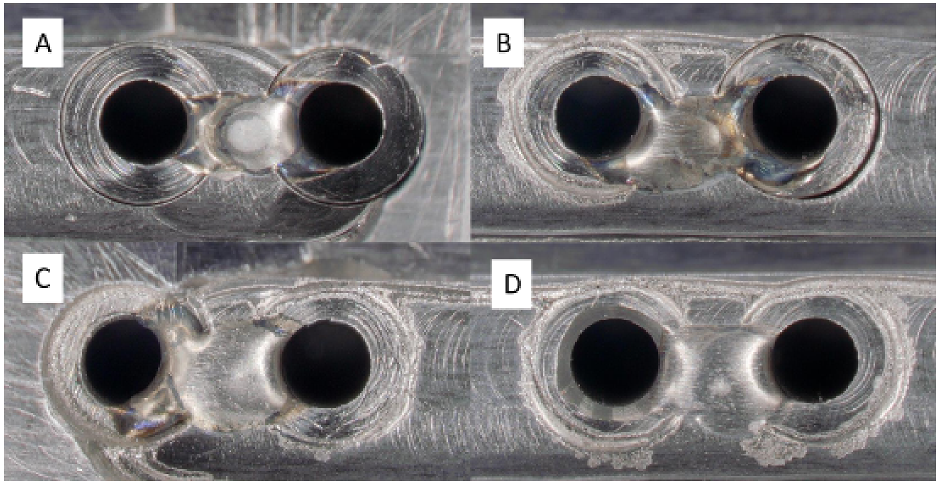
Designed to Absorb mm-Wave Electromagnetic Radiation at ~95 GHz.

Tiles Interface with the Gas Tubing Array by 15 Tubing Channels Machined into the Kovar bottom plate of Each Tile.

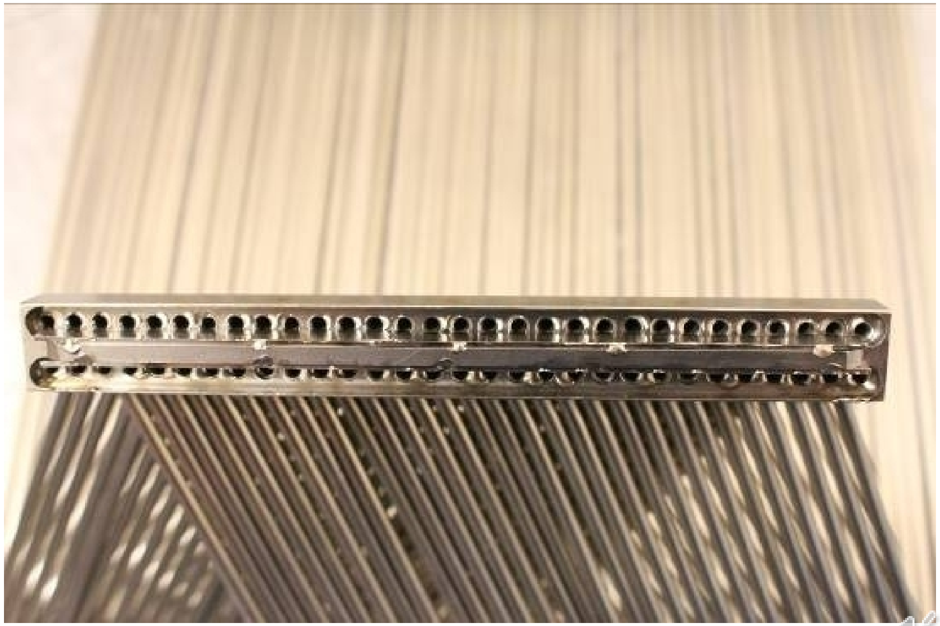
Conduct Heat to the Gas Tubing Array Containing the Working Gas (H_2) for the Stirling Engine

Tubing to Header Braze Joint Clearance Testing and TIG Spot Welding

Tube to Header braze joint clearance test specimens: A & B (<0.0005")indicate insufficient clearance, while C indicates the minimum braze clearance (>0.0005"<0.001") which allows complete braze flow, and D indicates excessive clearance (>0.001") that may result in a brittle centerline eutectic phase.

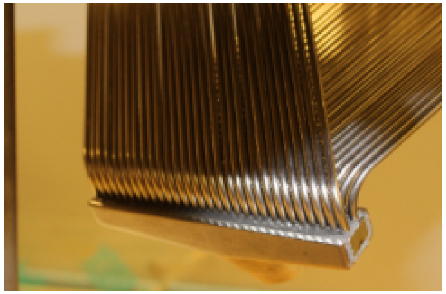


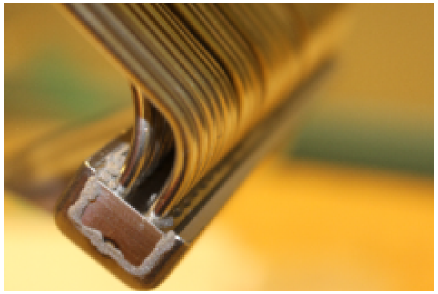
The 0.125"(3.175mm) gas tubes are set flush to the inside surface of the Header and TIG welded prior to brazing. The depth setting shims (TIG welded to the center divider) are removed prior to brazing



Gas Passage Assembly
BFM: Bni-2 Paste(1020°C)

The Collectors are spot welded by TIG process to the Tubing Headers and BNi-2 paste is placed along and between both rows of Gas Tubes also on each end of the collectors. The BNi-2 paste is then dried by placing the entire assembly under a heat lamp for several hours.



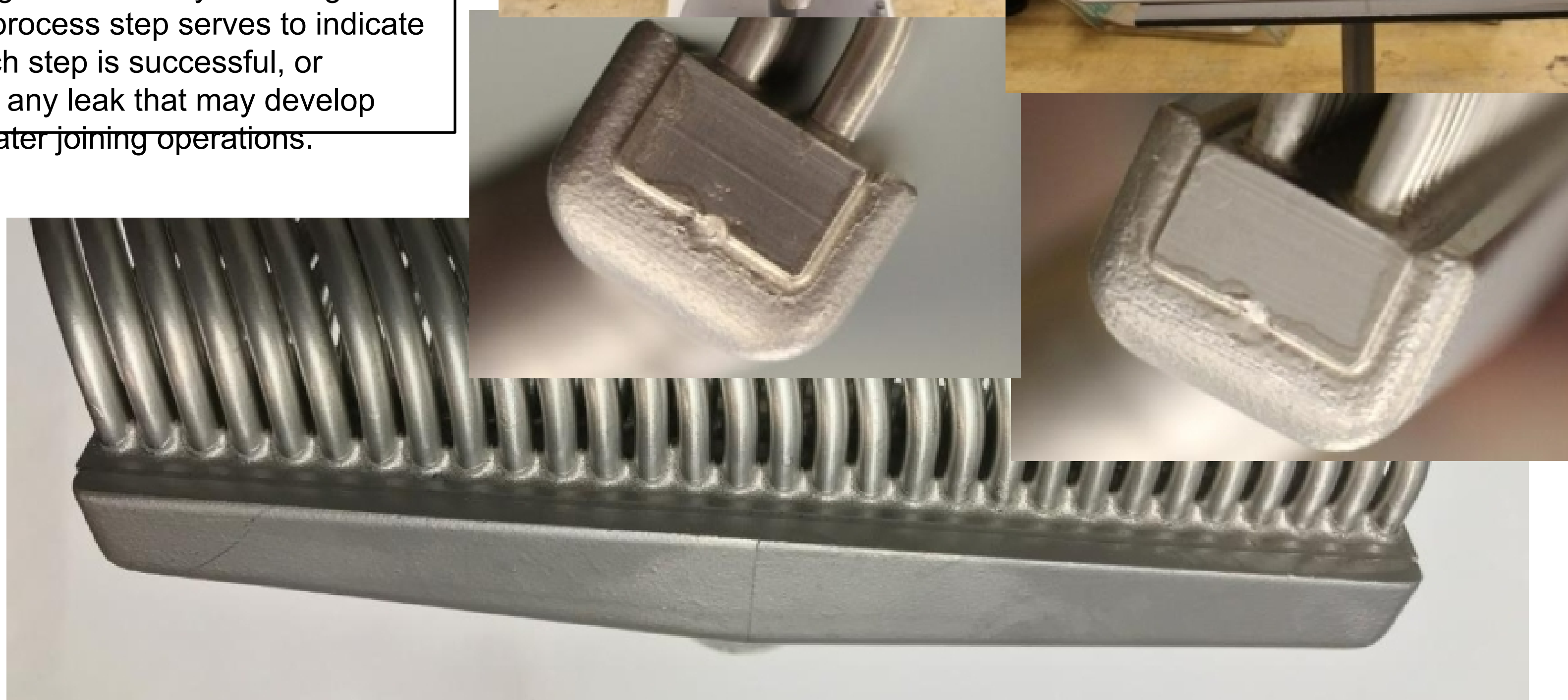


The Gas Passage Tubes are aligned lengthwise by clamping the ends between two Alumina rods. The EM Tile Array plane is fixtured by clamping tubes down to a Kovar setting plate with Alumina plates in between and Alumina strips separating the tubes from each other. More Alumina plates and SS304 weights are placed on top of tubes during brazing run.

The Gas Passage Assembly is leak tested following the braze cycle using a Varian QualyTest Helium Mass Spectrometer. Because the system is designed to contain Hydrogen at high temperatures and pressures there is no acceptable leak rate. No leaks are detected.

Brazed Gas Passage Assembly
BFM: BNi-2 Paste(1020°C)

Visual inspection of BNi-2 braze joints indicates adequate but not excessive application of paste. Leak Testing using a Pfeifer HLT265 QualyTest Helium Leak Detector following each of the joining operations indicates no leaks are detected within the detection limits of the helium MSLD (<5E-12 atm -cc/sec (4.9E-11 Pa-M^3/s). Leak checking the assembly following each joining process step serves to indicate that each step is successful, or indicate any leak that may develop during later joining operations.

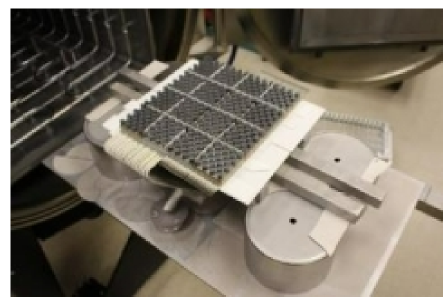


Final Braze: EM Susceptor Tiles Brazed to Gas Passage Assembly

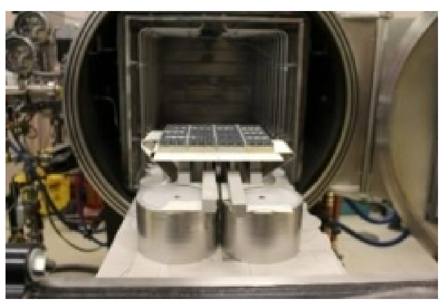
BFM: BNi-2 Paste(1010°C)
Work Bench: Cleaning, Assembly, & Fixturing
Furnace: Transfer & Placement, Supports & Weights

Bni-2 Foil 0.002” (0.051mm) tacked into tubing channels, 16 Tiles, Gas Passage Assy inserted-tacked, BNi-2 paste applied to backside of gas tubes. Also note thermo-wells (16) tacked to backside of tubing.

Assembly is lifted-clamped-then inverted for transfer to furnace raised platform (molybdenum bars, Kovar cylinders, Alumina shims) Note: Alumina shims between ALL adjacent tile faces.



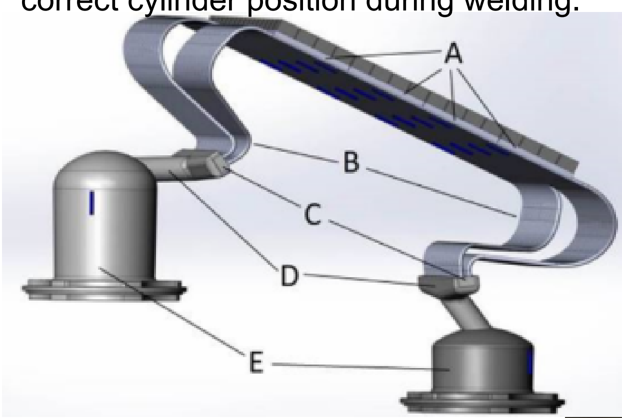
Assembly is centered between furnace hotzone sides/elements
& partially inserted into hotzone. SS304 Cylinders 6lbs (2.7kg) are placed atop each tile. Entire arrangement fully inserted into furnace.

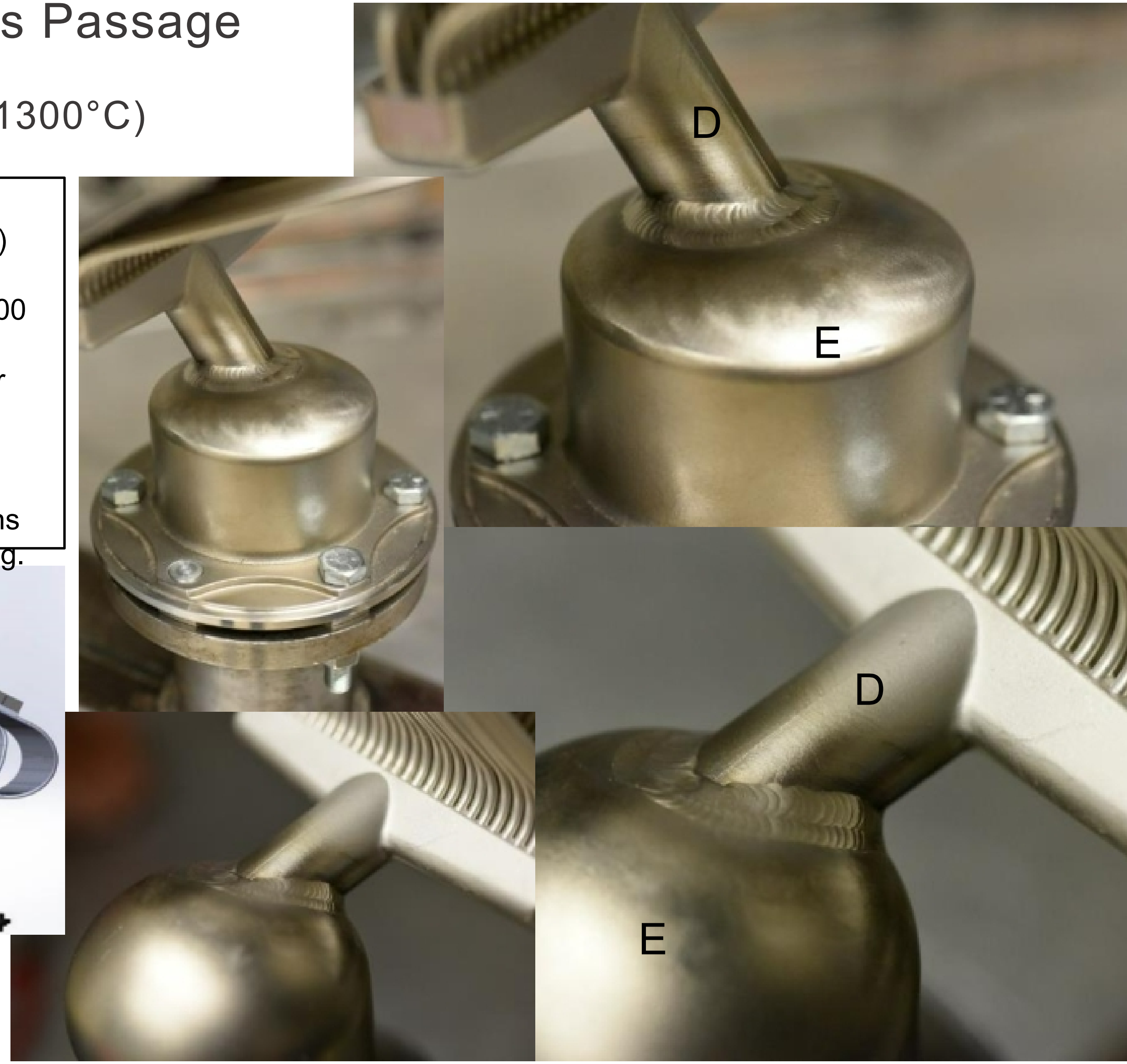


TIG Welding of Stirling Engine Cylinders to the Gas Passage Assembly

Weld Filler: Multimet (~1300°C)

Tungsten Inert Gas (TIG) Welding: Multimet Sterling Engine Cylinders (E) are TIG welded to Multimet Collectors(D)using a Miller Dynasty 700 with a Weldtec-20F torch, filler rod is Multimet alloy: 0.035” diameter rod for the root pass followed by 0.062” diameter rod for the fill passes & cap. Cylinders are bolted to a mild steel fixture which establishes and maintains correct cylinder position during welding.





Multi-Disciplinary Assembly Process Flowchart

EM Susceptor Tiles — Active Brazing (Vacuum Furnace) 1030°C

- Nickel Alloy Base Metals & Ceramic Composites
- Confinement Fixturing
- Active Au-Ni-Ti Alloy (Paste)

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Gas Tubing Array — Conventional Brazing (Vacuum Furnace) 1020°C

- Nickel Alloy Base Metals
- TIG Spot Welds (Autogenous)
- Moly Tie Wire
- Confinement Fixturing
- BNi-2 Braze Alloy (Paste)

⬇

Heat Transfer Assembly — Conventional Brazing (Vacuum Furnace) 1010°C

- Nickel Alloy Base Metals (Kovar, Inconel, Multimet)
- Resistance Tack Welding (Ball Tacks & Direct Tacks)
- Furnace Support Fixturing (Moly Bars & Kovar Cylinders)
- Confinement Fixturing (SS304 Weights 100 lbs / 45.5 kg)
- Nickel Based Braze Filler Metal Alloy (BNi-2 Paste)

✚

Sterling Engine Cylinders — Tungsten Inert Gas (TIG) Welding ~1300°C

- Nickel Alloy Base Metals (Multimet)
- Confinement Fixturing (Steel Cylinder Position Fixture)
- Nickel Based Braze Filler Metal Alloy (BNi-2 Paste)
- Multimet Alloy Welding Rod
  - 0.035” diameter rod for the root pass
  - 0.062” diameter rod for the fill passes & cap.
- Minimized Heating Far From Braze Joints with Inter-Pass Cooling

⬇

Complete Sterling Engine Heat Exchanger

Conclusions

- Step-Brazing simplifies setups & processes for large complex assemblies.
  - Decreasing the Brazing Temperature of successive brazing steps allows sub-assemblies to be brazed individually.
  - Implementing a diffusion hold during brazing increases remelt temperature of the BNi-2 braze filler alloy.

- Step-Brazing can reduce or eliminate the requirement for complex furnace fixtures.
  - By breaking up a complex assembly into discrete sub-assemblies and brazing those sub-assemblies separately the positioning and fixturing necessities of a large complex assembly are avoided.
  - Positioning and fixturing of smaller less complex sub-assemblies are simplified and more easily accommodated individually.

- A Stirling Engine Heat Exchanger is successfully constructed using multiple joining techniques.
  - Active Brazing in Vacuum, Conventional Vacuum Brazing, TIG Welding.
  - Step-Braze operations used: Au96.40-Ni3-Ti0.6 (1030°C), BNi-2 (1020°C), BNi-2 (1010°C)
  - Various filler formats are employed including Paste, Foil, and Rod form.
  - Resistance Tacking and Autogenous TIG Spot welding are highly effective fixturing methods.