Design and Fabrication of Alumina Micro Reciprocating Engine

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Abstract. Microengines are regarded as the potential replacements for batteries. They may also provide an alternative to comb drives for MEMS devices. Because the thermal property of silicon is not satisfactory when it is used in the combustion chambers. Ceramics have been chosen as the construction material in this paper. The paper discusses the fabrication process where alumina has been chosen as the microengine material. Vigorous FEA has been carried out, and it is found that the material satisfies the stress and deformation requirements of the design. The paper then describes alumina fabrication process. Soft reusable polydimethylsiloxane (PDMS) moulds are produced from SU-8 resist masters, and alumina microengine parts have been produced using the PDMS moulds. Images of the ceramic components show that the fabrication satisfies the design requirements.

1. Introduction
In fact, the low energy storage capability is one of the fatal problems the batteries are facing. In the calculations conducted by Jiang et al [1], it is shown that methane can possess energy in a unit weight 220 times more than a nickel metal hydride battery, and hydrogen can do even 563 times better than a nickel metal battery. Therefore, microengines have a good potential to replace batteries to power detached microdevices. For instance, the most widely employed micro actuator is the electrostatic comb drives, which can be found in the digital mirror display systems developed by Texas Instruments[2], and also in Sandia’s intricate safety lock for nuclear missiles[3]. In these moving microsystems, electric energy stored in the batteries is converted into mechanical energy through comb drives with some energy losses. Nevertheless, microengines can be used to avoid the conversion losses by transmitting the motions from the engines to the microsystems directly. It is calculated that a microengine with fuels could be equivalent to nearly 100 batteries after the consideration of the deduction of the microengine efficiency. This prospect encourages research into microengines moving forward rapidly.

In recent years, several research groups have been working on micro combustion engines of various types. The Gas Turbine Laboratory at MIT has made a prototype MEMS turbine engine and test-run it. The engine is made of silicon, fabricated using deep reactive ion etching (RIE), and bonded together [5]. The test result shows, as predicted, that silicon cannot withstand the high temperature of combustion, and high temperature resist methods are being sought now. A combustion research group in the Department of Mechanical Engineering at the University of California Berkeley has been working on a project to develop a micro Wankel rotary engine since 1999[4], and one of the key issues in the project is to identify the construction...
material for the micro Wankel engine. The reason that silicon is chosen as the first construction material for microengines, as in MIT microturbine engine project [5], is because MEMS fabrication processes are developed from semiconductor technology, silicon fabrication technology is more mature than any material related technologies [3-7]. However, the poor high temperature property of silicon has forced researchers to search for other construction materials with a proven fabrication process. High temperature resist materials and their fabrication technology become an important issue to be addressed in the microengine development.

Ceramics have the features of high strength, stiffness and low density. These excellent mechanical properties together with their high temperature resistant property put ceramics in a special position in the material selection list of microengines. Ceramic has been succeeded to apply in advanced heat engines such as high temperature gas turbines [8] and adiabatic diesels [9]. However, most existing micro ceramic fabrication processes are not suitable to the fabrication of complex structures of microengines. For example, it is difficult to use chemical vapour deposition (CVD) process to obtain high aspect ratio and thick structures due to its planar nature [10]. The screen printing process, ink jet printing process [11], and fused deposition process are generally limited in the range of 100 μm in the thickness of the structures. The biggest weakness of ceramics is their tendency to crack from a defect inside of the component.

In this paper, the research work in micro combustion engine is presented. The design of a micro combustion reciprocating engine is introduced, and the material chosen for construction is alumina. Finite element analysis (FEA) was employed to verify the design by predicting the deformation and stress of the alumina ceramic engine parts under high temperature condition. The paper devotes a large part in the ceramic engine parts fabrication. Based on slurry replicating process, the high aspect ratio alumina ceramic part has been achieved using reusable PDMS soft moulds, which were replicated from SU-8 high quality master. The fabrication results have been examined, showing alumina and its fabrication process can meet the design and mechanical property requirements of the proposed microengine.

2. The design of micro reciprocating engine
The microengine is designed based on the mechanism of a two-stroke reciprocating engine, and its construction is shown Figure 1, excluding the synchronization valve. With the consideration of MEMS fabrication features, the engine components are designed in 2D shapes. The piston has a square cross section. Its contact surfaces with the cylinder are much larger than that of a conventional engine, and fine grooves are made on the surfaces for prevention of gas leakage. The cylinder is a large trench of square cross section, to be covered by a silica glass allowing visual access into the chamber. A synchronization valve is to be placed at the bottom of the cylinder, and will be triggered open to release pressurized fuel. The outlet port of the engine is made on the wall of the cylinder as a groove.

![Figure 1. Assembly and exploded view of the single piston microengine.](image)

The cross section of the piston is 1×1 mm. This is designed with the consideration of quenching distance for micro combustion engines to be developed in the next phase. The sidewalls of the cylinder are 1 mm thick. The material selection in this project follows the methods recommended by Ashby[12]. Alumina ceramic has been selected to be the construction material of the engine. Compared with silicon and silica, alumina has advantages in density, Youngs Modulus, and strength.
The majority of components in the micro reciprocating engine, such as the piston, the cylinder, the connecting-rod and the gear, are subject to dynamic loadings and running under high temperature condition. In case that deformation of cylinder walls leads to excessive leakage, or overloading of an engine part causes fracture, finite element analysis has been used for predicting the dynamic stress and deformation of the piston, cylinder and linking rod under the high temperature conditions. Figure 2 shows the maximum deformation occurring in the piston for a working cycle. The amount of deformation on the cylinder is nano scale, which can be ignored. The maximum deformation occurring on the piston is 3.01 μm. A deformation on the piston as such will not affect the performance of the piston.

3. Ceramic Fabrication

SU-8 photoresist is chosen for making master moulds for the microengine. As the engine parts are designed 1000 μm thick, high quality SU-8 component fabrication has been challenging. When the SU-8 layer gets 500 thick or higher, the T-shape tends to appear on the exposed sidewalls. Based on the optimized SU-8 proces, the excellent aspect ratio of 40 has been obtained in 1000 μm thick SU-8 layers by using USP [7]. SEM image shows the width of piston is 1000 μm. The uniformed exposure and vertical sidewall structures have been achieved successfully.

The reusable soft polydimethylsiloxane (PDMS) moulds were replicated from SU-8 master moulds, which were fabricated using UV-lithography process on an ultra-thick SU-8 layer [7]. The process was following with paper

Figure 2. The FEA result to predict the maximum deformation.

Figure 3. Schematics of soft moulding procedures.

Figure 4. SU-8 master Molds.
Two schematics of soft moulding procedures are given in Fig. 3, where Fig. 3a is the embossing process and Fig. 3b is the microtransfer moulding (μTM) process. After drying from the procedures as above, the PDMS moulds are carefully peeled off from the alumina substrate. The PDMS moulds were cleaned by an ultrasonic processor in the distilled water and ethanol in sequence, ready for the next use. The sintering temperature is at 1550°C, and the process takes 2 hours.

4. Fabrication Results
Resulting piston at different steps is shown in Fig. 4 and Fig. 5. Figure 4 is the master mould of piston with vertical bars of which the aspect ratio is 10.

A sintered alumina piston is shown in Fig. 4. Features about 1000μm high and 100μm width vertical bar on piston side has been successfully moulded and demoulded by using soft PDMS moulds. In a reliable slurry process for producing micro features, the particle in slurry must be much smaller than the minimum feature size. Conventional ceramic powders have average particle sizes of 15μm, and cannot be used in this application. The particle size of described micromoulding process is smaller than 0.7μm. The feature of a few micrometers has been resolved successfully with this size level particle [14]. The high magnification SEM image shows that after sintered at 1550°C for 2 hours, the surface grains are less than one micron, clearly demonstrating the ability to replicate features of a few microns in dimensions.

![Figure 5. Alumina ceramic parts.](image1)

![Figure 6. Crack default caused by residual stress during the shrinkage.](image2)

Due to that the high concentration alumina suspension of 84.0wt% has been employed, a small shrinking ratio has been achieved. This is an important issue in fabrication when the tolerance control is required. The SEM image shown in Fig 4 demonstrates the width of sintered alumina piston is 812μm. Compared with SU-8 master moulds, shown in fig. 4, the final shrinking ratio is less than 17%, which is much better than the result has been report so far [15].

However, the excessive residual stress can be found in green status occasionally, which would lead to the crack in the sintered status ceramic parts. The SEM image is shown in Fig 6. It would decrease the fracture strength of ceramic parts seriously. To avoid the excessive residual stress in green status, two kinds of methods should be employed. The layout of mask design is an important factor to reduce the residual stress[16]. The low dry rate is also another effective way. The further study of residual stress in micro ceramics will continue and publications will appear in the near future.

5. Conclusion
This paper presents the research work on the development of a micro reciprocating combustion engine. The significant modifications of microengine design have been made to accommodate the 2D feature of MEMS fabrication. From the computer assembly verification and FEA results, it has been shown that the design is feasible and alumina is suitable as the engine construction material. Ceramic engine parts have been successfully produced based on slurry replicating process using soft PDMS reusable moulds. Features with aspect ratio of 10 have been achieved, and the strict requirement of the vertical sides of the piston and cylinder has been met. The ceramic fabrication process featured with SU-8 master moulds and PDMS soft moulds provides a low cost microfabrication approach. Compared with the existing MEMS materials and processes, soft moulding process offers a great chance for the manufacturability of MEMS for high temperature applications.
Acknowledgements
This work was partly supported by National Science Foundation of Heilongjiang Province (Grant Number: E2004-06).

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