POLYMERIC MICROCOMBUSTORS FOR SOLID-PHASE CONDUCTIVE FUELS

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ABSTRACT

This paper presents a micromachined SU-8 combustor for the ignition and reaction of solid conductive fuels. Solid fuels can be made conductive by doping the fuel with conductive powder. The conductive solid fuel serves to simplify device fabrication by allowing ignition to occur by passing current directly through the fuel sample from two MEMS-fabricated electrodes as opposed to relying on the transfer of heat from external or imbedded igniters. An array of high-aspect-ratio electrodes were patterned from SU-8 by multiple-exposure. The devices were filled with 3.97 mm^3 of graphite-doped conductive Glycidyl-Azide-Polymer (GAP). Nozzles with varying sizes are fitted on the microcombustors. Approximately 600mN was generated within 20ms. The easy fabrication and low cost/weight of these microcombustors or gas generators lend themselves to disposable, one-use, or short duration applications.

1. INTRODUCTION

In this work, we design and fabricate a microcombustor based on conductive solid fuels. Solid-fuel microcombustors for applications such as microrockets have been developed previously for kilogram-scale satellite control[1,2,3] and sensor platform deployment[4]. Teasdale[4, 5] demonstrates the design and fabrication of mm-scale solid-propellant rockets for deployment of sensor platforms, also known as "Smart Dust". The total device height was 8.5 mm, and thrust-to-mass ratios of 15mN/g were reported. Both Lewis et al.[1] and Rossi et al.[2,3] demonstrated integration of solid fuel with MEMS processing. Lewis fabricated an array of chambers for the combustion of lead styphnate that used a 3-layer bonding technique to integrated fuel, igniter, and a burst diaphragm into an array of microthrusters. Thrust was reported at 0.1 mN, and combustion was reported to be approximately 10% of the total fuel. Rossi also used a 3-layer bonding technique, but combusted Glycidyl-Azide-Polymer (GAP) to characterize nozzle performance. Thrust measurements for GAP-based microthrusters were reported to be 2.5 to 75 mN for 4mm diameter combustion chambers. Microthrusters offer the potential for more accurate control than their larger counterparts and simplified fabrication compared to liquid microthrusters. Furthermore, English et al.[6] demonstrates that the solid fuel actuators can be controlled by fuel mixture, nozzle design, and combustion chamber design. The mixture and nozzle design may be varied to control gas production rate, and therefore output magnitude, of a fluid actuator.

The above research demonstrates that solid fuel offers a reliable means for generating forces with thrust-to-weight ratios exceeding unity. However, the solid fuel is usually ignited by transferring heat from external or embedded igniters. To produce such devices, the combustion chamber and the igniter are commonly fabricated separately, and subsequently bonded together at the conclusion of the process. Also, as the microcombustors become smaller, heat losses to the chamber wall become significant. DiBiaso et al.[7] have demonstrated that the addition of at least 20% graphite by volume enables conventional composite propellants to become conductive, and the results of burn time testing indicates that the addition of graphite only slightly reduces the burn rate of the fuels. Conductive fuel, in which the fuel is ignited by direct Joule heating if current is passed through it, is particularly suited for microcombustors since:

- the igniter/combustor fabrication is greatly simplified;
- over a large range of operation, the burn rate of fuel in the overall combustor can be decoupled from the chemical reaction rate by changing igniter volume density;
- the combustor housing can be made of a low-temperature, low-cost material such as SU-8 epoxy, with integral conducting electrodes, since heat transfer from an external igniter is no longer required to initiate reaction;
- current sources can be placed closely together using MEMS technology, reducing thermal diffusion effects retarding fuel heating.

This approach is compatible with a variety of electrical ignition schemes, from DC to capacitive discharge.

2. DEVICE CONCEPT

The purpose of the actuator is to contain the fuel as well as to provide electrodes (current sources and sinks) for fuel ignition. Passing current through the

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fuel increases the fuel temperature by direct Joule heating. Many design tradeoffs are possible to control force generation rate. For example, in order to ignite the fuels in a short time, the MEMS combustor should satisfy the following requirements:

- the distance between the two opposing electrodes should be as short as possible;
- the contact area of the electrode and the fuel should be as large as possible;
- as much volume as possible should be reserved for fuel;
- the combustor should be thermally insulating;
- the generated current density should be uniform so as to uniformly heat the fuel.

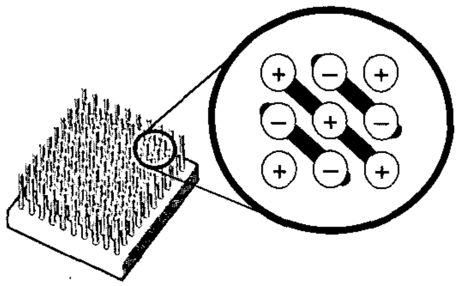

Figure.1 Conceptual view of the design. An array of alternately energized pillars is formed in a polymeric material. The fuel will be molded between the pillars.

Based on the above requirements, the microcombustor design is shown in Figure 1. Each device has 100 pillars as electrodes, and each pillar is 100 microns in diameter and 700 microns in height. The center-to-center distance of the pillars is 280 microns; therefore the distance between adjacent pillars for the fuel is 180 microns. The pillars and the substrate are made from the same material thus improving the mechanical strength. The pillars are interconnected so as to form the 'checkerboard' potential pattern shown in Figure 1. Adjacent pillars in a row or column have opposing electric potential to generate current within the fuel. In addition, the high-aspect-ratio pillars (7:1) maximize current flow through the conductive solid fuel.

Conductivity testing of the solid fuel indicates that when the GAP is doped with 20% graphite by weight, the resistivity is approximately 60 Ω-m. Besides making the fuel conductive, the graphite has the added benefit of reacting with oxidizer, generating additional gas. Figure 2 shows the resistivity versus percent of graphite in the solid fuel.

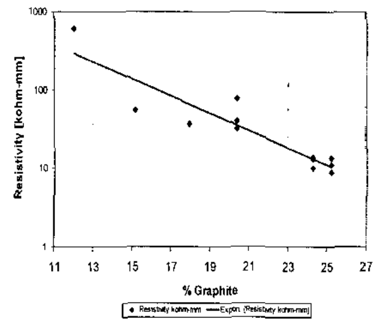

Figure 2. Resistivity of conductive fuel as a function of graphite loading.

The current density is simulated by ANSYS 7.0 FEM (Figure 3). It indicates that the maximum current is at the circumference of each pillar, and the minimum current density is at the center of every four pillars. At other areas, the current density distributes quite evenly through the fuel to ensure a uniform heating. This current density pattern does lead to a non-uniform heating rate throughout the fuel, however, with a self-sustaining reaction, all of the chemical energy should be recovered. The outer chamber walls will not be heated, and the polymeric mold is a poor conductor of heat, thereby minimizing losses. Greater uniformity could be achieved by fabricating alternating "ridges" of electric potential, however this alternating pillar design allows for more fuel to molded into the electrode structure.

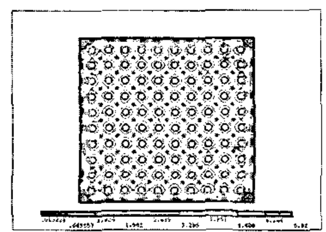

Figure 3. Current density simulation.

3. FABRICATION

The details of the fabrication process are shown in Figure 4.

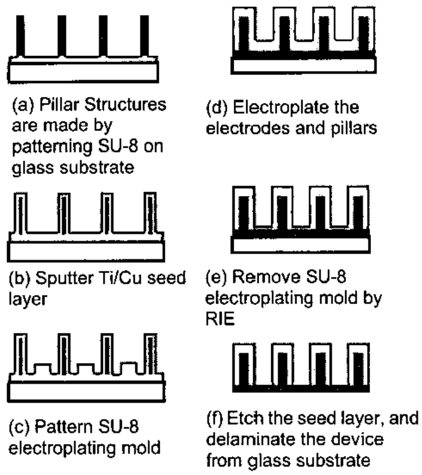

Figure 4. Fabrication Sequence

First, an approximately 1mm thick layer of SU-8 is spin-coated on a transparent glass substrate. After soft baking, the SU-8 is exposed from the front in order to form the 700 micron high pillar array and the rectangular walls which are used to hold the fuels inside. Then the SU-8 is weakly blanket-exposed from the back, i.e., through the glass substrate, to form the 300 micron thick substrate of the pillar array. The exposure is followed by a post-exposure bake to cross-link the SU-8 structure. After developing, a Ti/Cu seed layer is sputtered to cover the entire structure. An additional thin SU8-5 layer (10-20 um) is spin-coated on the device. After soft-baking, the thin SU8 layer is exposed to form an electroplating mold. After post baking and developing, a 10 micron thick Ni/Fe layer is electroplated into the mold to cover and interconnect the pillars. Then, the SU8-5 electroplating mold is removed by reactive ion etching (RIE), and the seed layer Cu/Ti is selectively etched. Finally, the devices are delaminated from the glass substrate by a short oven bake. The final device is shown in Figures 5-6.

This fabrication procedure results in pillars and substrate made from a unitary piece of SU-8, with no interlayers or bond lines. The absence of mechanical interfaces helps to seal the combustor and strengthen the pillars so that fuel may be molded into the chamber without breaking the pillars. To enable testing of the final device, the rubberized conductive GAP is molded into the device for ignition (Figure 7).

4. TESTING RESULTS

For testing, the devices are filled with 3.97 mm^3 of conductive GAP (75% GAP : 25% graphite). The total mass of device with fuel is approximately 60 mg. Nozzles with different sizes (200-500 micron) are made by rapid prototyping or laser cutting and fitted on the microcombustors (Figure 8). As is shown in Figure 8, the device with nozzle is mounted in a clamp that is super-glued to the actuator mount. A voltage of 35V is applied to the opposing electrodes, and both the current going through the electrodes and the resultant generated force, as measured by a dynamic force sensor (PCB Piezotronics Model 209C01) is recorded as a function of time. When the solid fuel is ignited, high-pressure gas is generated and ejected from the nozzle. The largest forces were obtained for nozzles of approximately 300μm in size.

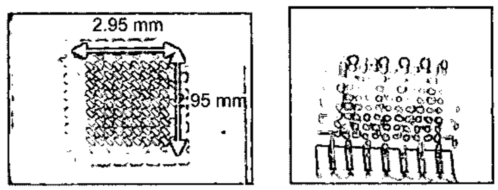

Figure 5. Top view and perspective view of device

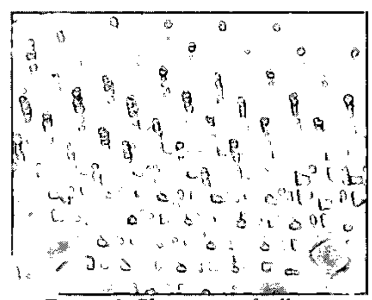

Figure 6. Close view of pillars

Figure 7. Device packed with fuel. The distance between adjacent pillars is 180 μm.

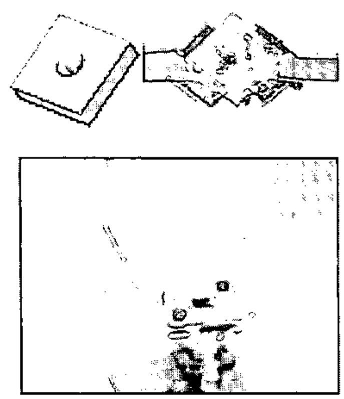

Figure 8. Nozzle Testing Setup

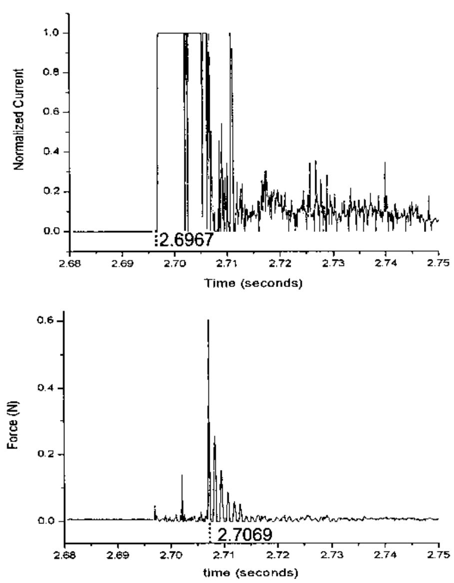

Figure 9. Test results. Current flow (normalized to initial current) and resultant force from a typical combustion event as a function of time.

All the resultant curves of current and force are quite similar, and Figure 10 is a typical curve. When the power is switched on, the current quickly rises to its maximum value. During this period of approximately 10 ms, the temperature of the fuel is raised to its ignition temperature. The fuel is ignited, which is reflected on the current curve as a falloff in current as the conducting paths are combusted away. The generated gas exits the nozzle and generates a maximum of 600mN force over a period of 10 milliseconds. Once the fuel is combusted, the force drops to zero, and the current is less than 10% of its maximum value, never fully dropping to zero. This residual current may be due to the accumulation of unreacted graphite at the base of the combustion chamber. However, this accumulation does not prevent successful combustor operation.

5. CONCLUSION

A micromachined SU-8 combustor intended for the ignition of conductive solid fuels has been designed, fabricated and tested. The device is composed of an array of electrode pillars made from SU-8. The electrodes are patterned into a large number of pillars acting as a "checkerboard" to minimize the decomposition time of the fuel. Due to the conductive nature of the fuel and the design of the combustor, no external igniters are required, and heat losses to the external environment are minimized. The device is tested by using conductive GAP, and the results demonstrate that ignition could occur over short time scales with significant force generation. The ease of fabrication and low cost/weight of these microcombustors or gas generators lend themselves to disposable, one-use, or short duration applications.

6. ACKNOWLEDGEMENT

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