FABRICATION OF CERAMIC COMPONENTS FOR MICRO GAS TURBINE ENGINES

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ABSTRACT

Assembly Mold SDM (Shape Deposition Manufacturing) has been used in combination with Gel Casting to fabricate ceramic micro gas turbine components. Full 3-dimensional ceramic turbines and compressors with a feature size down to 200 µm were built. The turbine has been tested and been spun up to 456,000 rpm. During the research, it was found that the development of a ceramic air bearing is desirable. Thus, a process utilizing MEMS techniques has been developed to fabricate patterns with 125 µm feature size. In this paper, the techniques used to fabricate functional rotor groups, improve accuracy, and pattern micro features will be discussed.

INTRODUCTION

Assembly Mold SDM (Shape Deposition Manufacturing) is a derivation of Mold SDM [1, 2], an additive-subtractive layered manufacturing process developed at Stanford University. A mold design is decomposed into several geometrical features, and then SDM is applied to fabricate each mold feature. After all the geometrical features are made, a complete mold is built by assembling the mold features. Figure 1 illustrates the fabrication of an example mold. In this project, the mold material is KC3230A wax from Kindt-Collins Company in Ohio, the support material is Soldermask^{TM}, a UV curable, water-soluble polymer resin from Advanced Ceramics Research (Tucson, AZ).

There are several advantages of Assembly Mold SDM compared to competing processes. First, complicated mold geometries are split into several less complex geometrical features. This provides a solution to build molds which are difficult to make by Mold SDM; second, for each split geometrical feature, one can choose the best fabrication strategy to apply, depending on the complexity of the geometry; third, each piece of the mold assembly can be fabricated in a parallel process, therefore, the overall fabrication time is reduced; the last point, but not the least, the change of design can be reflected rapidly in this process.

The major drawback of the Assembly Mold SDM is the possibility to have geometrical inaccuracy during the mold assembly process. The detail of the inaccuracy introduced in this process will be discussed in the FABRICATION PROCESSES section.

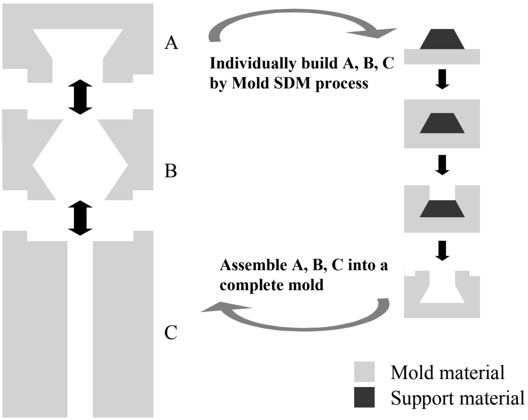


Figure 1. Principal process steps for Assembly Mold SDM

Once a fugitive assembly mold has been made, the gel casting process is applied to build a monolithic ceramic part. Gel casting is a ceramic forming technique first developed by Oak Ridge National Laboratory in the 1990s [3]. The basic concept of this process is to make a slurry of desired ceramic powders with gel precursors (monomers and cross-linkers). The polymerization process is initiated right before casting and completes afterward to form a solid gel network that holds the powders. The green part is then going through processes such as demolding (remove the mold), drying (remove water or solvent), debinding (remove polymeric binders), and sintering, in order to acquire the final part. Comparing with other ceramic forming techniques, gel casting has advantages such as short molding time, high green state strength, good mold material compatibility, minimal molding defects and minimal warpage in green and brown state [3].

MICRO GAS TURBINE ENGINE DESIGN AND REQUIREMENTS

By combining the assembly Mold SDM and gel casting processes, the Rapid Prototyping Laboratory (RPL) at Stanford University is developing a miniature ceramic gas turbine with its industrial partners. M-DOT Aerospace Inc. (Arizona, USA) designed the engine and RPL's responsibilities include the fabrication of ceramic components. The goal of this project is to develop a higher power density energy source by making palm-size gas turbine engines with ceramic components. The rotor group (a monolithic body of turbine, compressor, and shaft) is designed to spin at 800,000 rpm to generate 100 watts. Among several engineering ceramic materials, silicon nitride (Si_3N_4) has been chosen because of its good combination of thermal properties, corrosion resistance, and mechanical strength.

Figure 2 shows the design of this micro gas turbine and the major component to be made by silicon nitride. Due to the high rotating speeds, the straightness of the shaft and the shape accuracy is crucial for a functioning device. The target turbine inlet temperature (TIT) is above 1000°C, with an operation time of 100 hours.

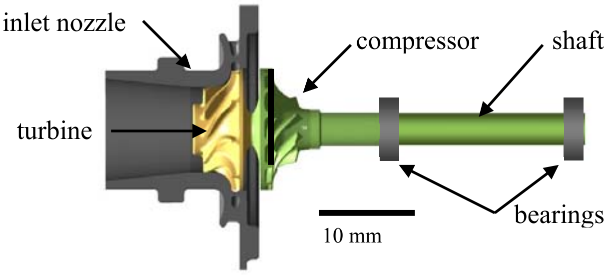


Figure 2. Design of rotor group and inlet nozzle. Both components are made of silicon nitride

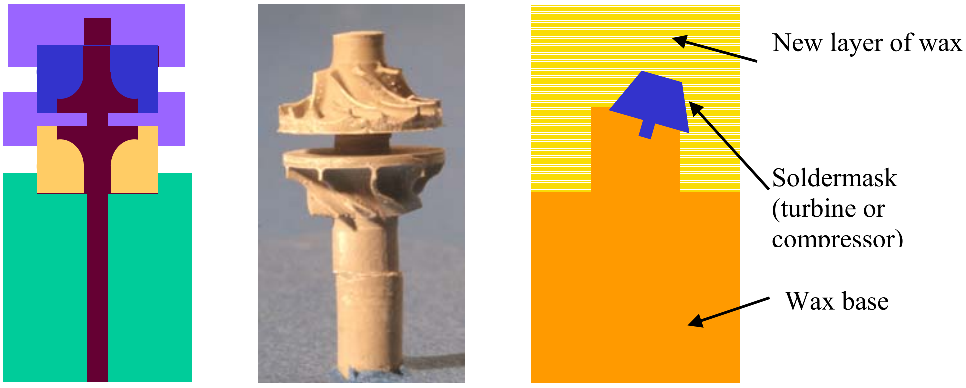
FABRICATION PROCESSES

Overview of Rotor Group Fabrication

The rotor group is a unitary rotating component that consists of turbine, compressor, and shaft. There is an interconnect structure between turbine and compressor, a short shaft connects to turbine and a long shaft on the compressor side. Due to the complexity of the geometry, this casting mold is decomposed into five pieces: cap, turbine, interconnect, compressor, and shaft. Each mold piece was made individually by the best strategy chosen form its geometry. Figure 3 (A) shows the schematic of the rotor group mold consists of 5 pieces. The turbine and compressor geometry are made using the SDM process, while the rest of the mold is made by CNC machining. Assembly Mold SDM allows a quick reflection of design change. For example, we can change the diameter of shaft or the shape of blades by replacing the specific mold pieces, without modifying the other mold pieces.

Sources of Geometrical Inaccuracy

After the rotor group is sintered, it is found that the geometry features are shifted from the concentric center. An obvious example is shown in Figure 3 (B), the shaft of the rotor has shifted and has eccentricity of 0.5 mm. This indicates the two possible sources of geometrical inaccuracy: the error from the shaping of each mold piece; the error from the mold assembly process.



(A) (B) (C)

Figure 3. (A) Rotor group mold assembly. (B) As-sintered rotor shows the eccentricity. (C) The schematic shows the drifting of Soldermask during wax casting.

A careful inspection of the fabrication processes indicates that the Soldermask compact geometry drifted during embedding with hot wax. This is illustrated in Figure 3 (C). During the fabrication of turbine and compressor molds, a Soldermask compact is deposited on a wax base. The Soldermask is machined on the wax base and a new layer of the wax is cast on it. Thus, the machined geometry of Soldermask is transferred onto the wax and after the Soldermask is sacrificed, the wax holds the negative geometry. (I don't think this sentence is necessary.) The new layer of molten wax on the Soldermask compact softens the wax base underneath the Soldermask compact and the following shrinkage during the wax solidification drags the Soldermask compact away from the original position and also tilts it out of plane.

Improvements of Geometrical Accuracy

To remove the errors from fabrication and mold assembly, the rotor group fabrication process has been modified to provide a better geometry support. Figure 4 shows the two major changes in the process: metal base for Soldermask, and metal guide for assembly.

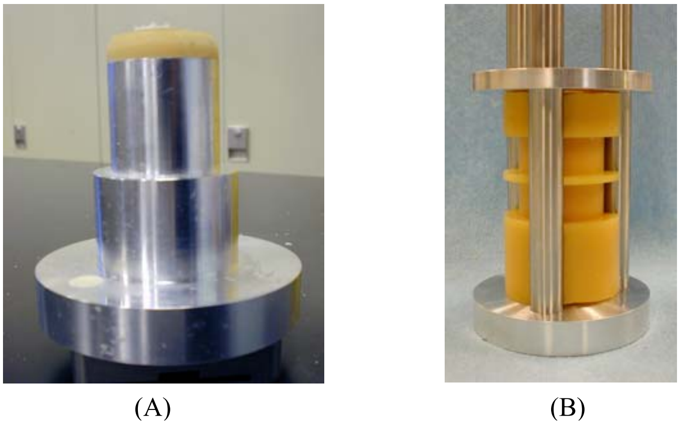

(A) (B)

Figure 4. Improvements of fabrication. (A) Metal base for Soldermask. (B) Metal guide for mold assembly.

The metal base provides a rigid support of the Soldermask material during both the CNC machining and the following wax casting steps. The replacement of the base from wax to aluminum alloy minimizes the possible tilting and drifting of turbine and compressor geometry. Once mold assembly pieces are separately made, each piece is turned on lathe to remove the eccentricity before being assembled. The assembly strategy has been modified to use external metal guide instead of the geometrical features on adjacent mold pieces. The metal guide is expected to provide a solid fixture for assembly alignment, and the external guiding for alignment is superior to the original method using interconnect features. Both metal base and metal guide are designed to work best with the dimensions of rotor group, however, the same concepts apply to the fabrication of other components. Furthermore, the metal guide assembly method provides a universal fit for any future design of the rotor group. For example, given the same alignment feature of the mold assembly, one can quickly change the shaft diameter or the turbine geometry by only changing the specific mold assembly piece. For conventional mold fabrication and any other rapid prototyping techniques that produce one piece molds, a whole new mold has to be fabricated even there is a tiny change in design. Table I and II present the comparisons of measured geometrical inaccuracy of molds with different fabricating strategies.

Table I. Effect of metal base for the eccentricity of turbine and compressor mold geometry.

Component	Base Material	Eccentricity (mm)		
		Minimum	Average	Maximum
Turbine	Wax	0.10	0.27	0.41
Turbine	Metal	0.06	0.08	0.09
Compressor	Wax	0.11	0.19	0.27
Compressor	Metal	0.03	0.13	0.19

Table II. Effect of metal base for the tilting of turbine and compressor mold geometry.

Base Material	Tilt angle (°)
Wax	0.42 ~ 0.54
Metal	0.12 ~ 0.17

Overview of Inlet Nozzle Fabrication

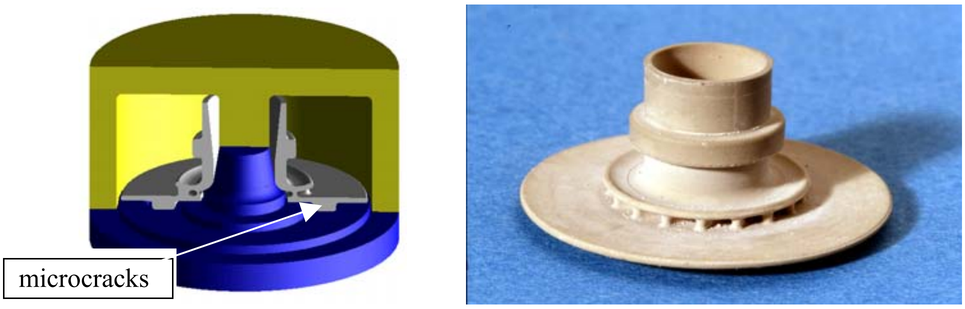
The silicon nitride inlet nozzle of the micro gas turbine engine is also fabricated using the Assembly Mold SDM process. The mold pieces are prepared using the SDM process with Soldermask support material and wax part material.

The mold for the inlet nozzle is decomposed into 5 pieces. The decomposition was done so that the position of the layer boundaries has minimum effects on the part quality and the mold pieces align by themselves.

The lower disk of the inlet nozzle green part is 0.76 mm thick and its diameter is 34 mm. To avoid the warpage of the disk sintering fixtures to support the disk are prepared and shown in Figure 5 (A).

The thin inlet nozzle vanes support the upper part of the inlet nozzle and the upper part of the inlet nozzle can sag due to its own weight during sintering. The cone with curved surface at the center of the lower sintering fixture is designed so that the weight of the upper part is supported by the sintering fixture rather than the inlet nozzle vanes.

The sintering fixtures are used in the brown state so that they can shrink with the same rate during sintering, causing no relative motion or friction between the part and sintering fixture. If the shrinkage rate of the fixture differs from that of the part, however, the mismatch in shrinking will produce constraint stress thus cause cracks during sintering. Inspections with fluorescent paint indicate the existence of micro-cracks on the bottom of inlet nozzle where the fixture might have smaller shrinkage rate and therefore constrained the shrinking of nozzle part.



(A) (B)

Figure 5. Ceramic inlet nozzle. (A) Cross-section of sintering fixture and inlet nozzle. (B) As-sintered inlet nozzle.

FUNCTIONALITY TESTS

The functionality of the rotor group fabricated with Assembly Mold SDM process has been demonstrated by a series of tests of the turbine and compressor.

The simplified rotor spun up to 456,000 rpm with room temperature pressurized nitrogen gas [4]. The turbine is designed to spin at 800,000 rpm under 1,000°C air. Comparing the speed of the sound and energy of room temperature nitrogen and 1,000°C air, the performance of the turbine is satisfactory.

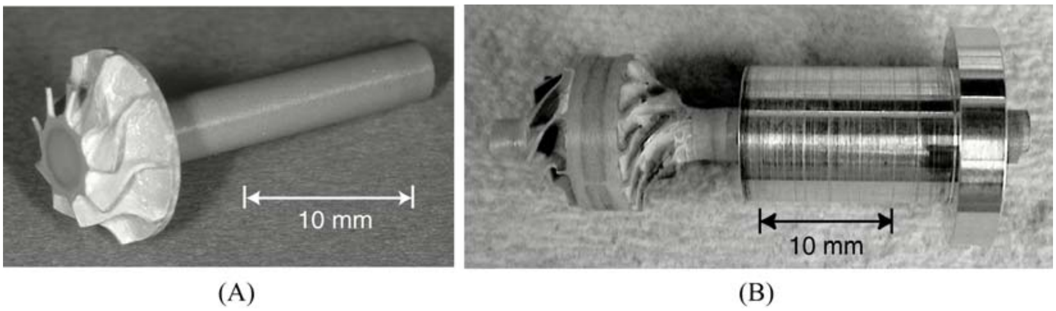


Figure 6. (A) Simplified rotor. (B) Rotor group spin tested up to 420,000 rpm.

The functionality of compressor has been demonstrated by the test of the whole rotor group. The rotor group is mounted on a test rig and pressurized nitrogen (N_2) was used as the driving gas. The compression ratio and flow rate of the compressed gas have been measured to characterize the compressor. The characterization result of the compressor up to 420,000 rpm shows that the performance of the compressor reasonably matches with the designed performance. The estimated efficiency of compressor using the pressure and mass flow data falls between 54 – 57%. The CFD estimation of compressor efficiency is 63%.

The rotor group was mounted on miniature ball bearings. The vibration measurement of the rotor group during the compressor characterization and rotor-bearing dynamics analysis suggested the bearings, as well as the use of the room temperature nitrogen as driving gas, are responsible for the limiting the current maximum speed.

The measure for the performance of ball bearing is surface speed, denoted as DN valued. It is defined as the pitch diameter[*]in mm and rotation speed in rpm. It is commonly accepted in ball bearing industry that 2E+6 mm·rpm is practical limit of miniature ball bearings. The performance of the ball bearings used in the rotor group test rig corresponds to DN = 2.0E+6 mm·rpm[†]. The spinning of the rotor group at higher speed requires bearings with higher number assuming the diameter of the shaft cannot be reduced. Since air bearings operate at

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[*] Pitch diameter of a ball bearing is approximately defined as the average of inner and outer diameter.

[†] Pitch diameter = 4.76 mm, rotation speed = 420,000 rpm.

higher surface speeds compared to ball bearings, the development of technologies for the fabrication of micro air bearings is attractive for the implementation of micro gas turbine engines.

MICRO CERAMIC BEARING PATTERN

An individual research activity of RPL demonstrates the capacity to fabricate the micro pattern for air bearing by combining gel casting and a MEMS related process called “Soft Lithography” [5]. The overall processes to fabricate the tilting pad bearing pattern is shown in Figure 7. The master pattern of tilting-pad bearing is generated by DRIE (Deep Reactive Ion Etching) silicon process. PDMS (Polydimethylsiloxane) is cast onto master to replicate the pattern; a gel casting process transfers the features from PSDM to ceramic part. PDMS is flexible and helps to minimize the damage during removal of molds.

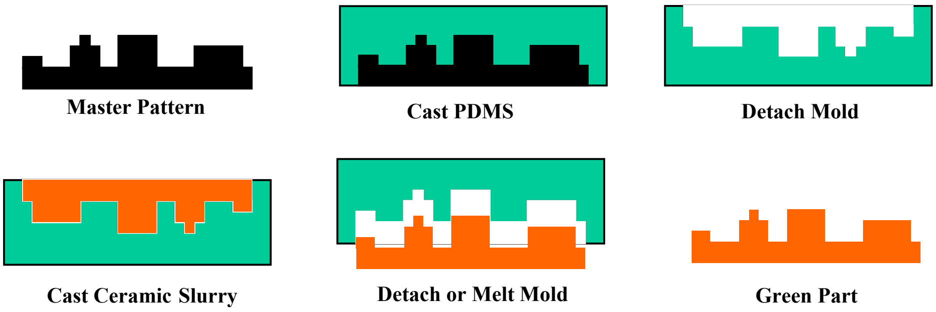

Figure 7. The soft lithography process used to fabricate bearing patterns.

Figure 8 presents the details of tilting-pad bearing patterns under SEM (Scanning Electron Microscopy) inspection. The straight sidewall shows a good definition of micro pattern, and the smallest feature is less than 125μm (the tilting pad) and has an aspect ratio of higher than 8. This work provides a potential to make ceramic air bearings for the micro gas turbine system.

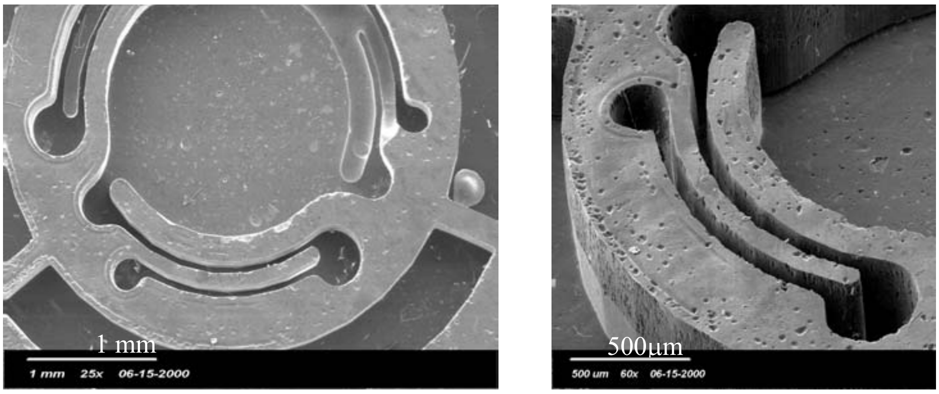

Figure 8. The SEM pictures show the details of sintered ceramic tilting-pad bearing pattern. Left: sintered silicon nitride (Si_3N_4). Right: sintered alumina (Al_2O_3).

CONCLUSIONS

In this paper, we have discussed the fabrication of ceramic gas turbine components by the combination of Assembly Mold SDM and gel casting techniques. The processes have been examined and the sources of geometrical inaccuracy are identified. New mold manufacturing strategy is applied to reduce the error in geometry features.

The rotor group has been tested for its functionality. The turbine rotor spun up to 456,000 rpm and the compressor (tested with the whole rotor) spun up to 420,000 rpm with pressured N_2 at room temperature. The characterizations of the rotor demonstrated the performance that follows the design intention.

The spin test suggests the possible improvement in the rotor performance with a better bearing system. An effort of fabricating micro tilting-pad bearing pattern is presented and demonstrates the capability to make ceramic components on a micro scale.

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