Replication Techniques for Ceramic Microcomponents with High Aspect Ratios

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Abstract Most processes for the manufacturing of ceramic components have in common that they are based on a powder-technological shaping process using a negative mold and subsequent thermal compaction. For microcomponents these processes require special adjustments especially when high aspect ratio structures have to be fabricated. Shaping methods that allow the application of silicone rubber molds, like low-pressure injection molding (LPIM) or centrifugal casting, not only have the potential to fabricate ceramic components with high aspect ratios but also offer a possibility for the rapid manufacturing of ceramic microcomponents.

keywords *ceramic injection molding, centrifugal casting, soft mold, rapid manufacturing*

1 Introduction

Use of ceramic materials in microsystems technology is of particular interest when their good mechanical and tribological properties, their thermal and chemical resistance or special physical, i.e. dielectric or piezoelectric properties, qualify them for uses that can not be covered by polymers or metals. Often, however, ceramic microcomponents are not employed due to the costs associated with their production, design, and development and because methods for the production of larger series have not yet been fully established.

Although ceramics have a number of material-specific advantages, considerable difficulties are encountered in molding and particularly in micropatterning. Due to the high hardness of ceramics machining in the sintered state by cutting tools is difficult and expensive or at least becomes impossible on microdetails. The processes developed in the past for molding in the millimeter and micrometer ranges differ in terms of manufacturing expenditure, design freedom, and achievable aspect ratio. Apart from rapid prototyping techniques for ceramics that either do not have a sufficient resolution for the fabrication of micropatterned ceramics [Greulich et al. (1995), Bandyopadhyay et al. (1997), Heinrich (1999), Doreau et al. (2000), Varadan et al. (2001)] or do not yet provide functional models with the final properties of conventionally manufactured ceramics [Griffith and Holloran (1996), Zhang et al. (1999), Dufaud and Corbel (2001)], the processes developed all have in common that the production is based on a powder-technological shaping process using a negative mold and subsequent thermal compaction [Nöker and Beyer (1992), Knitter et al. (1996), Bauer et al. (1997), Bauer et al. (1999), Chan et al. (2000)]. The negative mold that is applied as a molding tool can either be fabricated directly or replicated from a master model via electroplating, plastic embossing, injection molding or casting techniques. This results in three major requirements.

Firstly, replication always requires a master model with dimensions that already take into account the shrinkage during sintering. The master models or the molds can be fabricated by means of erosion methods, mechanical micromachining, silicon etching, the LIGA technique or by rapid prototyping methods. Secondly, the shaping process of ceramics has to be a net shape forming, as subsequent finishing of the micropatterned details is impossible in most cases. Thirdly, a demolding step is necessary after the shaping process in which the shaped part is separated from the mold. This step often results in damage of the micropatterns, especially in the case of high aspect ratio microstructures.

For this reason different strategies were investigated to improve the yield of the shaping process. Reducing the surface roughness of the mold is one possibility, as this procedure reduces the friction of the green body during the demolding step. High surface qualities are obtained by methods like LIGA, which are expensive and have long production times, making this method attractive for selected applications only. Another strategy is the enhancement of the mechanical strength of the green body [Piotter et al. (1998)]. This goal should be achieved by the substitution of the standard binder by high strength polymers. However, these materials are also known for having limited qualification as additives because they increase the viscosity. This degrades the plasticity of the feedstock and particularly aggravates the shaping of fine patterns. A third approach is the use of soft molds that improve the demolding by the flexibility of the mold walls. Soft molds are fabricated by a replication of a master model in silicone rubber and can only be integrated in selected shaping methods. As they require manual handling, the application of these molds is limited to small series production, but they are easy to produce and enable a fast and flexible production when combined with the fabrication of master models by rapid prototyping techniques [Knitter et al. (1999)].

2 Microfabrication of Ceramic Components

The microfabrication techniques for ceramic components presented here, all set out with the fabrication of a master model that is replicated into a silicone rubber mold. This mold will be used as a tool in the ceramic molding process (fig. 1). This opens up the possibility to use a great variety of master models as the replication in silicone rubber can be performed with a high molding precision even on very sensitive materials and shapes.

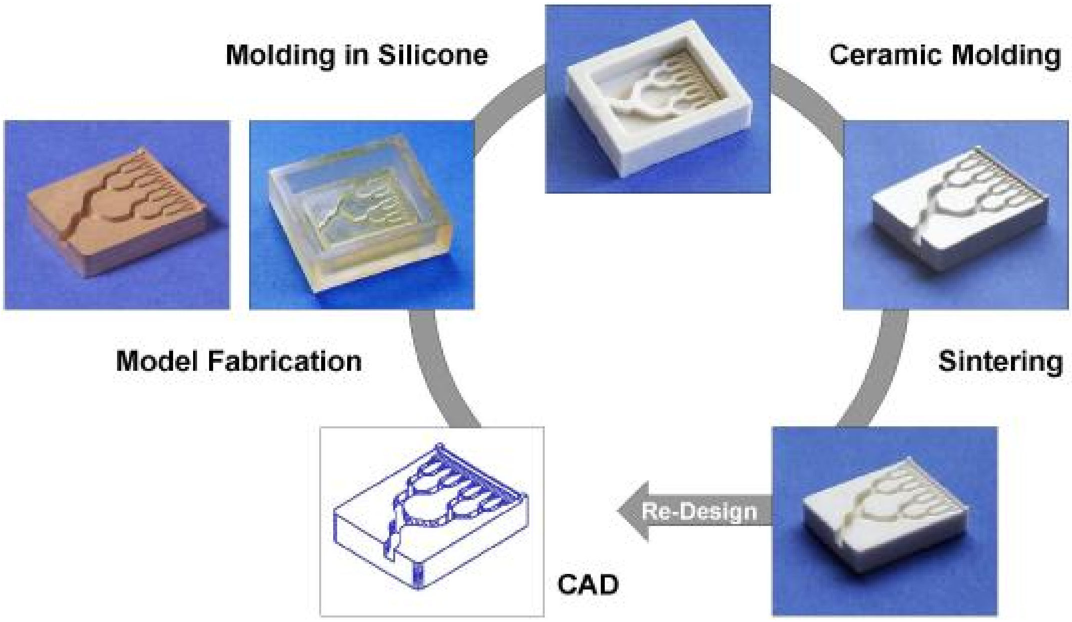

Fig. 1: Process stages of the replication process chain for the fabrication of ceramic microcomponents.

2.1 Mold Fabrication

The fabrication technique of the master model has to be chosen in order to meet the needs of the ceramic component to be produced. Depending on the design, the aspect ratio and geometry of the ceramic components master models were fabricated by LIGA technique, mechanical microfabrication or different rapid prototyping techniques. Whereas the LIGA technique and mechanical microfabrication provide high surface qualities but are time- and cost-consuming fabrication techniques, rapid prototyping techniques allow a fast and inexpensive fabrication of master models, although with lower surface qualities due to the layer-by-layer manufacturing. Three different rapid prototyping techniques were used for the fabrication of master models. These techniques differ in resolution but have in common that the models are built layer by layer based on the sliced data of 3D CAD models.

Several polymer models were built in a commercial stereolithography equipment (FS-REALIZER, Fockele & Schwarze). This facility has a positioning accuracy of 10 µm and a solid-state laser with a spot diameter of 100 µm is applied. For epoxide exposure, the construction platform was lowered in steps of 100 µm.

The thermopolymer models were made on a ThermoJet Printer (ACTUA 2100, 3D Systems) by multi-jet modeling (MJM) with a drop size of 90 µm. The models were built with a step size of 120 µm, but the layer thickness can be decreased to 40 µm.

Some of the master models were made of acrylates using the RMPD technique (Rapid Micro Product Development) at microTEC company, Duisburg [Reinhardt and Götzen (1999)]. This modification of stereolithography, which is suited for microdimensioning, allows to reach a precision of about 5 µm and enables parallel fabrication of a number of components. Objects with a layer thickness of about 1 µm only may be generated. For the given geometries, however, a layer thickness of 25 or 50 µm was sufficient.

In the next step the master models were molded with liquid silicone rubber which could be demolded easily after curing. However, different silicone rubber materials may be selected to meet the specific demands of different designs. According to the experience gained so far, each silicone mold usually allows more than 100 ceramic components to be produced without any wear effects being detected.

2.2 Ceramic Shaping Methods

The use of silicone molds for the shaping of ceramic microcomponents presuppose molding techniques that apply low loads on the tools. Furthermore, these molding techniques have to offer a high molding precision for the shaping of finest details and have to provide green compacts with a sufficient strength for demolding. To minimize firing shrinkage and to avoid warping and cracking during binder burnout these molding techniques should additionally enable the use of feedstocks with high ceramic loadings. In general, the preparation of the feedstock always plays a critical role, as all inhomogeneities have to be disrupted which would otherwise persist into the fired state as flaws.

2.2.1 Low-Pressure Injection Molding

One shaping process that has been proven to be especially suited for the fabrication of ceramic microcomponents is ceramic injection molding [Benzler et al. (1998)]. Depending on the molding conditions, two varieties are distinguished: the high-pressure [Mutsuddy and Ford (1995)] and the low-pressure injection molding, also called hot molding [Peltsman and Peltsman (1981)]. In contrast to high-pressure injection molding, where the feedstock is plasticized by thermoplastics of high viscosity [Rak (1998)], low-pressure injection molding of ceramics is based on the use of low-melting paraffins which allow molding at significantly reduced temperature and pressure loads [Lenk (1995)]. Due to the small mold loads involved, in this process besides metal molding tools, plastic molds may be applied as well as molds cast from silicone rubber [Knitter et al. (1999)].

For the preparation of the feedstocks, which is simple compared to those required for high-pressure injection molding, first paraffin and a dispersant are molten at about 80°C and are then mixed with the ceramic powder. Feedstocks with up to 85 vol% for a silica powder are described in literature [Shaffer et al. (2000)], however for most standard powders the solid contents are in the range from 50 vol.% to 65 vol.%. The silicone rubber molds are filled with a commercial low-pressure injection molding machine (Peltsman, Minneapolis, USA) using injection pressures below 6 bar. For complete filling of the mold, the tool has to be evacuated prior to injection and the mold has to be heated to a temperature that exceeds the melting point of the paraffin. Due to the elasticity of the silicone rubber mold, it is also required to adapt the machine parameters in order to ensure sufficient dimensional accuracy.

After demolding, the paraffin was removed from the green parts by a slow heating process up to 500°C. For sintering, e. g. the alumina parts were heated up to 1700°C. The heating rates for debinding and sintering depend on the geometry and the cross-sections of the parts, i. e. large parts with large or varying cross-sections are difficult to debind and sinter without introducing defects which may cause cracking. Total duration of the thermal treatment is in the range of 20 to 30 hours. Linear shrinkage of the prepared parts amounts from 12% to 20%, depending on the feedstock used.

Similar feedstocks as for LPIM but with a significantly lower viscosity can be prepared from selected powders. With these feedstocks a simple casting process without the need of machines is possible. In case of this manual procedure the silicone molds were filled with feedstocks heated up to temperatures of 80-100°C and the molds must be evacuated during or after casting to remove air inclusions. Feedstocks with up to 68 vol% for alumina, 50 vol% for zirconia, and of 58 vol% for PZT ceramic were used for this method.

2.2.2 Centrifugal Casting

Feedstocks prepared for low-pressure injection molding can also be used for centrifugal casting. In this technique the slip is not driven into the mold by pressure but by centrifugal forces. In contrast to the centrifugal casting described in [Bauer et al. (1997)] the centrifugation time is short and the sedimentation of the particles is prevented, therefore it resembles the spin casting or investment casting of metals. Centrifugal casting is of special interest for prototypes because no additional machine volume has to be filled. Only the small amount of slip for the mold volume is necessary, reducing also the time and cost for the slip preparation. Additionally no evacuation equipment is required as the entrapped air is displaced by buoyancy due to the higher density of the slip.

3 Results and Discussion

As a whole, the replication process chains exhibit a high precision and accuracy down to the micrometer range. The quality of the master model is of decisive importance for a repeatable quality of the ceramics. The achievable resolution and surface quality of the ceramic components are mainly limited by the quality of the master model rather than by the molding processes.

For high aspect ratios the demolding step plays the most critical role for a successful shaping. This step can be simplified by the use of flexible silicone rubber molds. Another aspect is a careful adjustment of the feedstock properties with respect to a sufficiently low viscosity and low yield strength. A low viscosity and a low yield strength support the removal of air from the feedstock and the filling of the mold. Also for high aspect ratios a reduced softening behavior is necessary to prevent the distortion of the structures during the binder burnout. In figure 2 the alumina component show an overturning wall due to softening during the debinding step. No deformation can be seen in the zirconia component, molded with an optimized feedstock.

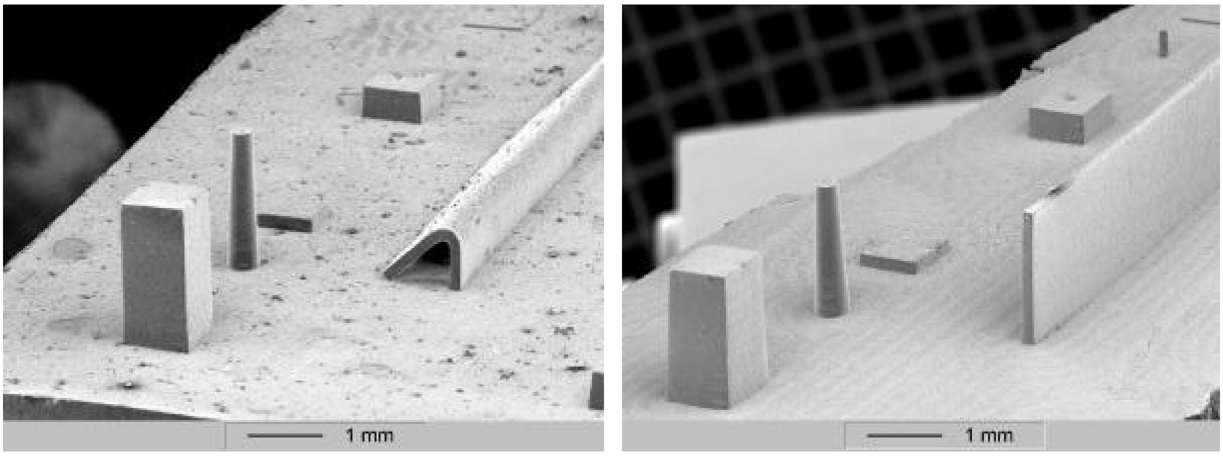

Fig. 2: Alumina (a) and zirconia (b) microparts showing different softening behavior during debinding.

When applying master models of high surface quality, e. g. fabricated by LIGA or mechanical tooling, aspect ratios of more than 10 can be obtained with very high surface qualities. Figure 3 shows an example of extended zirconia patterns, where the master model has been made by mechanical tooling.

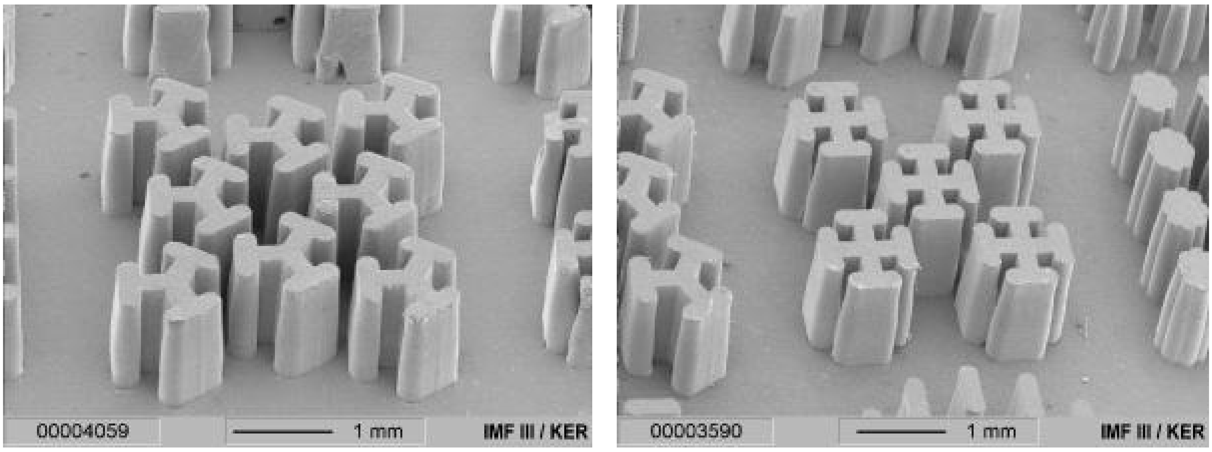

Fig. 3: High aspect ratio zirconia test patterns made by low-pressure injection molding.

For the development of new products and for the fast preparation of functional models the use of master models made by rapid prototyping is very attractive. By means of a rapid prototyping process chain (RPPC) that combines e. g. micro stereolithography and low-pressure injection molding, ceramic microparts can be manufactured within short time, at low costs, and with high precision (Knitter et al (2001)]. Due to the simple feedstock preparation, experiences have already been gained with materials such as alumina, zirconia, PZT, barium titanate, an electroconductive ceramic of alumina and titanium nitride, as well as hydroxyapatite. The components aim at different applications, such as chemical, medical, biological and mechanical applications, as well as dielectric, piezoelectric, and heating applications.

Due to the layer structure of the polymer models, where each inclined area of the component is approximated by steps, the surface quality of the replicated ceramic components is lower than of those replicated from high quality master models. The layer structure of the master mold is also reflected by periodic depressions on the vertical walls of the alumina component shown in figure 4, that was replicated from a stereolithography model. The higher the selected layer thickness of the master model is, the coarser is the reproduction of contours in the ceramic component.

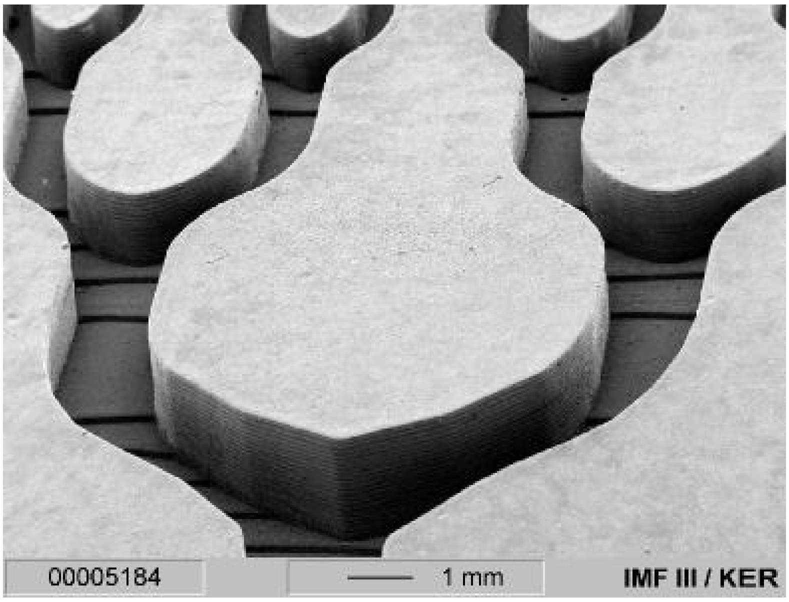

Fig. 4: Surface structure of an alumina component replicated from a stereolithography model by low-pressure injection molding.

In contrast to the replication of LIGA components, the much rougher surfaces resulting from the layer structure of the RP models considerably aggravate demolding of vertical walls with aspect ratios of >5 due to the relatively high friction forces. This may cause problems not only when demolding the ceramic green compact, but also when molding in silicone [Knitter et al. (2001)].

Figure 5 shows a zirconia component, replicated from an RMPD master model. The master model made of acrylic resin was built with a step size of 25 microns and these steps are visible at the vertical walls of the ceramic components. In this component aspect ratios of 10 and smallest details of 50 microns were realized. However, during the replication difficulties arose from two facts. First, the fine, free details of the master mold were very fragile because of the brittleness of the acrylic material, therefore they were quite easily destroyed during the handling and the molding process into silicone. The second fact is, that with higher aspect ratios sometimes details were damaged during demolding, like the small wall at the left side of figure 5a, which was probably tilted during the separation from the mold. In this case feedstocks with a high green strength would be favorable, but the use of high strength polymers would simultaneously increase the viscosity of the feedstock and it will become more difficult to fill tiny gaps of mold.

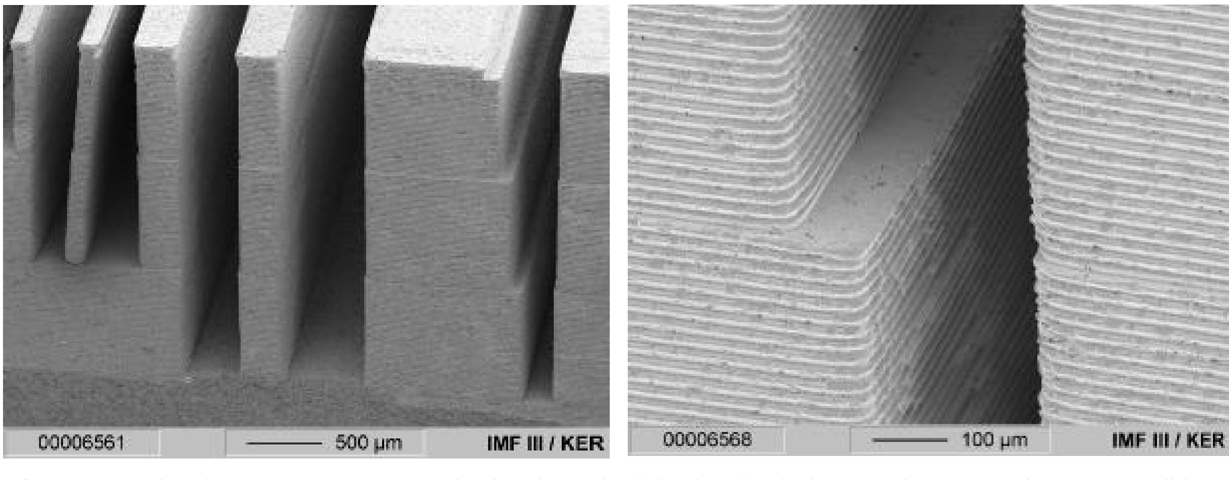

Fig. 5: Replication of a RMPD model in zirconia (a), detailed view of the ceramic surface (b).

Lead-zirconate-titanate (PZT) transducers were developed for a fingerprint scanner. As the theoretical background for this principle is still lacking, various functional models were important for the optimization of the concept. Smooth surfaces were obtained by the replication of sawn master models (fig 6a). For more complex designs rapid prototyping was used for the fabrication of the master models. Because of the narrow gaps of only 200 µm with an aspect ratio of 10, difficulties occurred in stereolithography to remove the liquid, partly cured monomer out of these gaps. Therefore, in this case multi-jet-modeling (MJM) was used for the fabrication of the master model. The components were molded with a high precision, but the walls are quite rough, due to the limited resolution of the MJM process (fig 6b).

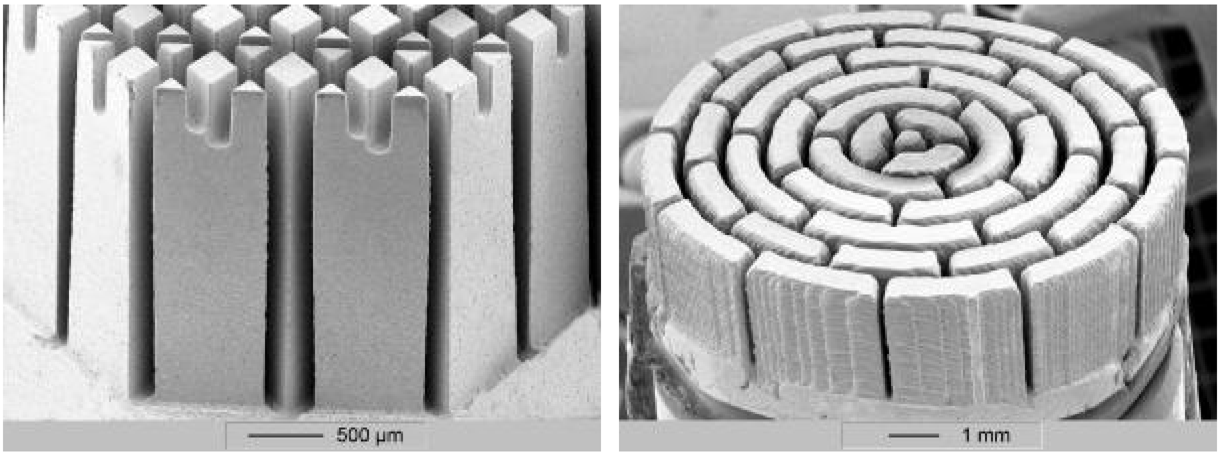

Fig. 6: PZT transducers molded via replication of (a) a micromachined model, and (b) a master model made by MJM.

PZT arrays for 1-3 piezocomposites were molded by centrifugal casting (fig. 7). To obtain rods with 120 µm square in cross-section and an aspect ratio of 4, master models were fabricated by micromachining. Silicone rubber molds were fabricated and filled with PZT feedstock at a temperature of 100°C. The molds were set into centrifuge beakers, which were heated to the same temperature, and centrifuged for 2 minutes at approximately 850 g. Due to thermal isolation of the mold and due to the low centrifugation time the feedstock remained above the melting temperature during the complete centrifugation procedure. At the centrifugation condition used no distortion of the green body could be found after demolding.

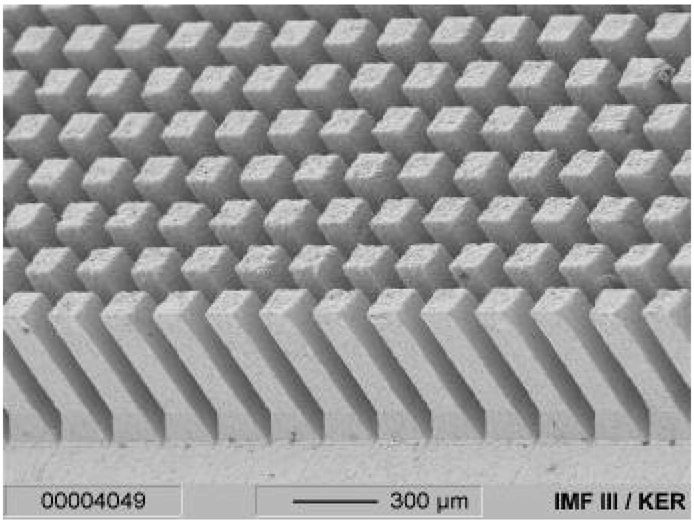

Fig. 7: PZT array with rods 120 µm square in cross-section, replicated from a micromachined model by centrifugal casting.

Due to the elasticity of the silicone rubber, the demolding of the green compacts is significantly simplified and even the demolding of small undercuts is possible without an intricate tool design. The flexible nature of the material supports the shaping of high aspect ratio structures as no taper of molds are necessary for the removal from the mold. It also enables the demolding from molds, even if they have a high surface roughness, which is e.g. a common feature of models or molds made by a rapid prototyping method.

The demolding of green bodies with high aspect ratios and tiny, free details is easier from silicone molds with a high surface quality like those copied from models made by the LIGA-process or micromechanically fabricated models. The demolding from rough silicone molds obtained from RP models make higher demands on the strength of the ceramic green body. However, the RPPC with its fast, flexible, and inexpensive supply of master models and with its rapid manufacturing of new ceramic functional models saves a lot of time when designing and developing new products.

4 Conclusion

It was demonstrated that processes like low-pressure injection molding and centrifugal casting are suited to fabricate finest details and structures with high aspect ratios. Examples were given of various ceramic materials processed by the replication of different models. With the use of silicone rubber molds aspect ratios of more than 10 can be shaped. Like in the macrorange the precision of the replication process is determined by the homogeneity of the feedstock in particular and by the amount of the sintering shrinkage. By using master models made by rapid prototyping the precision of the replication process, however, is limited by the quality of the master models rather than by the different molding processes. As the tooling costs play a major role in product development, the fast fabrication of inexpensive models by rapid prototyping is of great interest. By means of the RPPC, ceramic microparts can be manufactured rapidly, at low costs, and with high precision. Furthermore, modifications of the design may be carried out within a short period of time. This results in a considerable reduction of development and redesign costs and accelerates the commercialization of the microcomponents.

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