Thermofluidic Packaging Approach for the MEMS Rotary Engine Power System

Michael Pleskach, Paul Koeneman and Carol Gamlen
Harris Corporation
Mail Stop 1-9841, P.O Box 37
1000 Charlie Herbert - Bldg.21A
Palm Bay, FL  32905

David C. Walther, Albert P. Pisano
Berkeley Sensor and Actuator Center
University of California, Berkeley
BSAC/EECS #1774, Berkeley, CA 94720-1774

Abstract

Chip and system level packaging of microscale power generation concepts such as fuel cells and internal combustion engines is quite challenging. This work will address the development of one such packaging approach for the MEMS Rotary Engine Power System (REPS) [1]. In order for thermochemical engines to operate effectively on this scale, proper design of the overall thermal package is critical. A novel solution to this problem is to construct a package with cavities between the engine and the environment. In the current system, the micro-rotary engine is placed in a cavity that is filled with an aerogel-based material, which inhibits thermal conduction and blocks radiation pathways, preventing excessive heat loss. In addition, packaging of the MEMS REPS must provide microfluidic channels for inlet fuel, air and exhaust, electrical interconnects for power output, sensor lines and thermal isolation. These lines will be exposed to high temperature exhaust streams with excess oxygen present. The development of the final design is being carried out through an iterative process between a thermal mockup unit testing protocol and thermofluidic modeling. Novel and innovative fabrication processes that are included in this system are three-dimensional fluidics (e.g., intake, exhaust, and fuel channels in package), three-dimensional electronic packaging (e.g., multi-plane electrical interconnects), and high temperature electrical interconnects. The cooling of the exhaust prior to venting will be necessary to address IR signatures and personnel safety. The interface between the package electronics and the MEMS engine will be accomplished through a Low temperature co-fire ceramic (LTCC). Ceramic is the most commonly used substrate material for electronics in harsh conditions and is unmatched in reliability and cost. Low temperature co-fire ceramic (LTCC) combines the advantages of ceramic with well-developed thick-film manufacturing processes.
Overview

The objective of the MEMS Rotary Engine Power System (REPS) is to develop a liquid hydrocarbon fueled portable power system using a rotary (Wankel) engine as the power source. The selection of the liquid hydrocarbon fuel is due to the higher energy density available in liquid hydrocarbons when compared to conventional batteries. The ultimate goal of the MEMS REPS project is a power system capable of producing ~10-100 mW of electrical power through the coupling of an integrated electrical generator. At the heart of the REPS package is the power generation chipset (PGC), which contains the MEMS fabricated rotary engine and all other ancillary equipment. The MEMS REPS project is separated into several research avenues necessary to produce the complete electro-thermo-fluidic package. Research features include the design and fabrication of the micro-rotary internal combustion engine (including integrated seals, magnetic pole designs, and ignition module), integrated electric generator, internal thermal management and fluid delivery systems.

Packaging of the MEMS REPS must provide microfluidic channels for inlet air and fuel, exhaust, electrical interconnects for power output, and thermal isolation. Packaging and thermal isolation are important for the reliable, efficient operation of the engine. A novel solution to this problem is to construct a package with cavities between the engine and the environment. The micro-rotary engine is placed in the cavity, which is then filled with an aerogel-based material. Placement of the micro-rotary engine with respect to the generator, electronics, and fuel is critical for minimizing thermal losses. Novel fabrication processes used include three-dimensional fluidics (e.g., intake, exhaust, and fuel channels in package), three-dimensional electronic packaging (e.g., multi-plane electrical interconnects), and high temperature electrical interconnects.

MEMS REPS packaging requires considerable design, materials, and fabrication innovations. Figures 1 and 2 show the integration of the MEMS REPS PGC within the insulation. Note that the thermal insulation of the engine device occupies the bulk of the package. In addition to occupying much of the package volume, the insulation and heat transfer issues dominate all facets of the electronics and MEMS packaging design. The engine & insulation constitutes the "hot" package of the system and contains the PGC, thermal insulation material (which accounts for ~80% of the hot package volume), thermally insulative and EMI reducing cover, and all fluid and electrical interconnects. The interface between the package electronics and the MEMS engine will be accomplished through a ceramic substrate. Ceramic is the most commonly used substrate material for electronics in harsh conditions and is unmatched in reliability and cost. Low temperature co-fire ceramic (LTCC) combines the advantages of ceramic with well-developed thick-film manufacturing processes. Harris's expertise in embedded ceramic cooling with heat pipes and capillary pumped loops (DARPA funded) has been leveraged to package the required electronics with the appropriate temperature control in the required space.

The package insulation requires innovative materials and processes to minimize the heat loss and maintain optimum engine temperature (400°C to 700°C), to increase reliability and performance, while allowing the engine to function in ambient conditions with minimal IR signature and human safety concerns. The aerogel insulation is an extremely low-density material fabricated with sol-gel processes. Its thermal conductivity is typically 0.08-0.003 W/m-K in ambient conditions and can be further lowered by placing it in a medium vacuum. This represents an order-of-magnitude improvement over most other materials, allowing for significant reduction in package size. Additionally, aerogel tolerates temperatures in excess of 600°C and is available off-the-shelf in sheet form or can be custom-fabricated.
Packaging Issues

There are many challenging packaging issues brought about by the extreme requirements of the program, in both size and temperature. The insulating material must have a high thermal resistance, since the engine must keep running in the 400º-600ºC-temperature range to allow for optimal performance. The package must not only maintain this temperature range through low thermal conductivity, but the insulation and package should also be able to withstand the high engine temperatures without material degradation. The high temperatures of the engine limit the material choices for the package. Effective adhesives and seals are not typically designed to operate in the temperature range considered for this program. Materials must also be chosen to minimize thermal stresses at interfaces. The package must have the capacity for over 40 electrical inputs and outputs. In addition to the output power connections, the package must be able to accommodate several control input and sensor output signals. The signal integrity must be maintained over large temperature ranges as well as large temperature gradients. Simple wire connections will not be space efficient due to the extremely small package size (1in³). While the materials of the package must be able to withstand the high engine temperatures, assembly processes requiring global heating of the device above the Curie point of the permanent magnets in the generator may damage the system irreparably. Therefore, special techniques and materials are needed in the assembly process.

Packaging Concepts

The general concept that is being used for the packaging of the MEMS REPS is shown in figure 2. A 3-D model of the packaged system is shown with the silicon engine and associated magnetics surrounded by aerogel insulation. The package includes a conductive outer shell that will help to reduce electro-magnetic interference (EMI) as well as radiated heat. An integrated electro-fluidic interconnect fabricated in LTCC serves as the connection between the packaged PGC and the outside of the package. The ceramic interconnects will have integrated electrical lines in order to accommodate the large number of electrical connections. Traces are also embedded beneath the surface of the interconnects to allow for multiple connections on either side of the LTCC interconnect tubes. Ribbon bonds from the pads on the PGC surface will attach to the traces on the ceramic tubes. These traces will continue up through holes in the LTCC interface that acts as a cap for the package. Ribbon bonds can then be used to electrically connect the electrical traces on the tubes to traces on the outer surface of the ceramic interface (top of figure 2). These traces will progress to a connector socket on the surface for testing and control I/O. Special attention must be paid to the ceramic/silicon connection as shown in figure 3. Adhesives and sealants must be chosen such that the ceramic/silicon interface is secure at the extreme temperatures and that there is compensation for coefficient of thermal expansion mismatch.

Mockup Units

LTCC material processes are used in the packaging of the MEMS REPS due to its low thermal conductivity, high operating temperature, ease of processing, and design flexibility. Initial structures for the electro-fluidic interconnect are shown in figure 4. This interconnect design integrated 8 electrical and 1 fluidic connection into a tube with a cross section of about 8.5mm². These electro-fluidic interconnects are
used to provide the silicon engine with air, fuel, and exhaust, as well as electrical connections for sensors, controls, output power, etc. The fabrication of these structures is not trivial due to the fact that the relatively large cavity cross-sections ($5.0 \text{mm}^2$) coupled with relatively thin walls of ceramic ($0.3 \text{mm}$), must withstand the lamination and firing of the LTCC process. Fabrication was accomplished using a slightly modified LTCC process that accommodates these structures. While the shrinkage factor of LTCC from unfired “green” state to its final state after firing is typically uniform and predictable, the shrinkage for the structures created for MEMS REPS are not as predictable due to the large number and sizes of the cavities. Using the results of a first test vehicle enabled a more accurate prediction for the shrinkage in subsequent test vehicles.

Refined designs were needed to provide better solutions to such problems as tube adhesion to silicon PGC, engine cover plate integrity, and the number and placement of electrical connections to the PGC. Each revised tube was fabricated with 36-40 electrical connections integrated into a single LTCC tube with similar $8.5 \text{mm}^2$ cross-sections. The silicon combustion chamber cover plate holes were relatively large to accommodate this tube size, which caused the cover plate to be extremely fragile. To improve cover plate integrity, it was decided to decrease the size of the tubes to a $3.5 \text{mm}^2$ cross-section. The novel interconnect tube design shown in figure 3 would allow for an equivalent or even increased number of electrical lines for two tubes ($>80$). In the initial square-shaped tube design, the adhesive simply flowed up the side of the tubes. Thus the tube was only held in place by the sheer strength of the adhesive. The tubes shown in figure 5 show notches that adhesives can flow into to add strength to this critical bond. The notches may also be used in a “slide-and-lock” configuration for additional stability. One of the major benefits of the fabrication process used for all of the interconnects is that it uses standard LTCC processing steps. This provides for a more easily reproducible and cost effective fabrication process.

**Assembly**

The assembly process for this program is challenging due to a number of factors including the small package size, large number of electrical connections, high operating temperature, and low processing temperature due to the materials within the engine. This low processing temperature requirement coupled with the extremely high operating temperature ($600^\circ C$) greatly reduces the number of available assembly technologies. A number of assembly processes and materials were tested and defined. High temperature resistant adhesives, soluble silicone, and other non-traditional attachment technologies were investigated as candidate connection technologies. Surface preparation techniques such as sanding, etching, and bead blasting were also investigated for use on the silicon PGC as well as the LTCC tubes. Low temperature
Curing materials were used to create the structures shown in figure 6. These test structures were used to evaluate the adhesion strength between the LTCC tubes and silicon. The structures were also temperature cycled to 600°C for 30 minutes and then pull-tested at room temperature to reveal the effects of any CTE mismatches between the silicon, adhesive, and LTCC. As a result of these tests, suitable materials and processes have been identified for mechanical connection of the LTCC interconnects and silicon engine.

Typical ribbon bonding is a 180°-angle process. However, to make connections from the silicon PGC to the ceramic interconnects, a 90°-angle ribbon bond is necessary. A test vehicle was created to define the process and materials needed for a 90°-angle ribbon bond. The completed structure was then subjected to 400°C thermal cycling and showed no signs of degradation (Figure 7).

**Thermal Testing**

A test bench has been created for the thermo-fluidic testing of the MEMS REPS packaged system. Thermal testing has included different types and configurations of insulation materials that can withstand temperatures of 600°C. The thermo-fluidic test bench is designed to apply a simulated heat load near the combustion chamber of the Power Generation Chipset (PGC), supply airflow into and out of the package, and to measure various temperatures throughout the package. The thermo-fluidic mockup used in this test was created by first attaching the silicon cover plate to the silicon combustion chamber using a high temperature adhesive. Nickel-chromium wire was attached to the bottom of the silicon plates, underneath the combustion chamber, to simulate the heat from combustion. After the assembly was instrumented with thermocouples, the mockup was packaged using aerogel into the 1in³ cube shown in figure 8. During testing, input Nitrogen gas flows through tubing into the LTCC input tube, is heated in the combustion chamber by the NiCr wire, and exits through the output LTCC tube. The input heat, N₂ flow rate, and thermocouple readings are all connected to a data acquisition device driven by LabVIEW™, which collects the data and displays relevant results on screen in real-time. A number of measurements were taken using differing amounts of input power (heat) to the silicon ranging from 0 – 2 Watts (W) and differing amounts of input airflow ranging from 0 – 1 Liter per min (LPM).
**Thermal Modeling**

A thermal model of the thermo-fluidic mockup was constructed using FLOWTHERM™. The model has a volumetric heat source to represent the electrical heater and a nitrogen pass-through. The simulation results were compared to the thermo-fluidic experimental data obtained from the mockup. It was found that the simulated results were within 8% of the experimental results. The engine-to-ambient thermal resistance was found to be 139°C/W for the simulated package and 129°C/W for the experimental thermo-fluidic package.

A second thermal model was created to simulate the objective power generating system (Figure 9). The model includes fuel flow, air flow, and a variable heat source as energy inputs. Exhaust fluid flow, external radiation, and external convection are the energy outputs. In order to maintain a 400°C engine temperature with only a 1.9W engine heat source, the package must have a thermal resistance of 197°C/W. The current simulations suggest that this goal can be met. The simulation results show the combustion chamber temperature to be 475°C with ethanol as the fuel. This temperature translates to an engine-to-ambient thermal resistance of 237°C/W. Simulations were also run with heptane and octane as the fuel. This change had little effect on the engine temperature.

**Conclusions**

A package has been designed for a MEMS rotary engine power system. Thermal simulations and thermo-fluidic experiments show that the package is capable of maintaining an engine temperature above 400°C with only 2W of input heat. LTCC tubes have been shown to be viable fluidic and electrical interconnects in a high temperature environment. Fabrication of these electro-fluidic interconnect structures utilizes standard LTCC fabrication steps, resulting in no additional material or labor costs. All the materials in the package can withstand the high engine and exhaust temperatures, and the assembly does not require any processes above 150°C. High temperature adhesives have been tested for use at the ceramic-silicon interfaces. Multiple candidate adhesives have performed well during high temperature testing. It has been verified that surface roughing of the silicon is a large factor in improving LTCC tube adhesion. Utilizing LTCC processes, high temperature materials, and low temperature assembly techniques a robust MEMS package capable of enduring extreme environments has been produced.

**Acknowledgements**

This work was carried out under the DARPA MPG Program (PM: W. Tang and C. Nguyen) under Grant number NBCHC010060. The authors would like to acknowledge the efforts of Dr. Kelvin Fu for surface preparation techniques, Mr. Fabian Martinez for his efforts in the solid modeling and Si mockup unit development, Mr. Josh Heppner for efforts in thermal modeling and many helpful discussions from the MEMS REPS research team.

---