The Fourth International Workshop on
Micro and Nanotechnology for Power Generation and Energy Conversion Applications
PowerMEMS 2004
November 28 - 30, 2004
Kyoto, Japan

Design and Fabrication of Micro Combustion Rig for Micro Reciprocating Engine

J.Ogawa, Y.Okada, Y.Suzuki, T.Toriyama and S.Sugiyama
Ritsumeikan University
Noji-higashi 1-1-1, Kusatsu, Shiga 525-8577, Japan
Tel +81-77-561-2775, Fax +81-77-561-3994, E-mail rr003991@se.ritsumei.ac.jp

Abstract

A structure of micro reciprocating engine (hereafter we call "micro engine") has been proposed based on silicon bulk micromachining. An experiment of reciprocation of piston was conducted by using pulsed N_2 gas as driving source, in order to verify a validity of a design concept of the micro engine. In this paper, some improvements of the micro engine structure based on the previous works [1,2,3] are proposed, and design and fabrication processes of a micro combustion rig are reported to realize reciprocation of the piston by combustion of the mixture gaseous fuel composed of hydrogen and oxygen.

Keywords: micro engine, reciprocation, combustion, SOI structure, silicon bulk micromachining

1 INTRODUCTION

The micro reciprocating engine (hereafter we call "micro engine"), where we have proposed, has a combustion chamber and opposed-pistons supported by elastic springs. As a first demonstration, an experiment to operate the micro engine using compressed air (N_2) was carried out. As a result, the reciprocation of the pistons was observed and we have confirmed the validity of the design concept of the micro engine. However, some technical issues were pointed out through the experiment. An important issue is to determine an optimum size of the combustion chamber to realize stable combustion and to hold stable flame. Another issue is install method for micro ignition plug into the micro engine, which is, compatible to micro fabrication process. In this paper, we propose a micro combustion rig to overcome all of the issues of the previous works [1,2,3]. Fabrication processes of the micro combustion rig based on silicon bulk micromachining are briefly described.

2 STRUCTURE

Schematics of the micro combustion rig are shown in Fig.1. The micro combustion rig is composed of a cylinder case, a piston and an ignition plug. The cylinder case consists of a top cylinder case and a bottom cylinder case. The piston is sandwiched between the top and bottom cylinder cases. In addition, the ignition plug is attached under the bottom cylinder case. The ignition plug consists of a plug case and opposed-electrodes, which is located on the backing surface of the combustion chamber. Fig.1.b shows the internal structure of the micro combustion rig where the top cylinder case is removed. The mixture gas of hydrogen and oxygen is supplied from the trapping port, and passes through the trapping channel to the combustion chamber. After the fuel burns, the combustion products pass through the exhaust channel to the exhaust port, and are finally released into environment. Fig.2 illustrates the working cycle of the micro combustion rig. Reciprocation of the piston is accomplished by elastic springs formed at both sides of the piston (we call "spring-piston system"). We have demonstrated the reciprocation of the spring-piston by similar system in the previous works [3].

3 DESIGN

We have adopted the design approach for the micro combustion rig as follows.

1. Decide the dimensions of the combustion chamber.
2. Calculate the maximum combustion pressure from the working cycle determined from the compression ratio and the allowable temperature of Si.
3. Analyze the impulse response of the piston against the combustion and decide the spring constant and the mass of the spring-piston for the design stroke.
4. Decide the dimensions at the trapping and exhaust ports compatible to design stroke.
5. Decide the width, length and folded number of the spring from FEM analysis to obtain the spring constant decided in 3.

2.1 Dimensions of the Combustion Chamber

The dimensions of the combustion chamber have to be decided as small as possible, and more than a quenching distance, which causes combustion flame out. The dimensions of the combustion chamber are decided from view point of ease observation of combustion phenomena and an enough space which causes stable combustion. Thus, the dimensions of combustion chamber are found to be 5mm x 3mm x 1mm (W x L x H).

2.2 Maximum combustion pressure

The maximum combustion temperature of the micro combustion rig is determined by the allowable temperature of silicon. An allowable temperature of a substance is generally considered to be creep temperature. The creep temperature of silicon is approximately 850K, and the maximum combustion temperature of the micro combustion rig should be 850K. The excess coefficient is assumed to be 1 in the calculation of the working cycle and the compression ratio is assumed to be 1.5 as reasonable value for free piston engines [4]. The compression ratio is determined based the geometrical value from the displacement of the piston. As a result, the maximum combustion pressure is calculated to be 350kPa. The air standard Otto cycle as the working cycle of the micro combustion rig is shown in Fig.3.

2.3 Impulse response of the spring-piston

When the combustion pressure is applied to the spring-piston, the behavior of the spring-piston can be considered as a spring-damper vibration model. Assuming that the impulse force by the combustion pressure is half sine wave, the impulse response of the spring-piston against the impulse force can be calculated. In this calculation, we assume the maximum displacement and the damping ratio to be 2mm and 0.7, respectively. As a result, the maximum displacement, the spring constant and the mass of the piston are 1.8mm, 100N/m and 0.2g, respectively.

2.4 Dimensions at the trapping and exhaust ports

Conventional engines are started up by external starter, but the micro combustion rig has to be started up without starter.

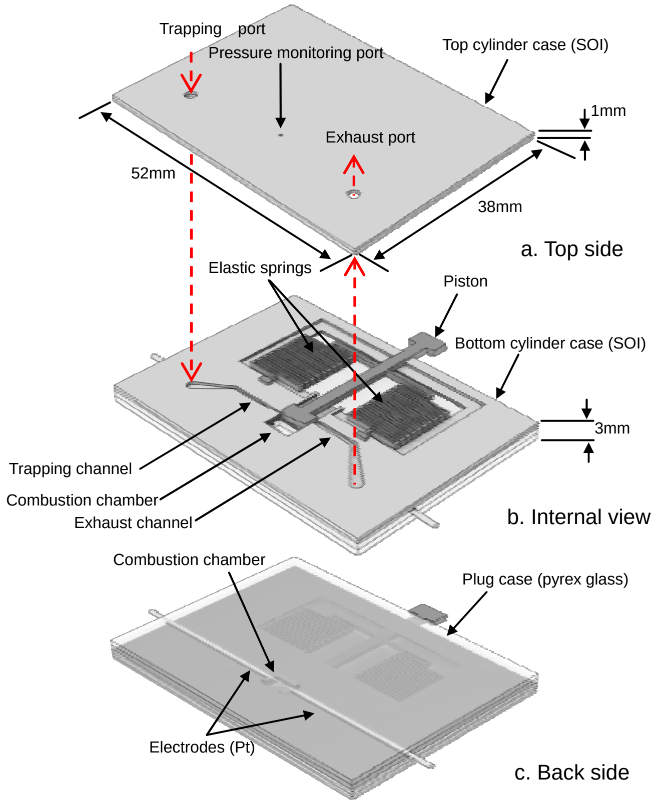


Figure 1. Schematic of the micro combustion rig.

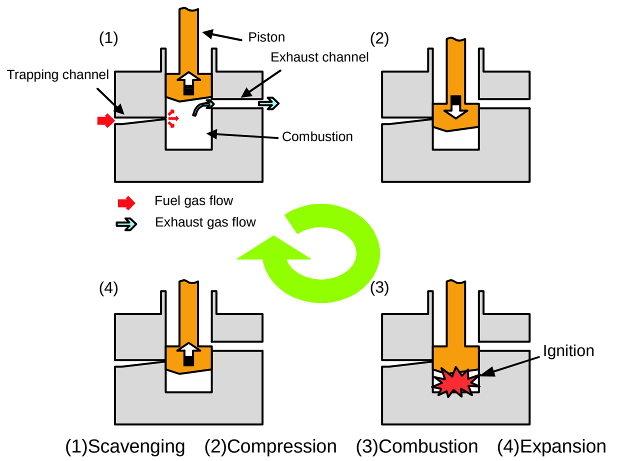


Figure 2. Working cycle.

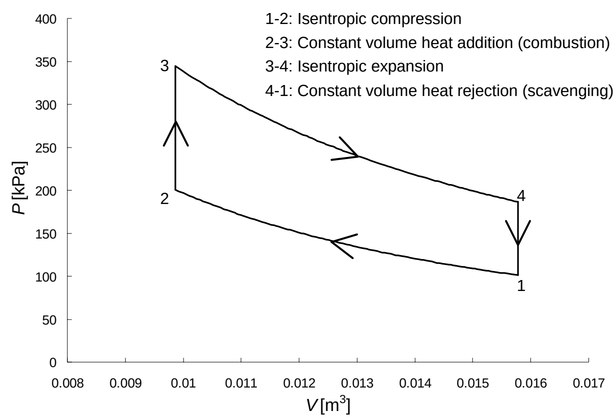


Figure 3. Otto cycle.

The trapping port of the micro combustion rig is designed to be opened when the piston is at rest position in order to trap the fuel at this position (Fig.4.a). The trapping port width is designed narrower than the quenching distance of hydrogen to prevent the backfire. The exhaust port should be designed much wider than the trapping port to scavenge smoothly. The exhaust port is arranged to be fully opened when the piston approaches the maximum displacement (Fig.4.b). The final dimensions are shown in Fig.5.

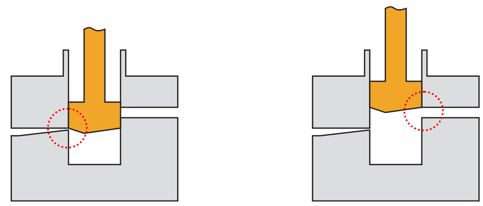
2.5 Design of the springs

The spring length relates directly to the overall size of the micro combustion rig. Thus it's not preferable from the perspective of engine miniaturization to lengthen the spring excessively. Therefore, the spring should be designed to obtain the desirable spring constant by varying its width. From the parametric calculation of FEM analysis, the spring width, length and folded number were decided to be 0.2mm, 12mm, and 10, respectively. Arranging this spring on the both sides of the piston, we obtain the spring-piston with 100N/m of spring constant.

4 FABRICATION

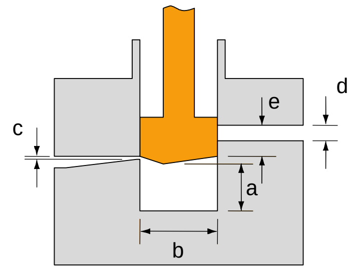
The top and bottom cylinder cases and the spring-piston are fabricated using SOI wafer based on silicon bulk micromachining by ICP-RIE. The ignition plug is fabricated by conventional mechanical machining. Fig.6 shows the fabrication processes of the top and bottom cylinder cases and the piston. These 3 parts can be fabricated by the same process. SOI wafer of 500μm device layer, 2μm BOX layer and 500μm handle layer is used. After patterning Cr mask for ICP-RIE on the one side of SOI wafer, Al mask is also patterned on the other side of SOI wafer. The Al mask is used for Al-Al thermo-compression bonding in the packaging process described later. After formation of masks on the both sides of SOI wafer, the one side of SOI wafer is etched to BOX layer. Then the other side of SOI wafer is etched to BOX layer. After finishing these processes, the exposed BOX layer is removed by RIE.

The ignition plug is composed of the plug case and the electrodes. The plug cases must be electrically isolated, and these are mechanically machined using pyrex glasses. Commercial micro probers are used for the electrodes. The material of the electrodes is Pt, because of its ability of low erosion by sparking [5]. Fig.7 shows the fabrication process of the ignition plug. First, a slit and a through hole are



(a) The trapping port is fully opened. (b) The exhaust port is fully opened.

Figure 4. States of the trapping port and the exhaust port.



a	Length of combustion chamber	3.0mm
b	Width of combustion chamber	5.0mm
c	Width of trapping channel	0.2mm
d	Width of exhaust channel	1.0mm
e	Distance until the exhaust channel fully open	2.0mm

Figure5. Dimensions of the combustion chamber and its surroundings.

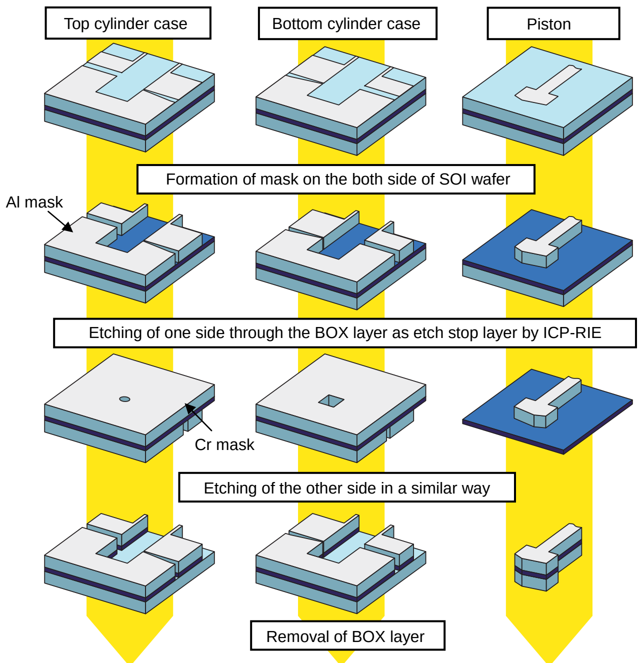


Figure 6. Fabrication process of the cylinder cases and the piston.

formed on a pyrex glass by conventional mechanical machining. Next, the electrodes are fitted and bonded to the slit. After that, another pyrex glass is bonded to the pyrex glass with the electrodes for packaging.

The piston is set in the bottom cylinder case, and the top case is capped on them. At this point, the top case is self-aligned with the bottom case by the piston. After assembling these 3 parts, Al-Al thermo-compression bonding is carried out to bond the top cylinder case and the bottom cylinder case. Finally, the ignition plug (Fig.7) is bonded to the assembled cylinder cases. Figs.8 and 9 show the internal view of the micro combustion rig, where the top cylinder case and the ignition plug are removed (Fig.9).

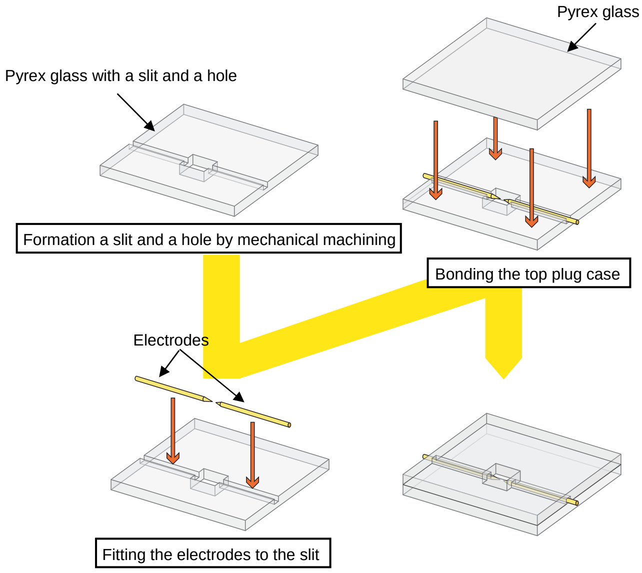


Figure 7. Fabrication process of the ignition plug.

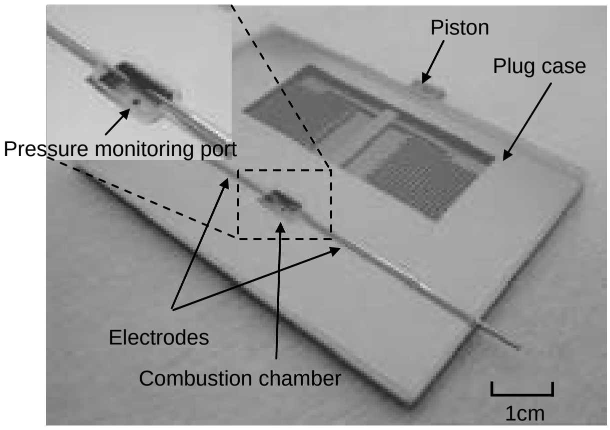


Figure 8. The fabricated micro combustion rig.

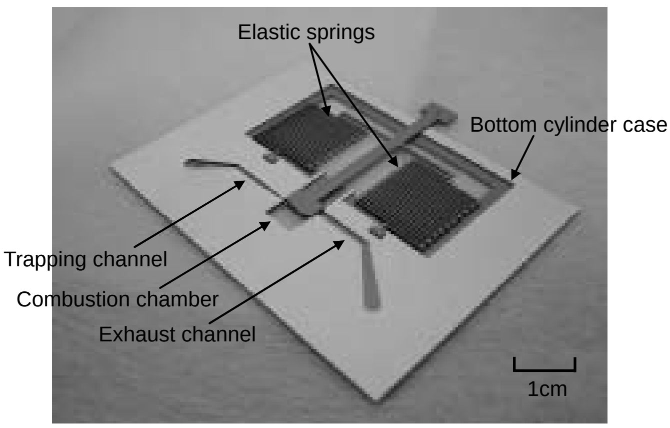


Figure 9. The internal view.

5 CONCLUSION

In this paper, we have proposed a new design of the micro combustion rig based on our previous works, and actually the micro combustion rig was fabricated using the proposed fabrication processes. Sparking of the ignition plug has also observed. Currently experiments are undergoing toward operation of the micro combustion rig by combustion of the mixture gaseous fuel composed of hydrogen and oxygen.

REFERENCES

[1]Toshiyuki Toriyama, Keiji Hashimoto and Susumu Sugiyama : ”DESIGN OF A RESONANT MICRO RECIPROCATING ENGINE FOR POWER GENERATION”, Proc. of TRANSDUCERS, No.12, pp.1303-1306, Boston, USA (2003-6)

[2]Toshiyuki Toriyama, Keiji Hashimoto, Junji Ogawa and Susumu Sugiyama : ”MICRO RECIPROCATING ENGINE BASED ON SOI STRUCTURE”, Proc. of PowerMEMS, No.3, pp.130-133, Makuhari, Japan (2003-12)

[3]Keiji Hashimoto, Junji Ogawa, Toshiyuki Toriyama and Susumu Sugiyama : “Design and Fabrication of a Resonant Micro Reciprocating Engine for Power Generation”, Proc. of MHS, No.14, pp.293-297, Nagoya, Japan (2003-10)

[4]D. H. Lee, D. E. Park, J. B. Yoon, S. Kwon and E. Yoon : ”Fabrication and test of a MEMS combustor and reciprocating device”, J. Micromech. Microeng., 12, pp.26-34 (2002)

[5]P. Seriburi, D. Kercher and M. G. Allen : ”An experimental study of microfabricated spark gaps: wear and erosion characteristics”, J. Micromech. Microeng., 11, pp.165-174 (2001)