

DIGITAL MICRO-THRUSTERS WITH SIMPLIFIED ARCHITECTURE AND RELIABLE IGNITION AND COMBUSTION

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Abstract: This communication reports on the development of a high performance propellant coupled with a reliable ignition technology based on Microsystems technology for the realization of solid propellant micro-thrusters with reliable performances. The concept for the ignition, the propellant formulation and the thrusters architecture was reviewed from scratch. A solid propellant was formulated in association with the development of a coating process and an igniting chip for a controlled and complete combustion of the propellant at the micro-scale level. The successful ignition and controlled combustion of the solid-propellant coated on the micro-igniting chips has been confirmed using a high speed camera, providing valuable real time data on the ignition and combustion characteristics of the propellant. Micro-thrusters with simplified architectures were designed and fabricated based on this ignition concept and the first results on their performances are reported.

Key words: Micro-thrusters, solid propellant, propellant ignition.

1. INTRODUCTION

Nowadays, the use of commercial solid propellants has lead to major concerns in terms of reliability of miniaturized pyrotechnical systems. Most of them are not adapted to operate in very small dimensions. Some of them are primary explosives that are not convenient to handle and their combustion produced a small amount of gases. In many cases the propellant was combined with micro-igniters available on the shelves and not specifically developed for the proper ignition of the given propellant. The lack of a robust technology to ensure the reproducibility of the ignition is recognized to be one of the main reason checking the exploitation of the micro-pyrotechnical systems, for instance in micro-propulsion modules for space applications.

This communication reports on the development of a high performance propellant coupled with a reliable ignition technology based on Microsystems technology for the realization of solid propellant micro-thrusters with reliable performances. A solid propellant was formulated in association with the development of a coating process and an igniting chip for a controlled and complete combustion of the propellant at the micro-scale level. Compared to the standard igniting concepts, the approach used in this project was to go back to an ignition happening underneath the propellant, but with an ignition concept allowing a complete and controlled combustion of the propellant.

It eliminates the problems associated with the other ignition techniques used so far such as the lost of the contact between the igniter and the propellant due to gas generation, particles generation and combustion of propellant outside the thruster. Micro-thrusters with simplified architectures were designed and fabricated based on this ignition concept and preliminary results on their performances are reported.

2. CONCEPT AND REALISATION

The complete structure of the thruster is very simple with only two parts. An igniting plate is covered with the propellant drop and the chamber/nozzle part is fixed to the igniting plate to form the complete thruster, as shown in Fig. 1.

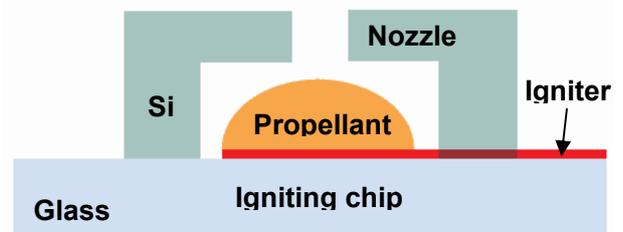


Fig. 1: Schematic view of the thrusters structure, composed of two parts, the igniting chip coated with the propellant on which is fixed the chamber/nozzle part.

The dimensions of the thrusters have been chosen for the easy handling and processing of the parts and devices. In this work, we concentrated our efforts to demonstrate the ignition concept and the suitability of the propellant developed for the application. The area of a single thruster corresponds to the area of the igniter chip and is of $5 \times 5 \text{ mm}^2$. For the chamber/nozzle part, the diameter and height of the chamber are of 1.75 mm and 325 μm , respectively. The nozzles have diameters of 150 and 200 μm and a length of 200 μm .

The igniters are based on the Joule heating of a metallic thin film patterned on 525 μm -thick glass substrate. A special care was given in the design and processing of the igniters to achieve a controlled and reliable ignition and combustion of the propellant. Basically, the igniters consist in a 250 nm-thick platinum film e-beam evaporated on the glass substrate and patterned using a lift-off process. After their processing, the igniter wafers are diced into chips prior to coating.

The main characteristics requested for a solid propellant applied to micro-propulsion are the following: it has to be safe, to exhibit a fast reaction (short ignition delay time), to be easy to ignite and to generate an extensive gas production. We have developed a propellant with micrometric grain size adapted for small scale applications. It has a relatively low temperature of ignition, but still high enough to be above the potentially high temperature that can be met in a space environment. To modify the burning characteristics of the propellant a chemically compatible binder was added. Different compositions of propellant were tested with a binder percentage included between 5 and 20 %. Figure 2 presents a typical three dimensional profile of a propellant drop coated on an igniting chip. The measurement was performed using an optical profilometer from WYKO: NT1100DMEMS. The propellant drop has a typical diameter of $1.6 \pm 0.1 \text{ mm}$ and a drop height of about 125 μm . The reproducibility of the quantity of propellant coated was evaluated ($n=10$): $0.18 \pm 0.03 \text{ mg}$ of propellant was coated on the igniter chips.

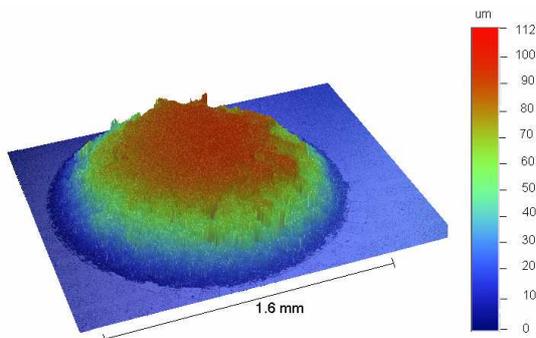


Fig. 2: Three dimensional profile of a typical drop of propellant on the igniter chip.

Once the igniter chips coated with propellant, they are assembled to the chamber/nozzle parts using a gluing process to realize the complete thrusters, as illustrated in Fig. 3. The chamber/nozzle parts are fabricated by deep reactive ion etching (DRIE) of a double side polished 525 μm -thick silicon wafer. DRIE of silicon was performed on both sides of the wafer to fabricate both the chamber and the nozzle. The process consists in dispensing locally an epoxy-glue (H70E from Epotek) on the chamber part. The chamber/nozzle part is aligned and brought in contact with the igniter part using a flip-chip-bonder. Finally, the two parts are definitely fixed together by curing the glue in an oven at 60 $^{\circ}\text{C}$ for 15h.

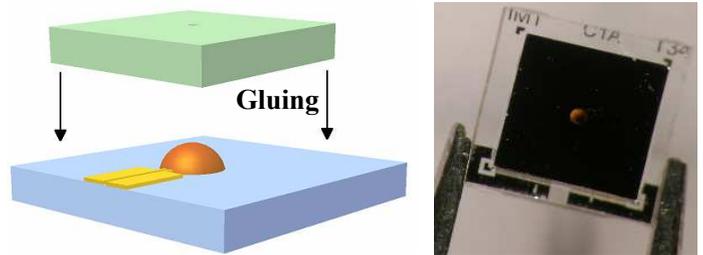


Fig. 3: 3D scheme of the assembling of the two parts composing the thruster and a picture of the thruster after assembling.

3. IGNITION TEST SETUP

To validate the ignition concept, igniter chips with specific designs and processes were coated with different formulations of the propellant and their ignition and combustion evaluated.

The ignition of the propellant was characterized electrically (the voltage via a transient recorder) as well as optically (via a high speed camera). The current was held constant and the voltage was measured, so the power and energy could be calculated. The ignition was performed with a constant current delivered to the igniters, in between 100 and 500 mA and with duration of 500 ms to 1 s. For most of the ignition experiments a current of 100 mA was used, corresponding to a ignition power of about 1.6 W.

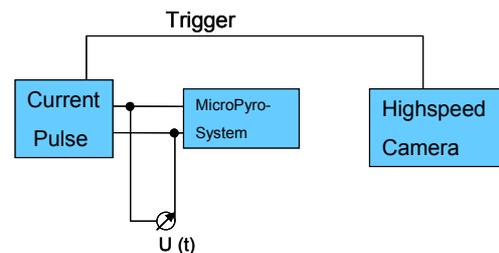


Fig. 4: Schematic of the electrical connection of the characterisation set-up.

The current pulse was generated with a current source (Löhnert / ZMP F1). The current source outputs a trigger signal, which was used for the time scale of the electrical and the optical measurements (Fig. 4).

The electrical characterization was done via a transient recorder (LTT / LTT 184- 8 channel) with a maximum sample rate of 2.5 MHz at 16 Bit up to 20 MHz at 12 Bit. The dynamic range was sufficient, as the lowest voltage range was 1 V up to 50 V. To measure the ignition delay time reproducibly, a high speed camera (Photron / Fastcam Ultima APX-RS) was used to record the ignition. As the camera was triggered by the current source, the ignition time could be measured as exactly as it could be optically determined on the video. Also the combustion process could be easily characterized with the recorded videos. The high speed camera uses a CMOS sensor with a spatial resolution of 1024 x 1024 pixel and a high sensitivity due to the large pixel size of 17.5 μm . The temporal resolution is 3000 fps at maximum resolution and up to 250000 fps at a reduced resolution. The minimum shutter time is 1 μs .

4. PROPELLANT IGNITION AND BURNING CHARACTERISTICS

Different types of igniters were evaluated using the high speed camera, at the best of the knowledge this is a premiere, in order to optimize their performances. Fig. 5 presents a video sequence of a typical non-controlled ignition and partial combustion of the solid propellant. Controlled ignition from the back side of the coated propellant was not achieved due to the non adapted igniter design, with pieces of propellant being lifted-off by the gas generated during its combustion. Fig. 6 presents a video sequence of the typical ignition and controlled combustion of the solid propellant using the newly developed igniting and propellant technology. Combustion starts at the outer of the coated propellant with a homogeneous propagation towards its centre. Ignition occurs in few milliseconds and the controlled combustion holds for up to 10 ms depending on the propellant formulation used.

The binder increases the adhesive strength of the propellant on the igniter surface and therefore improves the mechanical stability. A higher binder percentage in the mixture of propellant increases the time needed for ignition and the whole duration of the combustion process. The opposite was observed for an increase of the applied current in the igniters, with a decrease of the ignition and combustion times. These results for the same type of igniters are summarized in the Table 1.

Table 1: Summary of the burning characteristics of the igniting system (input current: 100 mA).

Binder	Ignition time [ms]	Combustion [ms]
5%	0.2	0.6
20%	0.6	5.5

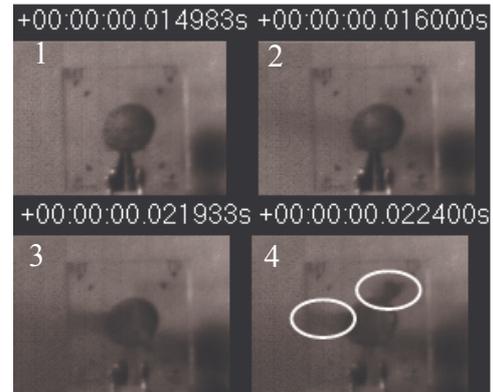


Fig. 5: Video frames of the propellant coated on the igniter, showing a non-controlled ignition (at 500 mA) and partial combustion, 1: before the ignition, 2: just at ignition, 3: at 22 ms after ignition, and 4: at 22.4 ms at the end of the combustion. White circles highlight the residues due to the partial combustion.

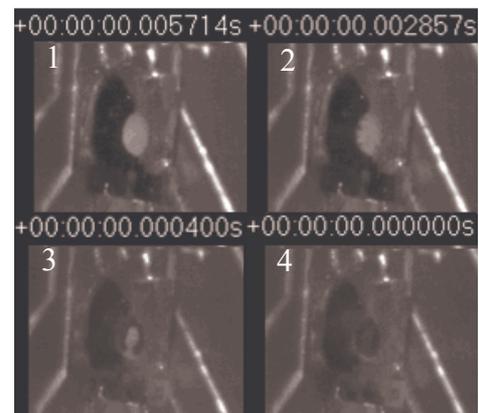


Fig. 6: Video frames of the propellant coated on the igniter, showing the controlled ignition (at 150 mA) and combustion of the drop, 1: before the ignition, 2: just at ignition, 3: at 2.5 ms after ignition, and 4: 5.3 ms at the end of the combustion.

5. THRUST FORCE MEASUREMENTS

The thrust force measurements were performed at LAAS-CNRS, Toulouse, France, using a pendulum type thrust stand [1]. Ignition was performed with a HP6644A power supply, with a constant current of 500 mA delivered to the igniters. Signal acquisition is

made via a PC using a National Instrument acquisition card (NI 6052 E) sampling at 300 kHz. The output signal is then filtered with a Butterworth type filter with a 100 Hz cut frequency. The torque created by the thruster weight was compensated by the feedback control system. The thrust force is obtained by converting the recorded voltage into a weight using a calibration curve and using the following equation: $F_{\text{Thrust}}=m \times g$, m being the mass corresponding to the output voltage recorded which is multiplied the gravity constant, g .

Thrusters with the same type of igniter design, coated with propellant (0.18 ± 0.04 mg) with two different percentages of binder, 5% and 20%, and covered with nozzles having two diameters, 200 μm and 400 μm , were tested. The highest thrust was obtained for the smaller amount of binder in the propellant and the smaller nozzle diameter, as expected with the saturation of the thrust balance at a value of 20 mN. A typical curve is presented in Fig. 8. The total combustion of the propellant is fast with an average thrust duration of about 4 to 8 ms. These values are in line with the values recorded with the high speed camera when validating the ignition concept.

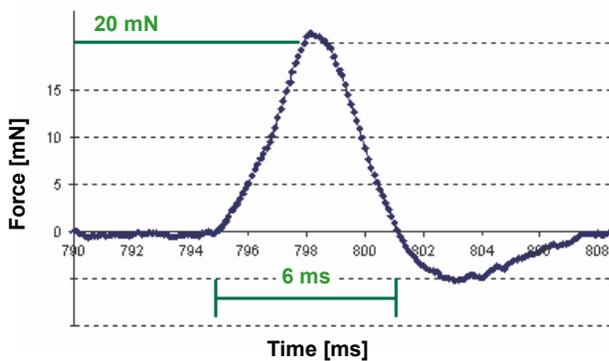


Fig.8: Thrust force as a function of time for a micro-thruster with the complete combustion of the propellant: $F_{\text{thrust}} = 21$ mN, combustion time: 6 ms. Nozzle diameter: 200 μm .

A second series of twenty tests have been performed to get some statistics on the performances of the thrusters. 95% of the thrusters have been successfully ignited and 80% with a sufficient measurable thrust. For an average propellant mass of $0.08 \text{ mg} \pm 0.02 \text{ mg}$, composed of 20% of binder, the thrust force generated was between 4 and 10 mN corresponding to a specific impulse up to 100 s.

Looking at these results, more specifically at the thrust force obtained for the small quantity of propellant used, the efficiency of the propellant developed is very good and the specific impulse

relatively high for this kind of chemical propulsion technology. The small thrust duration leads to relatively low total impulse and to thrusters that we could qualify of digital thrusters.

6. LOW POWER THRUSTERS ARRAY

A 2×2 array of micro-thrusters with a simplified structure has been realized (Fig.9). Indeed, following the validation of the igniting concept and propellant proposed, we have proceeded to a redesign and the establishment of a new process flow, minimizing the power consumption required for the ignition. Successful ignitions were recorded at a lower power down to 350 mW thanks to the suspended and therefore thermally isolated Joule heaters developed. Experiments have been conducted under vacuum (0.01 mbar) and at different temperatures (-20°C to 100°C). The devices were placed in a vacuum chamber with feed troughs for their electrical connections. The vacuum chamber with the devices was placed in a thermo regulated oven (ESPEC, model SH-661). Successful ignitions of the thrusters in these environmental conditions were obtained for the propellant and low-power igniter chips developed.

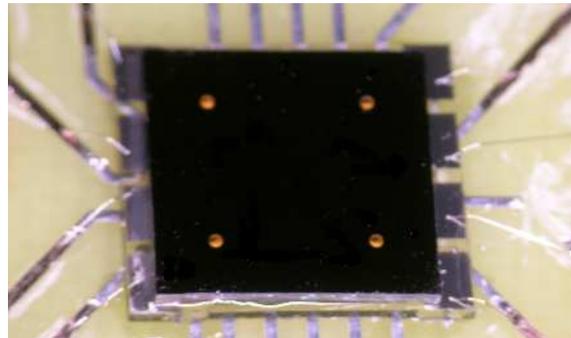


Fig. 9: Picture of the 2×2 micro-thrusters array on the printed circuit board for testing.

7. CONCLUSION

The developed propellant and igniting system enables the realization, with simplified processing and assembling procedures, of solid-propellant micromachined thrusters with reliable ignition for space applications. It represents a tremendous progress compared to the state-of-the-art in this field and a major break through for the commercial exploitation of micro-pyrotechnical systems.

REFERENCES

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