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Rapid Prototyping of Mesoscopic Devices

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Abstract. The trend towards miniaturization closes the gap between conventional macroscopic manufacturing techniques (milling, turning, casting,) and microfabrication techniques (lithography, etching, thin-film deposition, electroplating, LIGA). Yet there still exist some distinctive differences:

- Macrofabrication (part or feature size usually $>$ 1mm) deals with a wide variety of materials which can be fabricated in fairly complex, three- dimensional shapes. All three dimensions are equal and there is no upper size-limit in one dimension.
- Microfabrication (part or feature size usually $<$ 100μm) allows arbitrary shapes in two dimensions (the "wafer plane"), but shapes in the third dimension usually have to be decomposed into prismatic layers. In most cases these layers cannot exceed a certain thickness (due to limited cure or irradiation depth of photoresist, limitations of the etching process or constraints in the deposition of thin films). Additionally, the number of available materials is fairly small, due to restrictions in the etching or deposition process.

In this work we show how micro- and macro-techniques can be used together in order to fabricate mesoscopic parts (part or feature size between 100μm and 10mm) in a variety of materials, including ceramics, metals and polymers. The starting point for fabricating these parts are molds which are either machined conventionally or using photolithography and deep plasma-etching of silicon.

These techniques are applied to the fabrication of a miniature gas turbine engine. Two parts of this engine are described in more detail in this work: The ceramic rotor and a thrust bearing.

1. Introduction

Progress in the field of macromachining (CNC machining, Rapid Prototyping, ..) and micromachining (plasma etching, lithographic techniques) is beginning to close a gap that used to be very large: The macro-world (part or feature size $>$1mm) usually deals with a wide variety of materials in complex shapes whereas the micromachined parts are made out of a limited number of materials (mostly originating from semiconductor processes) in fairly simple shapes.

In this work an approach is presented in which macro- and micro-techniques are combined to fabricate ceramic and metallic parts for a miniature gas turbine. Miniature gas turbines are a candidate for replacing batteries as power source (high-power energy packages) for portable devices with high power consumption. Liquid fuels have an energy density twenty to two hundred times larger than current lithium-ion battery technologies [1]. Furthermore, the power that can be generated in a given volume in a combustion device exceeds existing electro-chemical devices.

In the following the fabrication procedure for two critical parts of this engine is described: The ceramic turbine rotor and inlet nozzle and a high speed thrust bearing. Both parts have feature sizes in the mesoscopic range and both need to operate in a harsh environment.

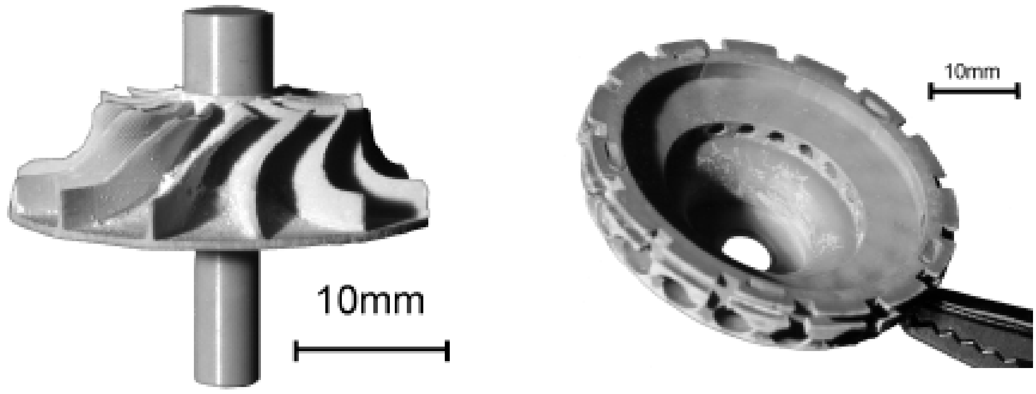

Figure 1. Silicon nitride turbine (left) manufactured with Mold SDM. The right picture shows the ceramic inlet nozzle for this turbine. This inlet nozzle has been tested up to 1250°C.

2. Case study I: A high temperature gas turbine

The exact shape of the turbine blades and the gas inlet section is crucial for the performance of the whole engine. Since the diameter of the current turbine design is 22mm, it is possible to fabricate these parts with CNC machining. Since the target material for the hot section of the engine is silicon nitride, direct machining is not possible. Instead we used Mold Shape Deposition Manufacturing (Mold SDM) [2], [3] to fabricate fugitive wax molds. These molds are filled with a gelcast formulation (commercialized by Advanced Ceramics Research, Tucson, AZ). After casting, the liquid slurry solidifies and the wax mold can be molten off. The obtained green part is dried, debinded and sintered in order to obtain the final ceramic part [4].

2.1. Mold SDM

Mold SDM is a layered manufacturing process involving an iterative combination of material addition and material removal. Wax molds are built up within a sacrificial support material (UV curable soldermask or water soluble wax) that encases each layer to provide a platform for deposition of the next layer and to support overhanging part geometry features. Unlike most other SFF techniques which decompose models into thin 2.5 dimensional layers, Mold SDM retains a three dimensional representation of the parts so that parts are built without stair-steps. Especially ceramics require an excellent surface finish in order to achieve high strength values. The surface finish of parts made with Mold SDM is only limited by the abilities of the CNC machine. On the finished ceramic part a surface roughness of 0.5 - 0.7 μm RMS has been achieved without post-processing.

In Fig. 1 the sintered turbine as well as the inlet nozzle are shown. The geometries for both parts are complex: The rotor blades are extremely thin (200μm) and the inlet nozzle has internal gas channels which are difficult to fabricate with conventional manufacturing processes.

Table 1. Material choices for miniature thrust bearings.

Material	Max. Temp. °C	Strength at 25°C MPa	Toughness MPa $m^{1/2}$	Wear Rate	Micromachin-ability
Silicon	700	>900	1-2	low	excellent
Si_3N_4	1200	950	4-7	low	good
Nickel	500	920	80-110	medium	very good
Copper	200	200	50-120	high	very good

3. Case study II: A thrust bearing

Since the movable engine parts are going to operate at elevated temperatures at high rotational speed, commercially available bearings cannot be used for this device. The final turbine/compressor assembly will be suspended by a pair of aerodynamic thrust- and a pair of radial bearings. The thrust bearing consist of a cylinder with 20-40μm deep “herring-bone” pattern on top of the cylinder. In Fig. 2 (a) a typical design for such a pattern is shown. When the rotor spins on top of these “herring-bones”, the turbulent air flow, which is created through the movement, lifts the rotor off and allows a non-contact suspension between the moving parts. Three materials offer the necessary properties for manufacturing these bearings (see Table 1): Silicon nitride, silicon and nickel. For tests at room temperature copper has also been included in Table 1 since it can be micromachined easily. Three fabrication techniques are considered to manufacture these bearings: Plasma etching of silicon, electroplating into a photoresist mold and gelcasting of ceramics into a photoresist mold.

3.1. Plasma etching

Silicon is a good choice for a miniature bearing because its wear rate is low, it can be used up to fairly high temperatures and it can be micromachined easily. The main drawback is its low fracture toughness. If the rotor runs unstable and hits the bearing, it is easy to chip off some of the sharp corners. To fabricate the silicon bearing shown in Fig. 2 (a, b), a plasma etcher (STS Multiplex ICP Deep RIE) was used. With etch rates up to 4μm per minute, deep patterns can be etched into standard silicon wafers. As can be seen in Fig. 2 (a, b) the obtained side walls are almost vertical and even very sharp corners are replicated very well. The bearing shown in Fig. 2 (a, b) has been used to spin a test-turbine with rotational speeds up to 3kHz.

3.2. Deep photolithography

To generate photoresist molds for gelcasting and electroplating two types of resists were investigated: The negative tone resist SU-8 50 (Microchem Corp.) and the positive tone resist SPR220-7 (Shipley). SU-8 is an epoxy based system [5] that, due to its low absorption coefficient, can be patterned to thicknesses up to 1mm. In Fig. 2 (c-f) the bearing pattern is shown in these two resists. SU-8 shows more vertical sidewalls and a better defined replication of the desired pattern. The absorption coefficient of SPR220 is high, and at the desired thickness of 40μm either the top region is overexposed or the bottom region underexposed. Table 2 summarizes the processing parameters for both photoresists.

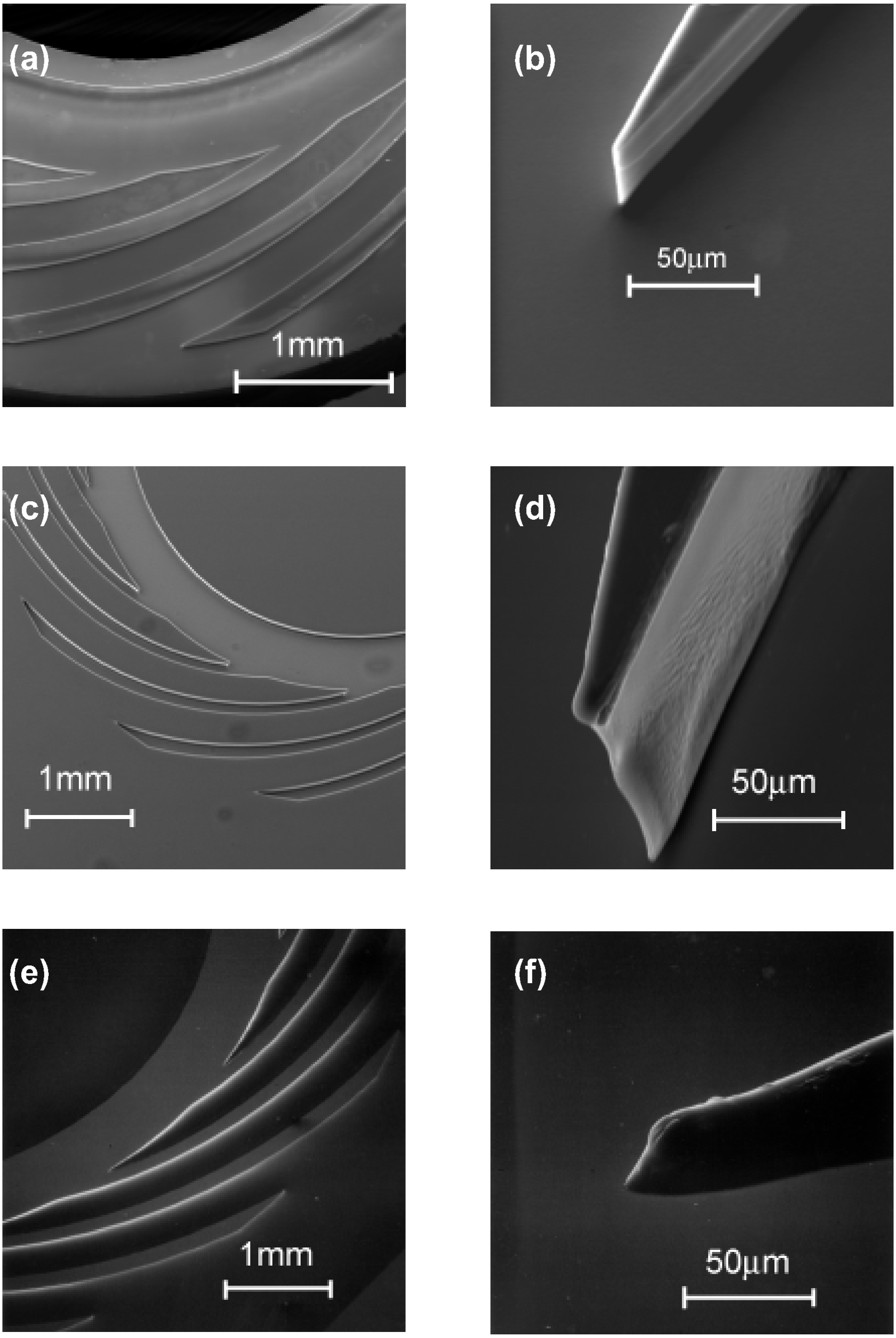

Figure 2. Scanning electron micrograph (full and detailed view) of a bearing pattern generated by plasma etching of silicon (a, b), lithography in SU-8 50 (c, d) and lithography in SPR220-7 (e, f).

Table 2. Properties and processing of deep photoresists.

Resist	Thickness μm	Prebake at 90°C hr	Exposure with $15mW/cm^2$ at 365nm mJ/cm^2	Postbake	Develop
SU-8 50	250	3	900	5min @60 °C	5min in PGMEA
SU-8 50	150	3	450	5min @60 °C	5min in PGMEA
SPR220-7	36	3	3750	4hrs @95 °C	10min in LDD26W
SPR220-7	54	3	6000	4hrs @95 °C	10min in LDD26W

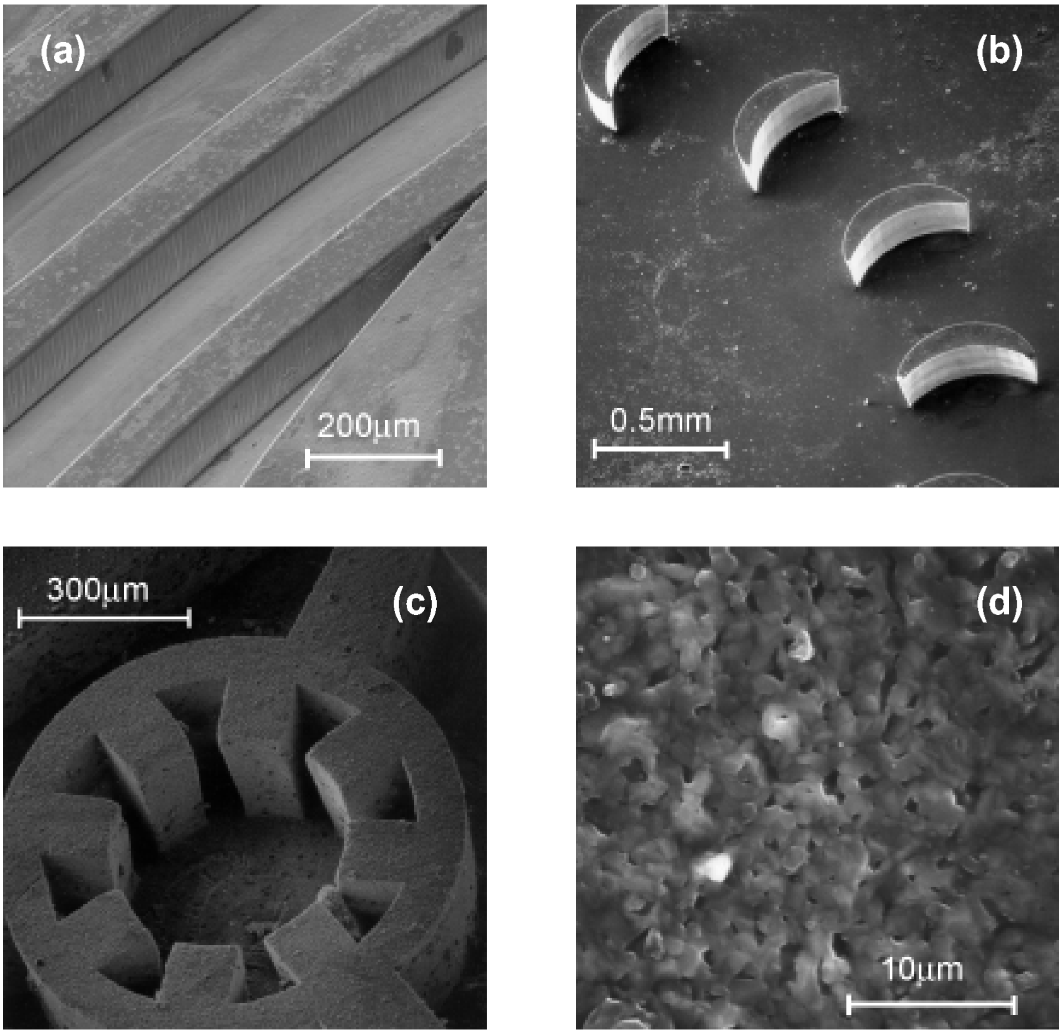

Figure 3. Scanning electron micrograph of a bearing pattern of plated copper (a). Micrograph of a gelcast ceramic green (b) and sintered (c) part. The as sintered Si_3N_4 surface (d).

3.3. Electroplating

By electroplating the patterns generated in SU-8 can be replicated in either nickel or copper. Fig. 3 (a) shows part of a thrust bearing out of copper which was fabricated in that way. The mold was placed in a copper sulfate bath and plated with a pulse-reverse current source at $30mA/cm^2$. Since polymerized SU-8 is inert to most chemicals, it is hard to remove the resist after plating. The best results have been achieved by thermally decomposing the resist at 600°C in vacuum. As an alternative to SU-8, silicon can be used as mold for electroplating [6].

3.4. Gelcasting

In order to avoid problems with varying coefficients of thermal expansion, it is desirable to use as few different materials as possible for the engine. In Sec. 2 it has been shown that gelcasting of silicon nitride is a technique that is suitable for fabricating complex shaped ceramic parts. Since the powder particles used in the slurry are fairly small (0.5-1μm), this technique is a potential candidate for the fabrication of much smaller parts. In Fig. 3 (b) a gelcast turbine green part is shown. The micromachined mold is easily filled by the slurry, and the "granularity" of the slurry can only be seen after sintering in Fig. 3 (c). In the case of silicon nitride it is important to maintain a sintering atmosphere that avoids the $\alpha - \beta$ phase transformation on the surface of the parts. As long as the phase transformation does not occur, it is possible to keep the surface roughness in a range which is defined by the size of the powder particles (Fig. 3 (d)).

4. Conclusion

By using a hybrid approach of macro- and micromachining techniques it is possible to achieve small feature sizes as well as complex shaped parts in a wide variety of materials. In cases where shape complexity is the dominant factor (like for the inlet nozzle or a turbine), Mold SDM is the preferred technique. For parts with small feature sizes and fairly simple geometries, micromachining techniques can be used to create shapes which can be molded into ceramic and metallic materials.

References

[1] C.K. Dyer. Replacing the battery in portable electronics. *Scientific American*, pages 88–93, July 1999.

[2] S. Kang, A. G. Cooper, J. Stampfl, F. Prinz, J. Lombardi, L. Weiss, and J.Sherbeck. Fabrication of high quality ceramic parts using Mold SDM. In D.L. Bourell et al., editor, *Solid Freeform Fabrication Symposium 1999*, pages 427–434, University of Texas, Austin, August 9-11 1999.

[3] R. Merz, F.B. Prinz, K. Ramaswami, M. Terk, and L. Weiss. Shape deposition manufacturing. In H.L. Marcus et al., editor, *Proceedings of the Solid Freeform Fabrication Symposium 1994*, pages 1–8, University of Texas, Austin, August 8-10 1994.

[4] A.C. Young, O.O. Omatete, M.A. Janney, and P.A. Menchhofer. Gelcasting of alumina. *J. Am. Ceram. Soc.*, 74(3):612–618, 1991.

[5] K. Lee, N. LaBianca, S. Rishton, and S. Zohlgharnain. Micromachining applications for a high resolution ultra-thick photoresist. *J. Vac. Scien. Technol. B*, 13:3012–3016, 1995.

[6] J. Stampfl, R.Leitgeb, Y.L. Cheng, and F.B. Prinz. Mikrostrukturierung von Funktions- und Strukturwerkstoffen mittels plasmageätzten Siliziums. In K. Kempter and J.Haußelt, editors, *Band I - Werkstoffe für die Informationstechnik, Mikrosystemtechnik*, Werkstoffwoche 98, München, pages 329–334. Wiley-VCH, 1999.

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