APPLICATION OF THE MOLD SDM PROCESS TO THE FABRICATION OF CERAMIC PARTS FOR A MICRO GAS TURBINE ENGINE

Sangkyun Kang*, Jürgen Stampfl, Alexander G. Cooper, Fritz B. Prinz

Rapid Prototyping Laboratory, Stanford University,
Stanford, CA 94305-3030, USA

Abstract

A micro gas turbine engine with silicon nitride parts is being developed. In this project, the Mold Shape Deposition Manufacturing (Mold SDM) process is used to fabricate high quality ceramic parts with complex shapes such as the rotor group.

The merits of micro gas turbine engines in general are described before focusing on processing and fabrication issues. The obtained silicon nitride parts are characterized concerning their mechanical and microstructural properties. The surface roughness, shrinkage during sintering, final density and achievable feature sizes have been determined. Using Mold SDM a functional rotor group has been successfully fabricated. During spin tests at room temperature with nitrogen as driving gas 456,000 rpm rotational speed has been achieved.

INTRODUCTION

Micro Gas Turbine Engine

A micro gas turbine engine with silicon nitride parts is being developed by the the Rapid Prototyping Laboratory (RPL) of Stanford University and its industrial partners. The engine is designed by M-DOT Aerospace (Arizona, USA) and the RPL is responsible for the manufacturing and materials processing of the silicon nitride parts. Figure 1 shows the original design of the micro gas turbine engine developed by M-DOT. This one is similar to current engine but it does not use ceramic parts. This type of engine can be used as a portable energy source or in small flying vehicles.

Figure 1: M-DOT micro gas turbine engine

Figure 2: CAD model of the silicon nitride rotor group of the micro gas turbine engine.

Silicon nitride rotor group

One of the key parts for the success of the micro gas turbine engine project is the rotor group. The CAD model of the rotor group is depicted in Figure 2. It is a monolithic part composed of the rotor shaft, compressor and turbine (from left to right). The diameter of the turbine is 12 mm and the minimum blade thickness at the tip is 220 μm. The part is designed to operate at 800,000 rpm.

Silicon nitride was selected as the material for the rotor group due to its superior high temperature properties and lower density compared to superalloys.

The turbine blades of the micro gas turbine engine cannot have the sophisticated cooling channel systems which can be found in larger engines due to their small size. So, a ceramic material is the better choice for the turbine application because of the better temperature resistance.

The turbine of the small engine must rotate at a higher speed than that of a bigger engine to achieve the higher power density. This results in a substantial centrifugal force. In this case, a higher strength to density (σ_f/ρ) ratio is important. Silicon nitride has higher strength than supperalloys at elevated temperature and it has 1/3 of the density. So, the use of silicon nitride will make the whole system lighter and, thus, increase the thrust/weight ratio of the engine.

Advantage of miniaturization

One of the possible merits of the small gas turbine engine is the increased power density which is defined as power/volume. Theoretically, the power density of a gas turbine engine can be increased as the size of the engine decreases. In that case, multiple small engines can be used instead of one big engine and the small engine system will occupy less volume due to the increased power density.

Since the same output power can be achieved in a smaller volume using multiple small engines, a redundant system can be implemented by adding more engines into the saved volume. A redundant system can have higher reliability. Figure 3 illustrates a redundant system. It was assumed that 16 small engines in the right system will generate the same power as the one big engine on the left. In this case, four engines are redundant.

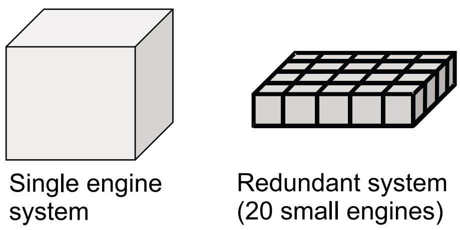


Figure 3: Single engine system and redundant system. In this system, 16 small engines is necessary to produce the same amount of power as the large engine.

Simple calculation of the probability of failure based on binomial distribution shows the higher reliability of the redundant system. (The formulation is in Appendix) Figure 4 compares the failure probability of one big engine and the redundant system illustrated in Figure 3. According to the computational result, assuming the failure probability of each engine is 2×10^{-2}, the failure probability is 2×10^{-2} for one engine but 3.8×10^{-5} for the redundant system.

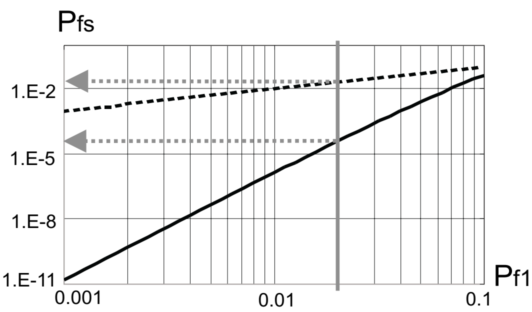


Figure 4: The failure probability comparison of one big engine engine (dotted black line) and 20 small engines (solid line) system. P_{f1}: failure probability of each engine, P_{fs}: failure probability of 20 engine system

The probability of failure of a large ceramic specimen is greater than a small ceramic specimen under the same stress and the Weibull treatment of failure incorporates this relation [1]. So, in terms of reliability, the application of ceramic parts in a small gas turbine engine is more beneficial than a large engine.

The volumetric relation of the reliability of the ceramic parts can be combined with the reliability of the redundant system. The failure probability of each small engine that has ceramic parts in it will decrease due to the reduced failure probability of the ceramic parts. This will reduce the P_{f1} value of each small engine in Figure 4. Therefore, further improvement of the reliability can be achieved form the miniaturization.

Manufacturing process for the silicon nitride rotor group

The silicon nitride rotor group (Figure 2) has a complex shape. Design iterations are anticipated during the progress of the project. So, the ability to fabricate high quality ceramic parts quickly is required.

The surface quality of the rotor is important because the strength of ceramic parts is highly dependent on the surface condition. It must also be noted that the rotor geometry does not allow postprocessing, such as grinding, due to its shape complexity.

A manufacturing process that can produce a ceramic part with complex shape and good surface finish is required for this project.

In terms of shape complexity, commercial rapid prototyping techniques are good candidate processes for the manufacturing of the rotor group. However, the surface quality of rapid prototyped parts is limited due to the stair step effect. The rough surfaces become good crack initiation site and this reduces the strength of the parts significantly. The surface quality can be improved by reducing the layer thickness but the improvement is linear, which means the stair step is halved as the thickness of the layer is halved [2].

The traditional ceramic fabrication processes, such as machining of green ceramic blanks, have limitations in achievable shape complexity due to the tool access constraint. However, machining can produce parts with good surface quality and the surface quality improves rapidly. For example, in ball endmill machining, if the space between two machining paths become 1/2, the scallop height reduces to 1/4 due to the quadratic convergence property of machining [2].

MOLD SHAPE DEPOSITION MANUFACTURING (MOLD SDM)

Mold Shape Deposition Manufacturing (Mold SDM) is a manufacturing process that can be used to build ceramic, metal and polymer parts. Mold SDM is a two step process. Fugitive wax molds are first built using an additive-subtractive layered manufacturing process. Then a variety of castable materials, including ceramic and metal gelcasting slurries as well as castable thermoset polymers, can be cast into these molds to produce parts [3].

Figure 5 illustrates an example sequence for the fabrication of a simple part. The mold is built up layer by layer in steps 1 through 4. Each step represents one material deposition and machining cycle. The mold material forms the mold itself while the temporary support material defines the mold cavity and provides support for undercut features in the mold. The support material is removed in step 5 and the part material is then cast into the mold cavity in step 6. After removal of the mold, in step 7, finishing operations, such as casting feature removal, are performed leaving the finished part in step 8. Sintering can be performed after either step 7 or 8 [4].

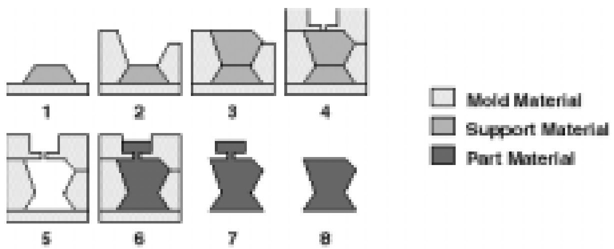


Figure 5: Mold SDM procedures

Mold SDM has several advantages over other manufacturing processes. As a layered manufacturing process Mold SDM is able to build geometrically complex shapes. As with other layered manufacturing processes, no part specific tooling is required. This reduces lead times and costs. Short production runs or prototype parts can be built rapidly and economically. There is minimal cost for design changes since no new or modified tooling is required. Unlike most layered manufacturing processes, which are purely additive, Mold SDM is additive-subtractive. The subtraction step, performed using CNC milling, enables the creation of smooth accurate geometries and also accomplishes this without the need to use extremely thin layers which would increase build time. Mold SDM is also capable of building parts from a wide range of castable materials. To date parts have been made from structural materials including silicon nitride, alumina, stainless steel, epoxy, polyurethane and silicone.

For the manufacture of complex ceramic parts, Mold SDM has two key advantages over other layered manufacturing processes. First, all surfaces are either machined or replicated from machined surfaces. This results in smooth accurate surfaces without any stairstep effect. Second, the part material is cast monolithically. There are therefore no layer boundaries in the finished part. Layer boundaries are potential sources of defects due to incomplete bonding between layers, or foreign particles or voids trapped at the layer boundaries. Both of these advantages are particularly important for flaw sensitive materials where surface roughness and internal defects can significantly reduce the mechanical strength.

Mold SDM currently uses a variety of waxes as the mold material, the preferred material being KC3254A wax (Kindt-Collins Company, Cleveland, OH). The wax is deposited by casting, usually at a temperature between 80 and 120C. It is removed from the final part by a combination of melting and solvent removal using BioAct 280 Precision Cleaner (Petroferm Inc., Fernandina Beach, FL). The support material is a UV curable polymer (Advanced Ceramics Research, Tucson, AZ) that is deposited as a liquid, cured under UV light, and then later removed by dissolution in water. Ceramic parts are made by gelcasting using silicon nitride or alumina gelcasting formulations developed by Advanced Ceramics Research.

PROPERTIES OF MOLD SDM PARTS

In Table 1 the mechanical properties for various gelcast 4-point-bend specimens are summarized [5]. To obain these results, wax molds were machined to produce different scallop heights on the machined surfaces. In some instances the scallops where parallel to the length of the beam, in some instances perpendicular. Perpendicular scallops are expected to degrade the mechanical properties since they serve as notches for crack initiation. This expectation is reflected in the results shown in Table 1: The highest strength was achieved for polished beams. The best "as sintered" beams where the ones with parallel scallops. The larger the scallop height for perpendicular scallops, the more the strength is decreased. By generating machining paths according to the requirements for the surface quality of the mold, Mold SDM can achieve surface qualities superior to other Solid Freeform Fabrication processes. Especially for ceramic parts, this high surface quality significantly improves the part performance.

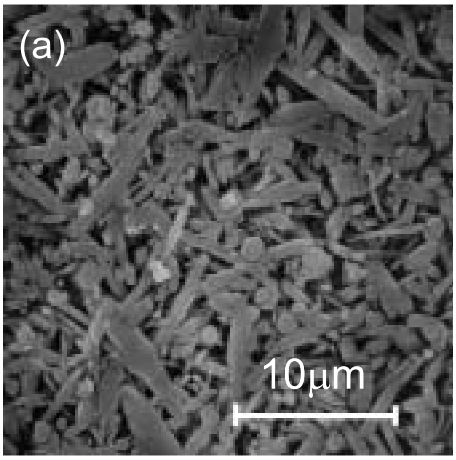
Since many features on Mold SDM parts are too delicate to be processed by grinding or polishing, it is necessary to achieve a smooth surface finish directly during manufacturing. One way to improve surface smoothness is by adjusting the furnace atmosphere so that the $\alpha - \beta$-phase transformation takes places only in the bulk material, but not on the part surface. In Figure 6 these two types of microstructure are shown: The bulk microstructure consists of the typical β-needles which give the material the necessary strength and toughness. On the part surface the grain growth is inhibited, and therefore a smoother surface is obtained.

By using a profilometer, the surface roughness on the bottom and top side of a sintered but not polished test part were measured. The bottom surfaces, where the geometry was replicated from machined surfaces, had root mean square (RMS) roughnesses

Table 1 Influence of mold surface quality on mechanical properties. ACR: Silicon nitride getcast formulation provided by Advanced Ceramic Research Inc. (Arizona, USA), SRI: Silicon nitride gelcasting formation provided by SRI International. (California, USA)

Sample	Slurry	Average Strength MPa	Max. Strength MPa
polished	ACR	930	1012
unpolished parallel scallops	ACR	414	600
unpolished parallel scallops	SRI	428	550
unpolished perpend. scallops 0.001mm	ACR	406	500
unpolished perpend. scallops 0.005mm	ACR	416	495
unpolished perpend. scallops 0.01mm	ACR	288	360
unpolished perpend. scallops 0.1mm	ACR	231	257

of 0.5-0.7 μm. The upper surfaces, where the casting features were cut off by manual machining of the green part, had RMS roughnesses of 1.3-1.8 μm. These values compare favorably with values of 4 μm reported for ceramic parts produced by stereolithography [6].



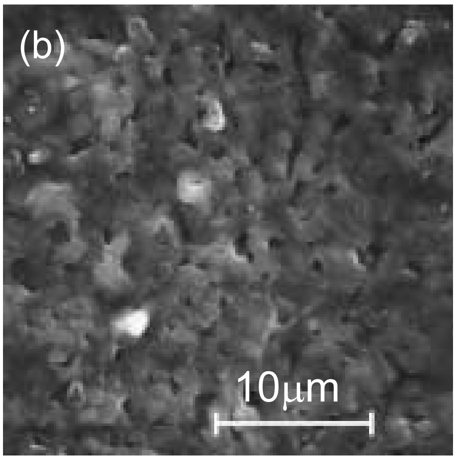


Figure 6: Microstructure of sintered silicon nitride in the bulk material (a) and on the surface (b).

The linear shrinkage of Mold SDM parts depends on the solids loading of the gelcasting slurry and the final density of the sintered parts. The shrinkage was calculated by comparing the major dimensions of the sintered parts with those of the CAD model of the mold geometry. An average linear shrinkage of $18 \pm 0.5\%$ was measured [2]. Since the radius of the rotor group is 6 mm, $\pm 0.5\%$ results in $\pm 30\,\mu$m difference in radius.

The sintered Mold SDM silicon nitride parts achieved 97% of full density.

RESULTS: SILICON NITRIDE ROTOR GROUP

The sintered turbine rotor group is shown in Figure 7. Small features such as the 220 μm thick blades were successfully fabricated. This one is slightly different from the CAD model illustrated in Figure 2. This turbine rotor group has two identical turbines back to back instead of one compressor and one turbine. However, this part demonstrates the capability of the Mold SDM process to build the actual rotor group. The molds for the rotor group were prepared using 5-axis machining. Wax was used as the mold material and soldermask as the support material.

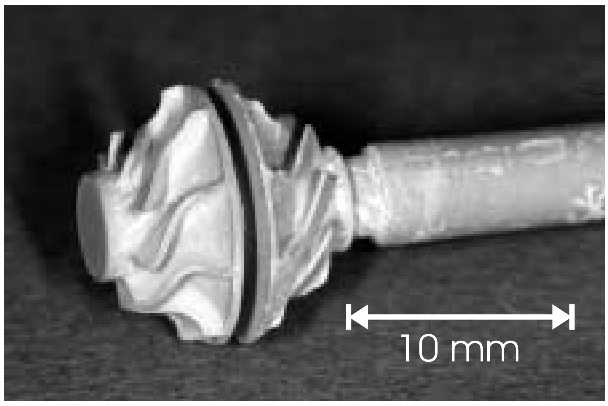


Figure 7: Sintered silicon nitride rotor group.

Since the rotor group will spin at high speed, the straightness of the sintered part is crucial for the performance. A set of special sintering fixtures (Figure 8) were designed to keep the part vertical during sintering. It helped prevent distortion due to sagging. The sintering fixtures were made of green material so that the part and fixture would shrink at the same rate.

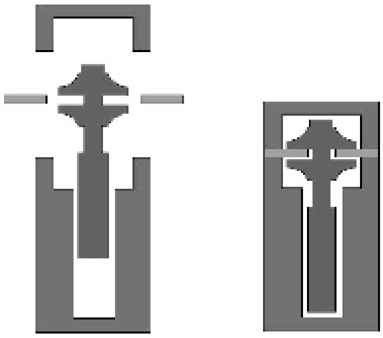


Figure 8: Sintering configuration for the silicon nitride rotor group to avoid distortion during sintering.

Table 2 shows the mold build time for the turbine rotor group. The deposition time per mold can be significantly reduced since the deposition can be done on multiple molds at the same time. It usually takes 4.5 days for the gelcasting, curing, drying, debinding and sintering.

Table 2 Turbine mold build time of the turbine rotor group

Process	Time (hr:min)
Machining	8:51
Soldermask deposition	2:40
Wax deposition	6:00
Total mold build time	17:31
Soldermask removal	1 day
Postprocess	4.5 days

Rotor group spin test

The sintered turbine shaft geometry (Figure 9) has been spin tested in a test rig. It has the same turbine as the rotor group but does not have the compressor because it is not necessary for the spin test. The only post-sintering process for this part was the grinding of the shaft to make it fit into the bearings. Pressurized nitrogen (N_2) was used as the driving gas. The inlet nozzle was made of polyurethane using SDM. A black line was marked using black ink on the side of the shaft to measure the speed optically. The reflected light was received by an optical fiber and the fluctuation of the amplitude of the received light was processed using a LabView spectrum analyzer to calculate the rotation speed.

The achieved speed was 456,000 rpm (Figure 10). The design speed of the rotor group is 800,000 rpm. However, the turbine is supposed to be driven using hot gas which has higher energy and speed of sound. This result shows that the Mold SDM process can successfully build functional ceramic parts.

CURRENT PROCESS ISSUES

Though it was demonstrated that the Mold SDM process can produce ceramic parts with complex geometry and good surface quality, there remain some issues.

The first issue is the deposition of wax. The imperfect deposition of wax on the machined soldermask surfaces may generate micro bubbles on blade surfaces (Figure 9). If wax is deposited at too high temperature, soldermask will soften and sag. It causes the distorted final geometry such as sagged blades. Optimal wax deposition parameters must be found to minimize the micro bubbles and the distortion.

The second issue is to preserve the straightness during the sintering. The relative angles among the shaft, turbine and compressor are crucial for parts operating at such high speeds. Currently, visible sagging is observed in the sintered parts even with the special sintering fixture set up and the repeatability of sintering process is poor. For this issue, better alignment scheme for the sintering should be investigated.

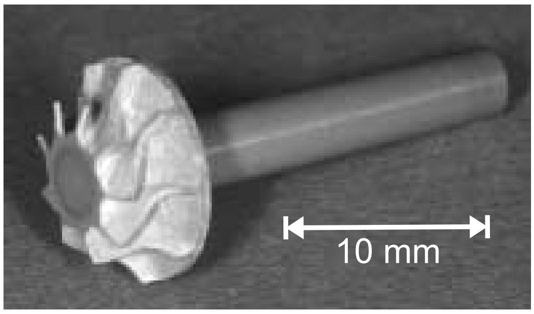


Figure 9: The sintered turbine shaft used for the spin test.

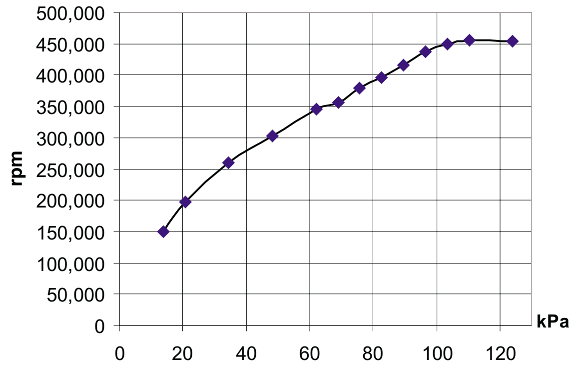


Figure 10: Spin test result of the turbine shaft geometry.

CONCLUSIONS

Mold SDM can achieve complex geometries and smooth surfaces at the same time by combining the merit of Rapid Prototyping techniques and conventional machining. Mold SDM was used as the manufacturing process for the silicon nitride parts of the micro gas turbine since it satisfies the requirements of the parts.

Unpolished, sintered Mold SDM silicon nitride has shown 400 MPa mean strength, 0.5 μm RMS surface roughness, $18\pm0.5\%$ linear shrinkage and 97% of full density.

Mold SDM has demonstrated its capability to build silicon nitride parts for a micro gas turbine engine. A turbine shaft geometry has been fabricated using Mold SDM and it was successfully spin tested up to 456,000 rpm.

ACKNOWLEDGEMENT

The micro gas turbine project has been funded by the Defense Advanced Research Projects Agency and the Office of Naval Research under contract number N00014-98-1-0734 titled “Solid FreeFrom Fabrication of Ceramic Components for Microturbine Engines”

The authors would like to acknowledge Tom Hasler and Tibor Fabian of the RPL for their effort on the spin test setup and measurements. The authors also would like to thank Hansjörg Schilp of the Technical University of Munich for this effort in the fabrication of the molds for the rotor group.

APPENDIX

Binomial formulation of the failure probability of redundant system

The definition of variables.

- P_{fs}: The failure probability of redundant system
- P_{f1}: The failure probability of each engine in the redundant system.
- n: The number of engines in the redundant system.
- r: The number of engines required to run the system successfully.

The failure of the system occurs when more than (n-r) engines fail. Assuming that the failure of each engine happens independently, the failure probability can be calculated as the following.

$$P_{fs} = \sum_{i=n-r+1}^{n} \left[\begin{array}{c} n \\ i \end{array} \right] P_{f1}^{i} (1 - P_{f1})^{n-i}$$

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