μ-MOLD SHAPE DEPOSITION MANUFACTURING OF CERAMIC PARTS

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ABSTRACT

Rapid Prototyping is a versatile method to build complex-shaped ceramic or metallic parts on a mesoscopic scale. In this work the fabrication of ceramic gas turbine engine parts with Mold Shape Deposition Manufacturing (Mold SDM) is described. Mold SDM exists of two steps: The pattern generation in wax using deposition and machining of wax layers and the pattern transfer process with gel-casting. For parts with feature sizes that are too small for machining, microfabrication methods are used to fabricate the mold. By combining micro- and macro-fabrication, complex parts in a wide variety of sizes can be manufactured.
The surface quality of the mold significantly influences the mechanical properties of the final ceramic part. The contribution of the mold quality to the final mechanical properties is studied in this work.

INTRODUCTION

Non-oxide ceramic materials such as silicon nitride and silicon carbide have been thought to be good candidates for high-temperature engine applications. In particular, silicon nitride has been recognized for high temperature applications because of its excellent high temperature strength, high temperature stability, high toughness, good creep resistance, excellent thermal shock resistance, low density and good chemical resistance. However, the application of Si_3N_4 material is inhibited by the difficulty and high cost of fabrication of ceramic parts that have complex shapes as shown in Fig. 1. Rapid prototyping is one of the candidates to build a complex-shaped part easily and cost-effectively.

For mesoscopic parts such as a turbine and inlet nozzle, Mold SDM is applied which is a variation of Shape Deposition Manufacturing (SDM), an additive-subtractive layered manufacturing process that has been used to build metal or polymer parts.[1] In Mold SDM, the mold is built with the SDM technique that can make such a sophisticated, complex shaped mold by machining of a mold material and a temporary part material. After building a mold with SDM, the temporary part material such as solder mask can be removed by etching with water, thereby allowing us to mold the green parts with gel-casting. As a result of this combination of SDM and the gel-casting technique, the final surface quality is only limited by the ability of CNC machining. Fig. 1 shows the turbine engine parts fabricated with Mold SDM and Fig. 2 shows the simplified process of Mold SDM.

For microscopic mechanical parts such as a thrust bearing, we used conventional thin film fabrication process such as photolithography, plasma etching and electroplating with various materials such as silicon nitride, silicon and nickel.[2]

In this study, the possibility of rapid prototyping on the fabrication of engine parts is reviewed and the mechanical properties of Mold SDM parts are analysed.

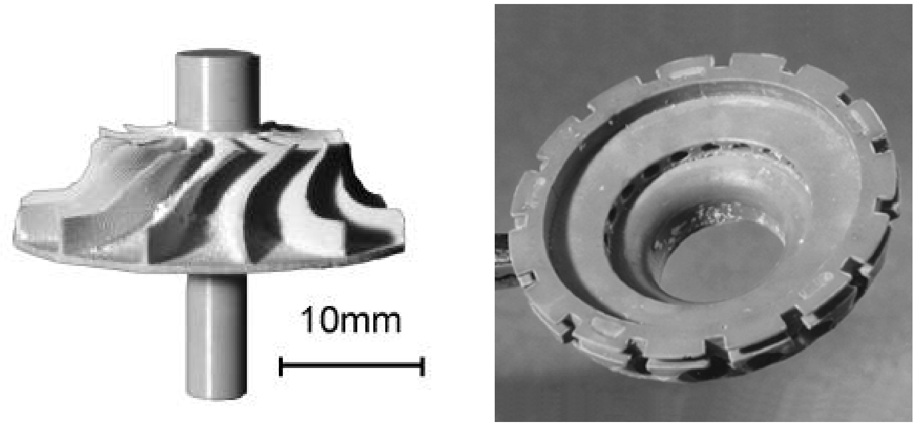

Fig. 1 Silicon nitride turbine engine parts fabricated with Mold SDM:
turbine-rotor (Left), inlet nozzle (Right).

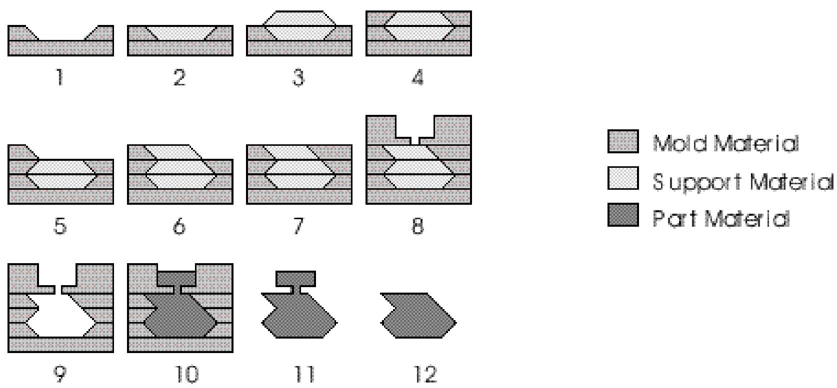

Fig. 2 Schematic representation of the Mold SDM process: the mold is constructed layer by layer. After that, the support material is dissolved and the ceramic part is gel-cast.

EXPERIMENTAL PROCEDURE

For building molds of mesoscopic parts such as a turbine rotor and inlet nozzle, the Haas VF-0E 3-axis CNC milling machine is used that can deposit and cure the wax materials and the solder mask. This CNC machine can be controlled by a computer system which can read and manipulate machining code generated by the CAD program, UniGraphics. For mechanical testing, the wax molds for standard testing specimen (3×4×45mm) are prepared with this Haas CNC machine. The bottom of the testing specimen mold is machined in short raster patterns with two types of end mills: 1/8 inch flat-end mill and 1/8 inch ball-end mill.

For building microscopic parts such as the herring-bone type thrust bearing, negative photoresist SU-8 50 (MicroChem Corp.) is deposited on the silicon wafer with a thickness of 250 micron and developed with the desired pattern.

After that, these molds are filled with a gel-casting slurry containing ceramic powder (Advanced Ceramic Research, AZ, USA). The composition of the ceramic powders is 87wt% Si_3N_4, 7.4wt% Y_2O_3 and 5.6wt% Al_2O_3 are added as sintering aids. Before casting, additives of the slurry are added for curing with the amounts shown in Table 1. Lauroyl peroxide ($(CH_3(CH_2)_{10}CO)_2O_2$, Aldrich, USA) is added as the initiator of the polymerization of the silicon nitride slurry and dibutyl phthalate (C_6H_4-1,2-$[CO_2(CH_2)_3CH_3]_2$) is added as a solvent for the lauroyl peroxide. Small amounts of N,N-dimethyl-m-toluidine (Aldrich,USA) are added to accelerate the polymerization process.

Then, the slurry is gelled at 55°C for 12 hours in a nitrogen atmosphere. After the slurry has solidified completely, the surrounding mold is melted off. After drying and de-binding, the part is sintered at 1750°C in a nitrogen atmosphere.

Room and high temperature four point flexural strengths were measured with a mechanical testing system with a lower span of 40mm, upper span of 20mm and a cross-head speed of 0.5mm/min (Shimitzu, Japan)

Table 1. The recipe of the additives for curing of ACR slurry.

Additive	Quantity
Lauroyl peroxide	0.16g
Dibutyl phthalate	0.48g
N,N-dimethyl-m-toluidine	27μl
ACR Slurry	70g

RESULTS

The flaking on the surface of the silicon nitride green parts, which occurs when the parts are gelled in air, can be avoided by performing the gelling process in nitrogen. The so obtained surface quality can be seen in Fig. 1.

However, large surface cracks can be found with SEM (Scanning Electron Microscope, S-4200, Hitachi, Japan). Cracks like that, which can cause an abrupt strength drop, might have been generated during the drying and de-binding procedure which removes the solvent and polymers from the green part[4]. In order to reduce these processing defects, a more careful drying and de-binding schedule is needed as the dimension of the specimens become larger and thicker. Except for these rare surface cracks, no other process defects were observed.

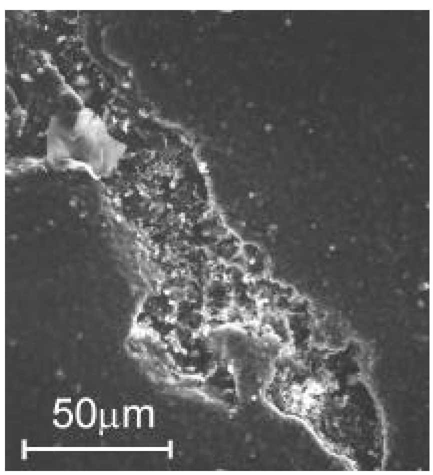

Fig. 3 Surface crack on the surface of the Mold SDM Si_3N_4 specimen.

For as sintered specimens the mechanical testing of 4-point-bend-beams gave an average strength of 430MPa. Fig. 4 shows the strength distribution of the as-sintered specimens as a function of the failure probability. With this Weibull diagram, we can predict the failure probability of the Si_3N_4 specimens under certain stress conditions. In order to measure the bulk properties of gel-cast silicon nitride, polished specimens were prepared and tested under 4-point bend conditions. The mean strength of the polished specimens was 950MPa. However, the strength of some of the as-sintered specimens nearly approached this value and it can be expected that improved processing conditions could yield higher strength values of as sintered beams.

Fig. 5 shows the strength variation as a function of the height of the machined scallop patterns. The strength decreases abruptly when the scallop height of the wax mold increases. We can assume that processing defects are the dominant factor for mechanical failure if the scallop height is between 0.001 and 0.01mm. Above 0.01mm the machining defects seem to be dominant because the strength as well as the standard deviation of the strengths is significantly lower when the scallop height is larger than 0.01mm. By examining the beams after failure it could be found that nearly all cracks initiate on the surface of the specimen.

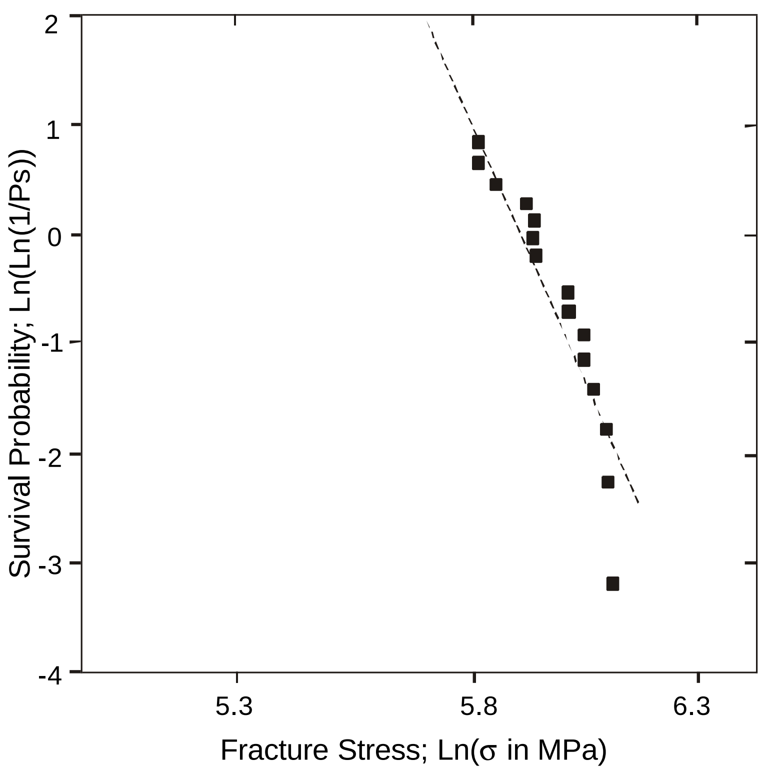

Fig. 4 Strength distribution of as-sintered Si_3N_4 specimens relative to the survival probability at a certain strength.

Fig. 6 (Left) shows a herring-bone air bearing pattern fabricated with SU-8 50 photoresist (PR). The replication of the pattern is very good up to a depth of 1mm. This is due to the low

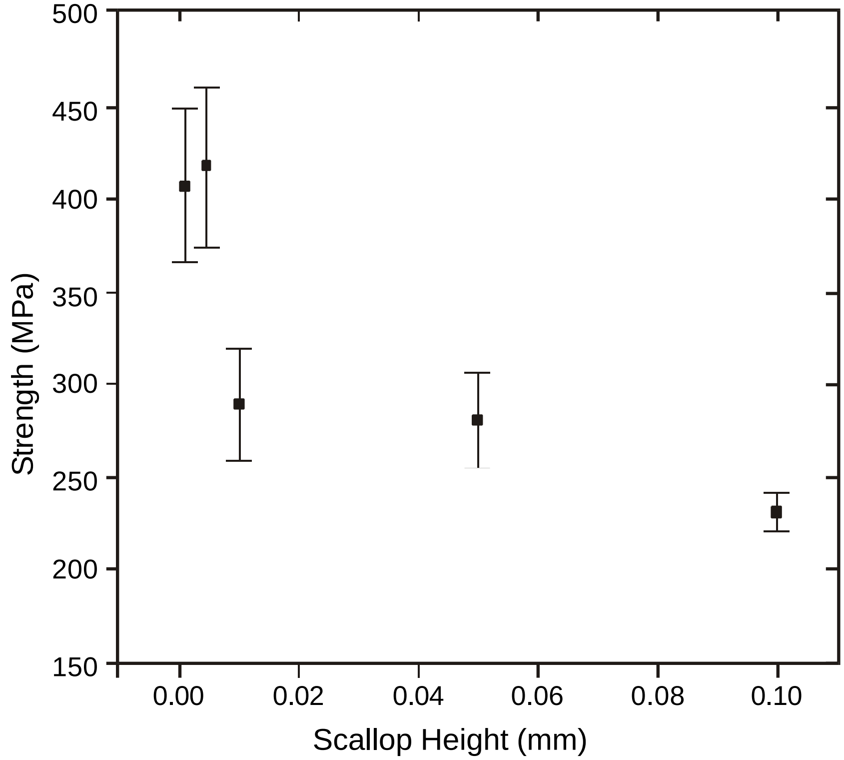

Fig. 5 The strength degradation of Mold SDM parts in dependence of the scallop height. The scallops were machined into the wax mold using a ball mill.

absorption coefficient of SU-8. Fig. 6 (Right) shows the green micro ceramic parts fabricated by gel-casting in a SU-8 50 mold. It shows sharp edges and good replication of the pattern of the SU-8 PR mold can be achieved by gel-casting. The low viscosity and small particle size of the silicon nitride slurry allows the fabrication of such small features.

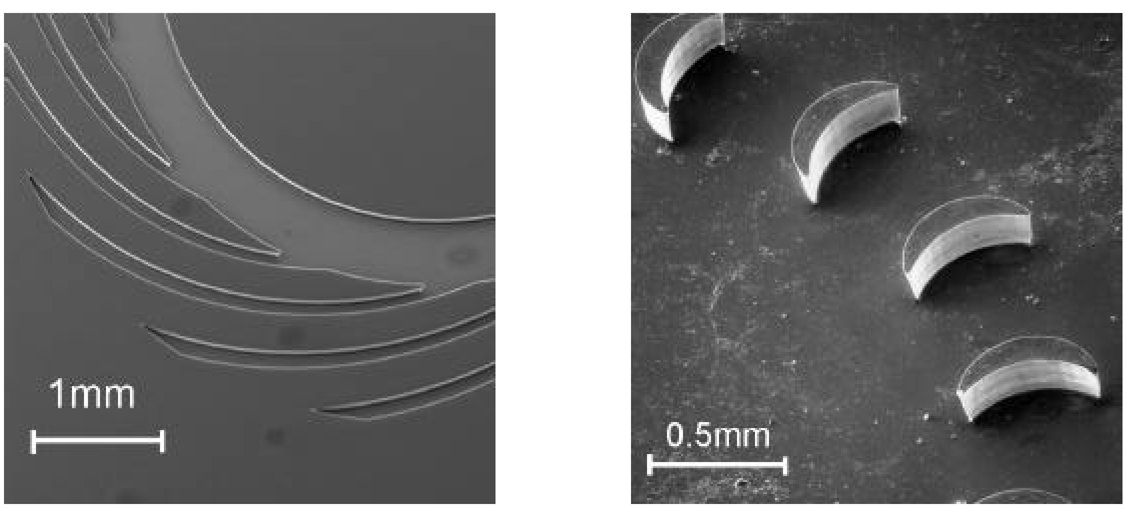

Fig. 6 SEM picture of an herring-bone bearing pattern generated by photolithography with SU-8 50 (Left) ; gel-cast ceramic green body fabricated with SU-8 PR mold (Right).

CONCLUSIONS

Mold SDM which is the combination of SDM and gel-casting can build high quality mechanical parts which can be used without any post processing such as machining. The surface quality improved dramatically after introducing nitrogen during the curing process. To improve the reliability of final product, a more careful drying and de-binding procedure is required.

The result of mechanical testing shows that the mean strength of as-sintered specimens is 430 MPa, and the polished specimens show somewhat higher mean strength, 950 MPa. It shows the surface condition of the specimen is important on the mechanical properties and we can improve the strength of the ceramic parts with improving the surface condition.

The Weibull modulus of as-sintered specimen was 10.5, which is a relatively high value for specimens without any surface modification. The relation between the machining condition of molds and strength is studied. The scallop pattern can act as the initial crack on the surface which can degrade the mechanical properties of Mold SDM parts. The critical value of the scallop height is thought to be 0.005 mm and if we set this machining variable below this value, the ceramic parts with higher quality can be manufactured more effectively.

The microscopic mold can be fabricated with photolithography of SU-8 50 photoresist. The ceramic body can be built with gel-casting and this method shows a high potential for making parts with small features easily and cost-effectively.

REFERENCE

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