PROPULSION SYSTEMS FOR MICRO AERIAL VEHICLES

Adrian COMAN, Mircea BOŞCOIANU, Corneliu AXENTE

Military Technical Academy, Bucharest Romania, mircea_boscoianu@yahoo.uk.com, adrico59@yahoo.com, adrico58@yahoo.com, cornell2you@yahoo.com

***Abstract* - Micro-scale rockets offer the possibility of attaining increased thrust-to-weight ratios Because of its simple fabrication, such devices could be used in a wide range of microapplications. The three different designs analyzed are: microturbojet, gaseous propellant, and solid propellant rockets.**
A general overview of each design and possible applications, outlining their respective advantages and disadvantages which include wear properties, friction, efficiency, robustness, fuel energy densities, and fabrication processes is presented. This is followed by an analysis of the solid propellant rocket, including design parameters, fabrication techniques, and materials. The results and future direction of R&D are discussed for this solid propellant design and the micro-scale rocket field as a whole.

Keywords: *micropropulsion, microrockets, microturbojet.*

1. INTRODUCTION

In miniaturizing Micro Electro Mechanical Systems (MEMS), one can achieve unique responses from materials in ways that benefit performance and efficiency. Innovations requiring miniaturization have resulted in the advancement of MEMS designs, pressure and chemical sensing devices, accelerometers, communications devices. Scaling devices to a microscale allows surface interactions to dominate behavior, creating increased sensitivity in some sensing applications. Approaches to microfabrication, have undergone plentiful examination and optimization, allowing for accurate tolerances and design freedom on the microscale.
Microrockets are MEMS devices which deal with scaled-down versions (the order of millimeters, with parts extending to tens of microns, depending on the particular design) of common macro-scale rockets. Motivations for creating these millimeter-sized rockets include mobility for attached MEMS sensing devices (Smart Dust), guidance systems, and efficient micro aerial vehicles (MAV). Advances in microfabrication allow us to manipulate materials including semiconductors, metals and ceramics. Materials considerations are paramount in establishing adequate and reliable performance; ceramics, are of interest due to their structural stability under extreme thermal operating environments.
Three classes of rockets are summarized, highlighting their respective advantages and disadvantages in performance and fabrication. Following this, a comprehensive investigation into the microfabrication of the solid propellant microrocket is presented.

2. SOME ASPECTS ABOUT THE MICRO-TURBOJETS

The microfabricated high-speed gas turbine is modeled after its more common "macro-scale" counterparts. While the MGT's use as a source of propulsion is limited in most applications to MAV rather than micro-rockets, both the design and the fabrication process provide important advances to the current state of the art in micro-scale propulsion.

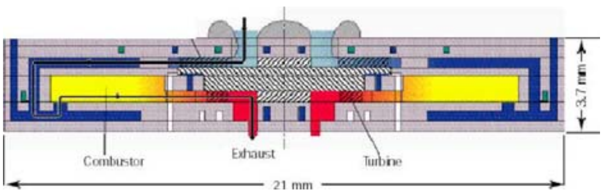

Fig 1: Micro Gas Turbine/ MGT (Livermore, 2001)

MGT has about 20mm square with a depth anywhere between 3-5mm and the main feature is a rotating disk, 8mm in diameter, mounted along a shaft in the middle of the system. The disk is driven by feeding an air/fuel mixture into a chamber surrounding the disk then igniting this mixture to drive the turbine and exhaust the resulting pressurized gas. Because of the complex geometry and relative motion of the components the microfabrication steps to build the micro-turbine engine are quite complicated. Six individual silicon wafers are etched using deep reactive ion etching (DRIE) and then wafer bonded together. This stack-up, makes alignment accuracy a concern during fabrication. Because the pressurized exhaust, and thus the propulsion, is created by the rotating turbine, the speed at which the disk spins in relation to the shaft is also of critical importance to the efficiency of the system. To have a comparable power density to macro-scale turbines used in large-scale propulsion, like airplane engines, micro-turbines must rotate with a rotor tip speed of about

500 m/s, or at approximately 1,200,000 rpm (Fréchette, 2000). While this has been achieved, there are problems in efficiency that arise from this high power density. As larger speeds are reached, energetic losses and the chance of failure increase due to frictional forces. In fact the development of novel, micro-bearings to increase the average 20% efficiency that micro-turbines get is a major focus of current research. While the uses and benefits of micro-turbine engines are clearly there, the problems associated with downscaling rapidly moving parts has been the major stumbling block in fully realizing micro-turbine powered micro-rockets.

3. GASEOUS PROPELLANT MICROROCKETS

Because of the problems associated with frictional losses and moving parts, some research is being directed towards micro-rockets designed with no moving parts. These designs are expected to be used in future spacecraft and small micro-satellites because of their reusability and the long service life associated with no moving features. The rocket is made from 6 single crystal silicon wafers, each approximately 4" square. To allow for the high aspect ratio features, deep reactive ion etching is used in conjunction with more standard chemical vapor deposition and buffered oxide etching techniques to fabricate the micro-rocket.

Unlike the micro-turbine, this rocket gains all of its thrust force from careful design of the chamber and nozzle geometry. Thus, 3D contours must be created using largely 2D microfabrication techniques, creating a challenging and relatively slow process. The difficulties in microfabrication are more than made up for in the success of the device, however. Recent tests on the first generation liquid cooled, gaseous propelled micro-rocket were largely successful; the device created a good thrust, useful thrust power and thrust to weight ratio (twr).Future tests planned to increase the chamber pressure by an order of magnitude, experimenters expect that the gaseous propelled rocket will eventually yield up twr.

While the micro-turbine and the gaseous propelled rocket are both steps forward in micropropulsion, they both have disadvantages: difficult fabrication procedure and the need for a bulky external system to provide the liquid and gaseous fuel components. Solutions to these problems have been explored in the solid propellant rocket.

4. SOLID PROPELLANT MICROROCKETS

This design has a lower total thrust force than the gaseous propelled rocket (0,1-1 N), but it is smaller and also has the ability to provide a greater energy density than conventional batteries and other small power sources. The solid propellant rocket design also has the advantage of being easier to fabricate and customizable in regards to fuel selection. The main limitation (Rossi, 2002) could be overcome by fabricating large arrays of rockets and using a digital control scheme to control the firing. The size of the solid propellant combustion chamber and nozzle make assembling arrays feasible.

The specific design and current performance progress of the solid propellant microrocket is of particular interest because of the greatest opportunity for advancements in micro-satellite and other future small spacecraft propulsion. The solid propellant rocket is relatively easy to fabricate with simple techniques such as anisotropic etching and the fuel source is both customizable and self-contained. The high energy density makes this design the best choice for space-based applications. Thus, to fully explore the cutting edge of micro-rocket research, an in depth case study will follow which focuses on the specific attributes of the solid propellant micro-rocket. The design's step-by-step fabrication techniques and geometric and materials considerations will be examined in an effort to fully realize the extent to which this design has revolutionized both micro-propulsion and the use of micro-rockets.

5. SOME ASPECTS ABOUT THE FABRICATION OF SOLID PROPELLANT

An analysis of some of the fabrication methods utilized in microrockets with solid propellant will be presented in detail. In Fig 4 is presented Rossi (2002) design with the dimensions of the microrocket components with cylindrical shapes, when in actuality, all components, due to anisotropic etching constraints, are limited to rectangular and pyramidal shapes. This fabrication technique is lacking certain details that can be filled in using inferences from the procedure and other sources pertinent to the topic. The fabrication of this design can be broken down by its components: a convergent/microheater, propellant chamber and divergent.

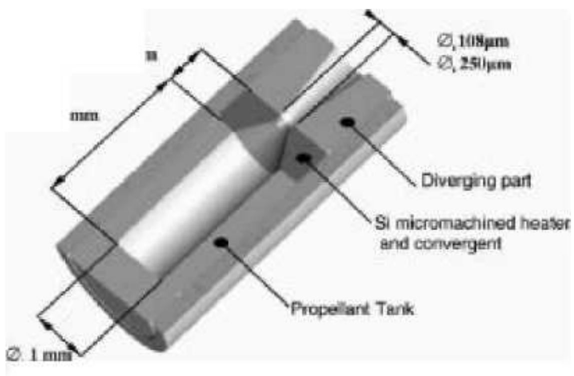

Fig 2: Rossi (2002) microrocket design including component nomenclature.

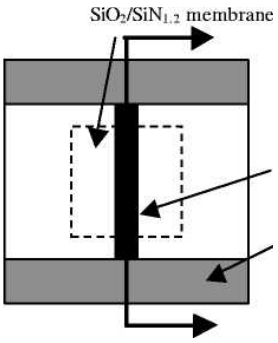

Fig 3: The microheater with the representation of cross-section

6. MATERIALS CONSIDERATIONS

a) Propellant Chamber

The propellant chamber should be made of a material with a low thermal conductivity so that less thermal energy from the combustion of the fuel leaks out and more thrust can be obtained from the rocket. Silicon, while amenable to established micromachining processes, may not be the optimal choice in this respect given its moderately high thermal conductivity. On the other hand, ceramic materials can have a thermal conductivity 4 -10 times less than silicon and can be considered as an alternative material for the construction of the fuel chamber. For microscale applications, chambers can be fabricated by conventional drilling, in this case using the commercial ceramic Macor® (Corning). Tab. 1 gives a comparison of selected properties of silicon and Macor®.

Micromachining the ceramic becomes somewhat of an issue for smaller size scales, although the possibility of adapting ceramic injection micromolding techniques for this application is promising.

Property	**Silicon**[1]	**Macor®**[2]
Thermal Conductivity	124 W/mK	1.46 W/mK
Thermal Expansion Coefficient 25° - 300°C	$2.49x10^{-6}$ - $3.61xlO\sim^{6}$/°C	$9.3xlO\sim^{6}$/°C
Density	2.33 g/cm^3	2.52 g/cm^3
Elastic Modulus	112.4 GPa	64 GPa
Temperature Limit	1412°C (melting point)	1000°C

Table 1: Different properties for Macor® and Silicon

b) Solid Propellant

These propellants are preferred for their stability and relatively high energy density. A composite fuel consists of a binder material (polybutadiene or glycidyle azide polymer), an oxidizer (NH4ClO4), and a metallic fuel (Al, Zr, B, Mg). While composite propellants have a relatively low specific heat value and leave metallic particle residue after combustion, they have a greater specific impulse than homogeneous fuels such as nitrocellulose or nitroglycerine and are low vulnerability ammunititions. In particular, the mixtures can be adapted such that the rheological, ballistic and kinetic properties are optimal for the given application.

7. CONCLUSIONS

The solid propellant micro-rocket shows significant progress towards commercial feasibility. In utilizing various techniques of microfabrication, it is possible to scale a propellant system down to dimensions of technological interest. It was analyzed the fabrication process, design considerations and performance resulted from a solid-propellant micro-rocket system. It was demonstrated the advantages over other types of micro-rocket devices. In particular, the solid-propelled micro-rocket is an interesting solution relative ease of fabrication, fuel energy density, and efficiency. To be able to apply appropriate techniques of fabrication reliably on such a small scale will inevitably enable the production of such useful devices to flourish. Materials considerations allowing for structural stability and fuel efficiency, including a larger specific impulse for composite propellants than traditional fuels, is one of the leading motivations in continuing this design. Integrating rockets into guidance, positioning, and sensing systems in the end will rest on the reliability of fabrication, a field which continually is evolving and maturing.

References

[1] Livermore, Carl. Here Come the Microengines. The Industrial Physicist. Vol 7, Issue 6. December/January 2001.

[2] Fréchette, Luc G. et al, Demonstration of a Microfabricated High-Speed Turbine Supported on Gas Bearings. Solid-State Sensor and Actuator Workshop, Hilton Head Is., SC. June 4-8, 2000.

[3] London, A.P. et al. Microfabrication of a High Pressure Bipropellant Rocket Engine. Sensors and Actuators: A Physical. Vol 92. 2001.

[4] Rossi, C. et al. Design, Fabrication and Modeling of Solid Propellant MicroRocket-Application to Micropropulsion Sensors and Actuators: A Physical. Vol 99. 2002.

[5] Madou, M. Fundamentals of Microfabrication: The Science of Miniaturization, Second Edition, CRC Press LLC, Boca Raton, FL, (2002) pgs. 104-105, 214-216