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Development of a rapid prototyping process chain for the production of ceramic microcomponents

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Cost-intensive and time-consuming manufacturing of new miniaturized or micropatterned ceramic components may profit decisively from the use of rapid prototyping processes. However most known generative processes do not provide a sufficient resolution for the fabrication of microdimensional or micropatterned components or are restricted to polymer materials. In contrast to this, a rapid prototyping process chain (RPPC), which combines e.g., micro stereolithography and a low-pressure shaping method using soft molds, allows the rapid manufacturing of ceramic microcomponents from functional models to preliminary or small lot series.

1. Introduction

The definition of the term "microcomponent" ensues primarily from a size description, for which the use of the micron scale is beneficial. This can either mean, the size of the component is in the micron or millimeter range ("micropart"), or the overall size of the part is larger, but specific details are scaled in the micronrange ("microdetail"). At present the materials mainly used for the manufacturing of microcomponents are silicon, plastics, and some selected metals. However with this limited range of materials many interesting material properties may not be available for the microsystem technology (MST). Especially the application of ceramic materials is of particular interest because good mechanical and tribological properties, 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.

Moreover, design guidelines that might support the development process are still lacking in MST. A design tailored to the manufacturing process and the loads arising is exclusively based on experience gained in the macrorange. This experience may not be transferred directly to the microrange, as material anisotropy and the increasing influence of effects, negligible in macroscopic parts, require an adequate dimensioning concept. Until appropriate construction guidelines will be available, functional models and prototypes play a crucial role, as they allow an early assessment of the product and, hence, a detection of faults and verification of the concept in due time. For the accelerated supply of models and prototypes a large number of rapid prototyping (RP) methods have been developed. However, at the moment these methods are not suited for the production of ceramic microcomponents, as they either exhibit deficits in molding accuracy or are restricted to polymer materials only. This problem can be bypassed by establishing a rapid prototyping process chain (RPPC) consisting of a rapid prototyping method and a subsequent ceramic shaping method that enables the replication of the RP model into multiple ceramic materials within short times.

2. Generative processes

In recent years, a number of processes were developed with the objective to reduce the time needed for the development of new products by generative manufacturing methods. The first process of this type, which was patented by C.W. Hull in 1984, was stereolithography for the production of three-dimensional models from photopolymer resins [1]. However, it was increasingly desired to use these objects not only for design studies, but also for a functional testing of the products. This resulted in the development of tool-free processes which do not only allow the generative design of plastics or waxes, but also enable direct fabrication of functional models from metals or ceramics. Examples of such processes are laser-supported sintering (SLS, LENS), extrusion techniques (FDC, MJS), laminating techniques (LOM) or inkjet methods based on MIT's 3D printing process [2–6]. The development of UV-curable resin suspensions with high solid content now also allows the application of stereolithography for the direct prototyping of ceramic parts [7–10]. However, most processes for the rapid prototyping of ceramic models still exhibit a limited resolution, a restricted level of detailing, and mostly a rather high roughness, especially on vertical and inclined surfaces. The dimensional accuracies which are in the order of 0.1 mm and above [11] do not allow for a production of small or micropatterned parts.

The objective is to use rapid prototyping methods in MST and, thus, avoiding cost-intensive manufacturing of the original models and to enable a real 3D fabrication instead of a more 2.5D fabrication by lithography techniques. This led to further developments in the generative production of polymer parts. Microscopic systems based on either highly focused laser spots or on the irradiation of UV light through a patterned projection mask are now available for industrial applications. They offer a resolution down to a few micrometers and some of them enable parallel fabrication of a number of components [12–17]. Although the fabrication of ceramic parts by microstereolithography has been demonstrated, this method still lacks in the low solid loading of the usable suspensions resulting in distortions and low sintered density [17–20]. For higher solid contents the viscosity of the suspension increases and therefore the spreading of a thin suspension layer becomes impossible. Also light scattering by the solid ceramic particles affects both the spot width and the curing depth, therefore the resolution of the ceramic-polymer-composite is poorer than that of polymer microstereolithography. It can be expected that due to these problems industrial application of the method will take some time or will even remain impossible. Therefore it is necessary to introduce alternative methods to enable rapid prototyping of ceramic microcomponents.

3. Usage of rapid prototyping process chains

Rapid prototyping process chains (RPPC) have already been described, e.g., for the manufacturing of parts for the automotive industry [21]. In contrast to these investigations, the following paper is focussed on the demands and particularities of microcomponents. These structures require special attention due to the sensitivity of filigree details and due to the high resolution that exceeds most standard rapid prototyping methods. For that reason a RPPC was established for the fabrication of micropatterned ceramic components by combining the high resolution of microstereolithography, as a rapid supply of primary models, with a suitable ceramic shaping method. For this method also the term "Indirect rapid prototyping" is sometimes used, however rapid prototyping process chain describes the sequential character of the method and will therefore be preferred.

A schematic of a RPPC for the production of ceramic microcomponents is shown in Fig. 1. The process chain starts with a CAD construction of the desired part. The data are transferred to a rapid prototyping machine where a three-dimensional model is fabricated. This model is embedded into liquid silicone rubber that after curing will be used as a tool in the ceramic molding process. Suitable shaping methods are casting and molding techniques that use thermoplastic suspensions with a low viscosity. Examples are low pressure injection molding (LPIM), centrifugal casting or, in case of sufficiently low viscosities, even pressureless casting (hot casting).

4. Fabrication of models

The advantage of a RPPC consists in the flexibility of the model preparation. In principle the full range of rapid prototyping methods can be used, as far as the resulting models have the correct dimensions. However, due to drawbacks of the methods with respect to resolution, processing time or costs, a careful choice of the rapid prototyping method is strongly recommended to obtain the desired model properties. For the presented components a standard stereolithography, multijet modeling (MJM) and the RMPD technique (Rapid Micro Product Development) were used. With these three methods all applications could be realized with sufficient accuracy. Each route starts with the generation of a three-dimensional CAD model of the ceramic component to be produced. The 3D model is subjected to triangulation, i.e., it is approximated by a structure consisting of triangles [22]. By varying the number of these triangles, the amount of data and the resolution of the component are influenced. If the sintering shrinkage of the ceramic is assumed as uniform in all dimensions it can be compensated by a simple rescaling of the model size. However even an inhomogeneous shrinkage may be compensated by an anisotropic scaling.

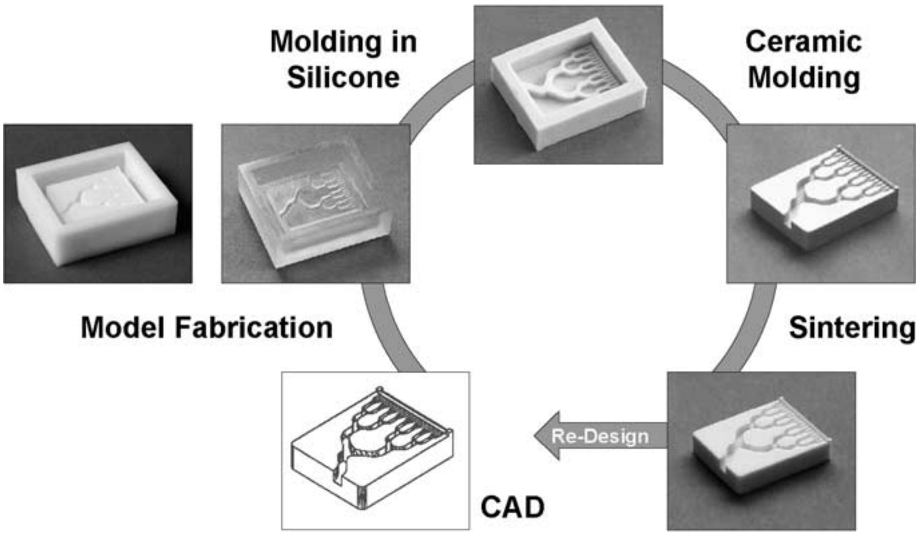


Figure 1 Schematic presentation of a rapid prototyping process chain (RPPC).

For the preparation of models with a lower resolution a commercial stereolithography machine has been used (FS-REALIZER, F & S GmbH, Paderborn, Germany). 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 50 or 100 μm. Due to the large spot size, parts with a relatively large volume can be fabricated within short times.

If small-sized holes or narrow trenches are to be manufactured by stereolithography, problems arise from the epoxides or acrylates, which are used as precursor resins. After removing the part from the resin bath these details can not be cleaned sufficiently from the adherent resin residues, therefore the parts are replicated with poor accuracy. For the fabrication of such items an extrusion based rapid prototyping method like fused deposition modeling (FDM) or a ballistic method like multi-jet modeling (MJM) should be preferred. Although these methods are less suited for microfabrication because of the inherent limited accuracy, it has been demonstrated that they meet the requirements for applications where the high surface roughness can be tolerated [23]. Wax models used for that purpose were made by MJM on a ThermoJet Printer with a drop size of 90 μm (ACTUA 2100, 3D Systems, Valencia, CA, USA). Most models were built with a step size of 120 μm however the layer thickness can be decreased to 40 μm on demand.

For parts with fine details or high resolution the models were made of acrylates using the RMPD technique at microTEC (Duisburg, Germany) [24]. This type of stereolithography, which is suited for microdimensioning, allows to reach a precision of about 5 μm. Objects with a layer thickness of about 1 μm only may be generated. For the given model dimensions, however, a layer thickness of 25 or 50 μm was sufficient, saving time and costs with shorter fabrication times.

5. Preparation of the mold

As far as macroscopic parts are concerned, rapid tooling of ceramics has already been demonstrated, i.e., negative polymer molds were produced, e.g., by stereolithography, and used directly for the molding process. Here, a mold release agent has to be applied prior to the molding step to enable the separation of the green body from the rough stereolithography surface [25]. However, conventional mold release agents may not be employed when molding microcomponents. This is due to the film thickness of the release agents which can no longer be neglected for microdetails and which leads to inaccurate reproduction of edges.

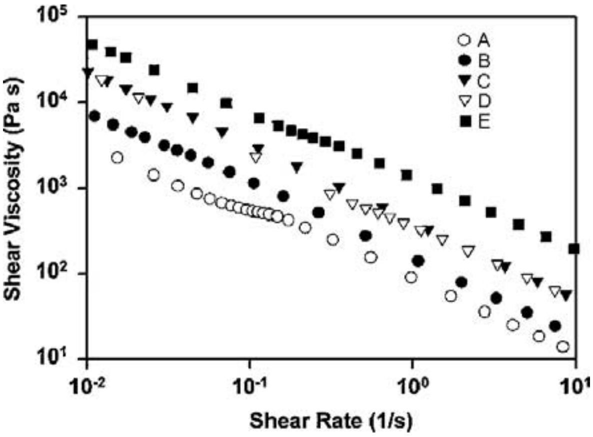


Figure 3 Shear viscosity at different shear rates of zirconia feedstocks (50 vol% solid content, powder properties according to Table I).

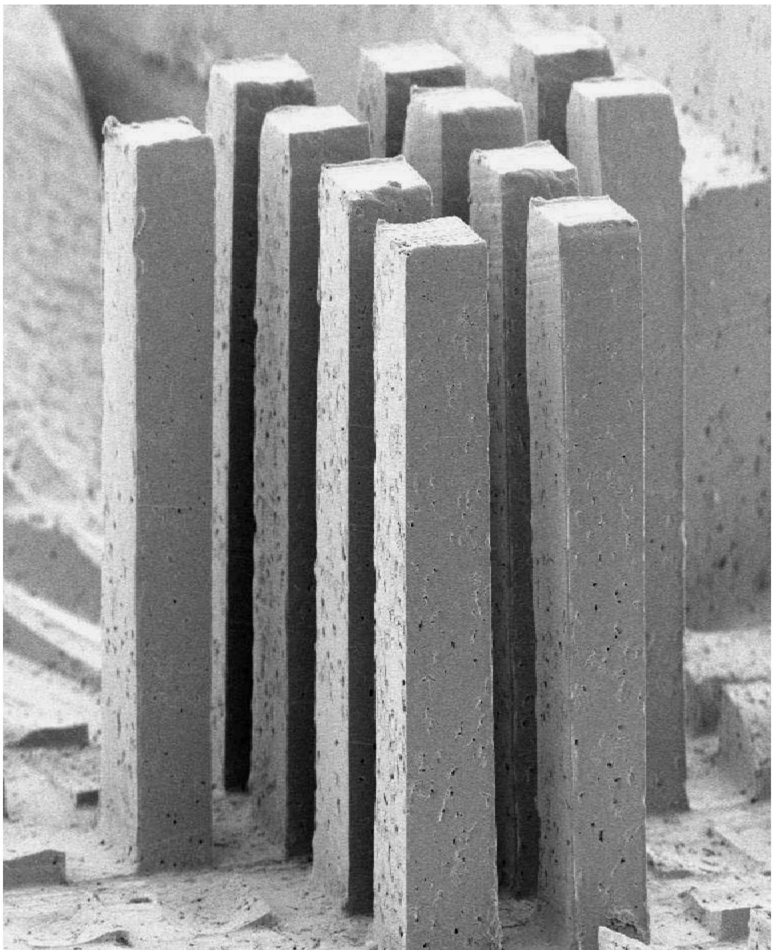
Figure 2 Low pressure injection molding machines from GOCERAM I. V. (left) and Peltsman Corp. (right).

An alternative concept is the application of silicone rubber which can be used as a soft mold material in the subsequent ceramic shaping processes [26]. Such molds are simply fabricated by embedding a positive model with a commercial silicone rubber and evaporating the silicone to remove entrapped air bubbles. After curing of the silicone, which lasts from a few minutes up to 24 hours, depending on the curing temperature and on the silicone used, the model can be removed from the flexible mold. For complex shapes, even multipart molds can be built by casting a monolithic component and cutting the mold into suited parts. Alignment pins that are previously integrated into the silicone enable a precise assembling for the shaping process.

The elasticity of the molds not only simplifies the removal of the model, it also supports the demolding of the green body. As a result of the negligible affinity of silicone rubber to most materials and of the elasticity of the material, it becomes possible to demold fragile details and parallel walls with high roughness, which are normally received from RP methods. Even slight undercuts can be demolded without a sophisticated tool design. However, during the shaping process the elasticity is an unfavorable property as filling forces can lead to distortion of the shape. For that reason a decisive adjustment and controlling of the molding process to the demands of soft molds is required. For high precision parts this also includes accurate temperature control due to the noticeable thermal expansion of the silicone rubber. Distortion may also result from the weight of the green ceramic part but this problem is usually negligible for microdimensional parts. The elasticity of the mold can be adjusted by using selected silicones, but improving the shape stability by enhancing the stiffness of the material on the other side deteriorates the demolding benefits. For each shape a balance between those contrary demands has to be found based mainly on practical knowledge. According to the experience gained so far, each silicone mold usually allows more than 100 moldings to be produced if moderate pressures, i.e., less than 5 bar, are applied during filling [27]. Hence, the original model may also be used for the production of larger series.

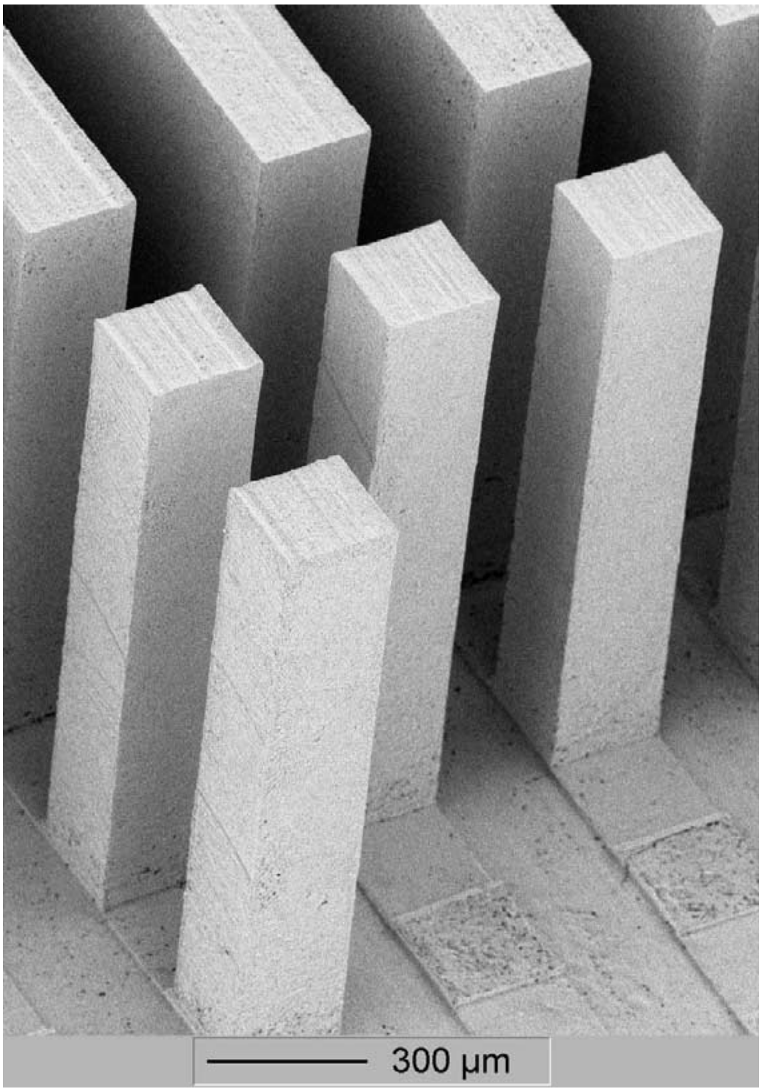
6. Manufacture of ceramic microcomponents

The processes developed in the past for the shaping of complex ceramic parts in the millimeter and micrometer ranges differ in terms of manufacturing expenditure, design freedom, and achievable aspect ratio. But



(a)

Figure 4 Sintered zirconia columns, prepared by molding of 50 vol% feedstocks with high viscosity (powder F, (a) and low viscosity (powder B, (b). *(Continued.)*



(b)

Figure 4 (Continued.)

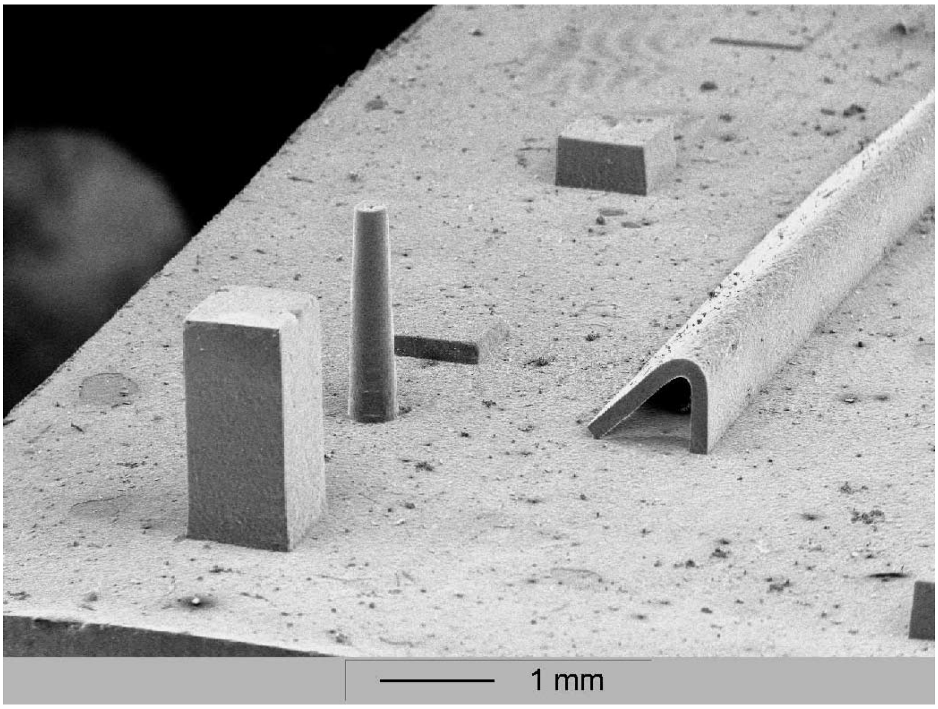
they all have in common that production is based on a powder-technological molding process using a negative mold and subsequent thermal compaction [28]. This results in three major limiting conditions. Firstly, replication always requires a mold with dimensions that already take into account component shrinkage during sintering. Secondly, molding has to be a net shape forming method, as for microcomponents subsequent finishing of the structural details is usually impossible. And as a third, a demolding step is necessary where the green body is separated from the mold. Due to the sensitivity of the details of microcomponents frequently this phase is of crucial importance for the success of the molding process.

In slip pressing [29], centrifugal casting of aqueous slips [30], and sol-gel casting [31] a ceramic slip is molded into a tool of plastic or wax. This mold is then used as a sacrificial "lost mold" i.e., removed chemically or by burning out after shaping. Processes with an increased mechanical load of the molding tool, e.g., high-pressure injection molding of ceramics (HPIM) [32] or tape casting and stamping [33], require metal tools, from which the ceramic green compact has to be mechanically separated prior to thermal treatment. Especially ceramic injection molding (CIM) has been demonstrated to be a rather versatile method for the production of ceramic microcomponents [34].

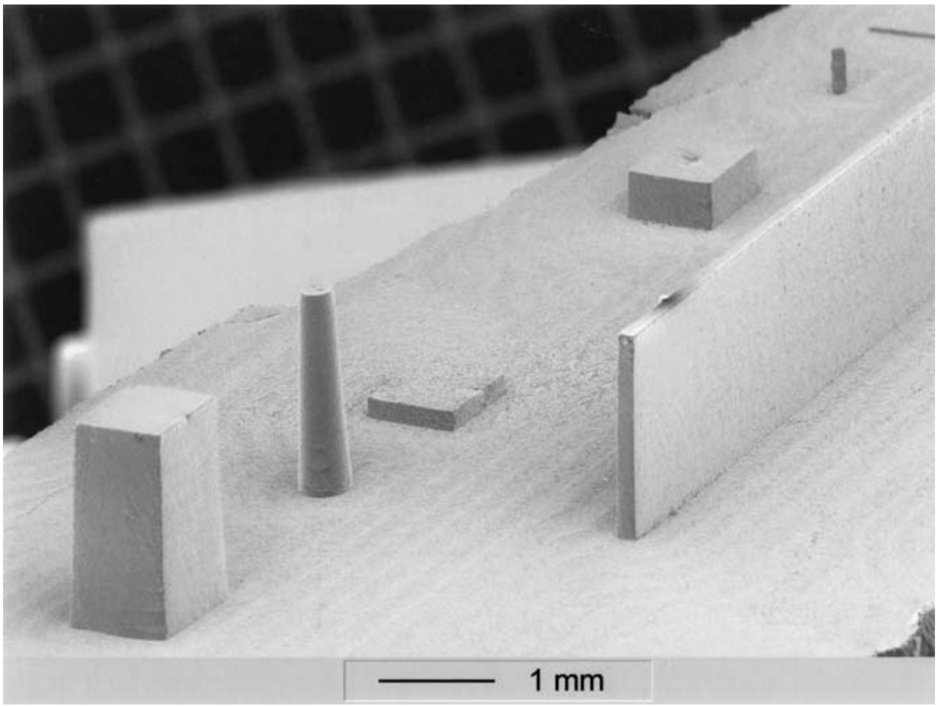
The selection of shaping methods is strongly limited if soft molds are used. In this case only methods will be qualified which can be performed with low loads and at low pressures. Examples which have been proven to be suited for silicone rubber molds are e.g., low-pressure injection molding (LPIM), centrifugal casting or hot casting. These methods have in common that they are based on the use of low-melting waxes and paraffins which allow molding at temperatures below 100°C and at pressure loads significantly below 1 MPa [35]. Therefore, they enable the use of plastic molds as well as molds made from silicone rubber.

Due to a simple feedstock preparation, LPIM, centrifugal casting and hot casting may be applied easily and rapidly to various ceramic materials. Feedstocks have been produced from Al_2O_3 and other materials, e.g., ZrO_2, $BaTiO_3$, PZT, hydroxyapatite, and an electrically conductive Al_2O_3/TiN ceramic [27]. For the preparation of the feedstock, paraffin and one or more dispersants are molten and mixed with the dried ceramic powder in a heated sigma kneader. Solid contents for standard powders are in the range of 50 vol% to 72 vol%. A still low viscous alumina feedstock, for instance, consists of about 68 vol% ceramic powder (Martinswerk MR52, mean particle size 1.2 μm) and about 32 vol% organics [23]. The later consist of paraffin and 0.5 wt% (based on the feedstock) of a suited dispersing agent. For submicron zirconia powders currently the solid contents are in the range of 50 vol% to 55 vol%. Significantly higher solid contents can be reached if selected powder blends are prepared. By that technique solid contents up to 82 vol% for a silica powder has been described in literature [36].

After demolding, the paraffin is removed from the green parts by a slow multistage heating process up to 500°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. In general, microcomponents allow faster heating rates than macroscopic parts due to the smaller cross sections. Whereas for the debinding of larger parts usually a powder bed is used for the removal of the molten paraffin, this support can be abandoned for small pieces.



(a)



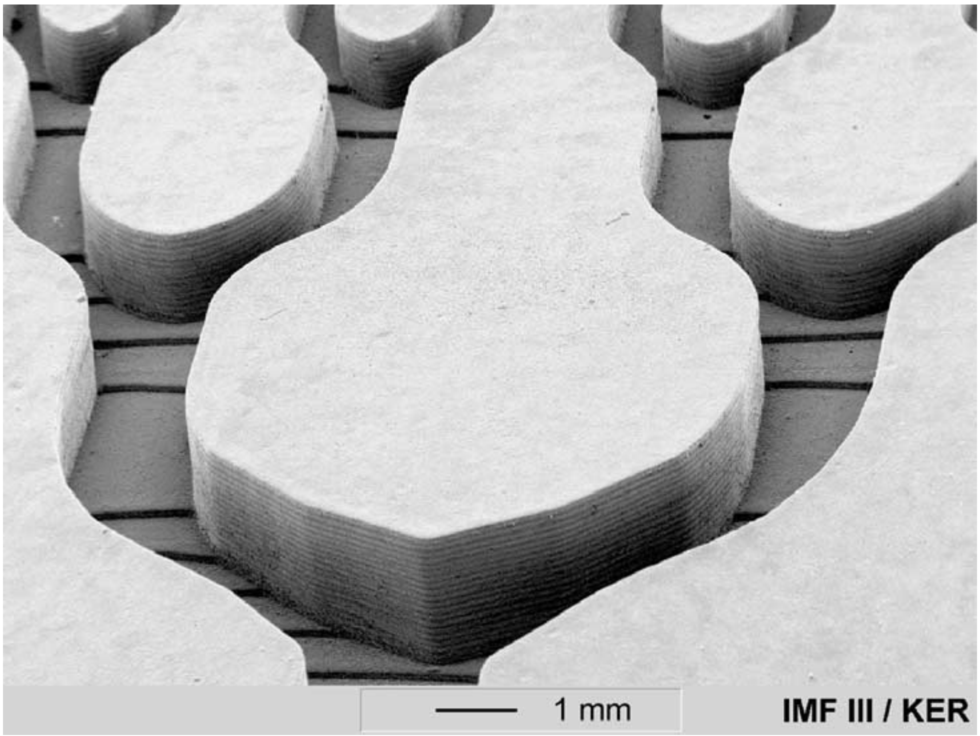
(b)

Figure 5 Overturning wall during debinding of an alumina feedstock (a) and dimensionally stable details for a zirconia feedstock (b).

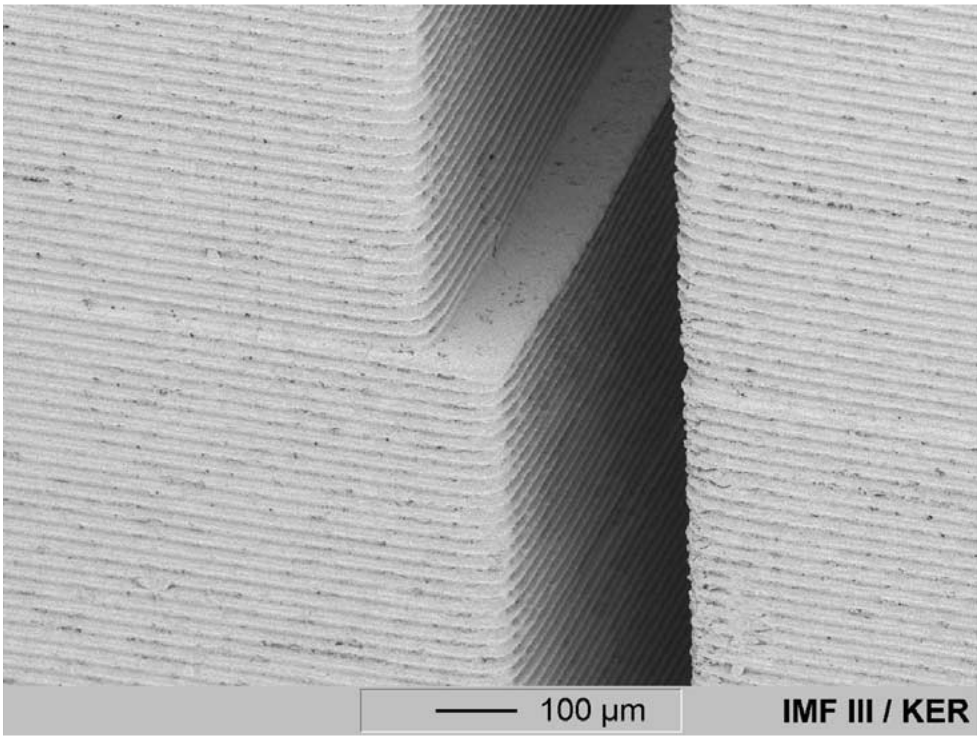
Fortunately, for these parts the usage of a porous plate is already sufficient as particles from the powder bed may hamper the shrinkage of holes and trenches and consequently induce crack formation within thin walled structures. Total duration of the thermal treatment is in the range of 20 to 40 hours. Linear shrinkage of the prepared parts amounts from 12% to 20%, depending on the used feedstock.

6.1. Low-pressure injection molding (LPIM)

In contrast to high-pressure injection molding, where the feedstock is plasticized by thermoplastics of high viscosity, low-pressure injection molding (LPIM), which is also called hot molding, uses waxes and paraffins as binders [37]. This allows injection pressures below 0.5 MPa and feedstock temperatures below 100°C. Although the strength of a LPIM green body is lower



(a)



(b)

Figure 6 (a) Alumina part with surface structure affected by the stereolithography model, (b) detailed view of a zirconia component, replicated from an RMPD model.

compared to high-pressure injection molding, it has already been demonstrated that LPIM feedstocks are suited to mold finest details and structures with high aspect ratios [38].

The silicone molds are mounted into commercial LPIM facilities from Peltsman Corp. (Minneapolis, USA) or GOCERAM I. V. (Moelndal, Sweden) (Fig. 2). Due to the elasticity of the silicone mold, it is required to adapt the machine and process settings in order to ensure sufficient dimensional accuracy. To obtain a complete filling of the mold for complex shaped microcomponents, prior to injection the tool has to be evacuated and the mold has to be heated to a temperature that exceeds the melting point of the paraffin. Finally, the holding pressure has to be released before a solid green object is produced by mold cooling.

6.2. Centrifugal casting

The same feedstocks prepared for low-pressure injection molding can normally also be used for centrifugal casting. In centrifugal casting the feedstock is not driven into the mold by air pressure or by a piston but by centrifugal forces. The used method resembles therefore the investment casting of metals. In contrast to the centrifugal casting performed in aqueous media, where a complete deposition of the particles and the separation of the media take place [30], during the centrifugation of feedstocks no sedimentation of the powder should occur. Any segregation of the ceramic powder in the high viscous feedstock would cause variations in the green density and hence, warping of the part during sintering.

The filling of the molds is performed at rotational speeds below 3000 RPM, respectively 2000 g. Thermal isolation of the mold and short centrifugal times below 2 minutes ensure that the feedstock temperature remains above the melting point of the binder during the complete centrifugation procedure. The silicone mold has therefore the opportunity to reduce tensions and to obtain the correct size.

Centrifugal casting is of interest for prototypes because no additional machine volume has to be filled. Only a small amount of feedstock for the mold volume is necessary, reducing also the time and cost for the feedstock preparation. Additionally no evacuation equipment is required as the entrapped air is displaced by buoyancy due to the higher density of the slip.

6.3. Hot casting

Feedstocks with a remarkably low viscosity can be prepared from selected powders. With these feedstocks a simple casting process with small powder quantities and without the need of machines is possible. In case of this procedure the silicone molds were manually filled from beakers heated up to temperatures of 80–100°C. The molds are also heated and 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 handled with this method [23]. For these high solid contents the sintering shrinkage of the ceramic is low enough to ensure good accuracy.

7. Results

7.1. Feedstock properties

For the feedstock preparation a low viscosity and a low yield strength are desired because these properties support both the filling of the mold and the removal of air bubbles from the feedstock. Rheological properties

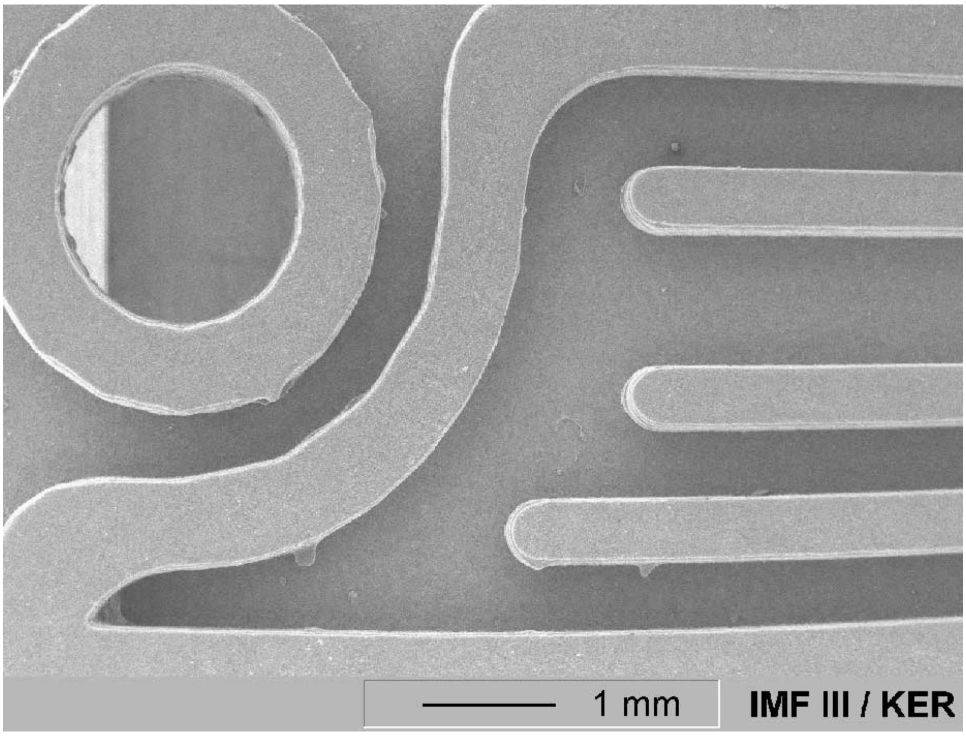


Figure 7 Detail of an alumina sample from a low resolution STL data set.

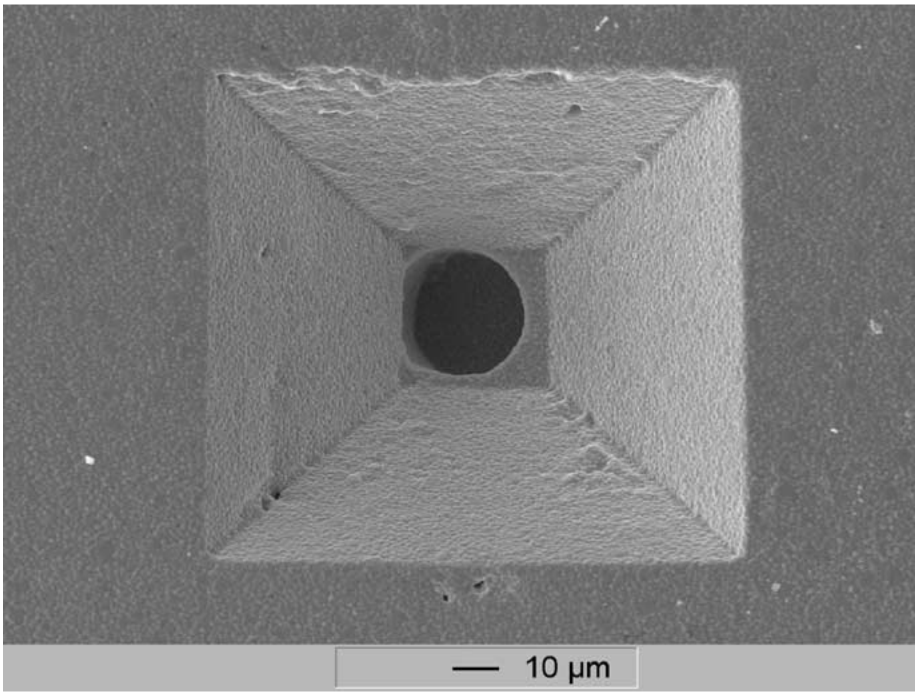
TABLE I Properties of used ZrO_2 powders

	Powder	Stabilizing oxide	d_{50} (μm)	BET surface (m^2/g)
A	Unitec M3.5-5 PSZ	3.5% MgO	1.13	4
B	SEPR YZ01	3% Y_2O_3	0.55	8.5
C	Tosoh TZ-3YS-E	3% Y_2O_3	0.63	6.6
D	Tosoh TZ-3YS	3% Y_2O_3	0.59	6.6
E	Mel Melox 3Y	3% Y_2O_3	0.60	8
F	Tosoh 3Y-E	3% Y_2O_3	0.57	16

are strongly dependent on the used powders and surfactants. To demonstrate the influence of the powder properties, small samples of zirconia feedstocks have been mixed at 85°C using a dissolver stirrer. The characteristics of the powders used are shown in Table I. At a solid content of 50 vol%, approximately 0.4 to 1.5 wt% (based on the feedstock) of a dispersant has been added to the feedstock, depending on the specific surface of the powders. Within a temperature range of 70°C to 100°C, the flow behavior of the feedstocks can be described as liquid up to paste-like fluids. The viscosity was measured by a viscometer in the shear stress controlled mode using a plate-plate geometry (Physica MCR 300). Within the range of 0.01 to 10 1/s the viscosities differ significantly although the mean particle size and specific surface area are often very similar (Fig. 3). Different particle size distributions, different particle morphologies or different surface chemical groups may be responsible for this observation. Not included in Fig. 3 is powder F as it has a distinctly higher viscosity and no acceptable viscosity measurement could be obtained with the used viscometer equipment. Although the mean particle size is comparable to the other zirconia powders, the large specific surface suggests that it is an agglomerate of a finer powder.

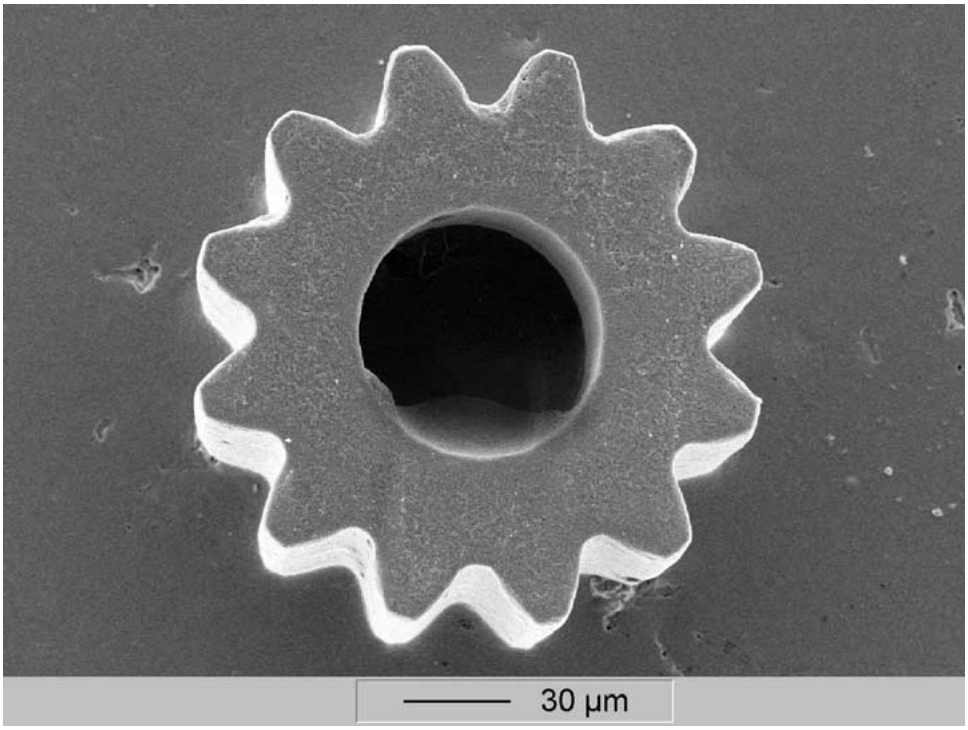
Fig. 4 shows sintered micro columns which were molded from zirconia feedstocks. Centrifugal casting was used for shaping as the available feedstock amount was too small for injection molding and the viscosity of some feedstocks was to high for hot casting. With the used mixing equipment complete homogenization of high viscous feedstocks was hardly obtained, hence powder agglomerates remain in the feedstock producing a coarse surface and inaccurate outlines (Fig. 4a). A high porosity can be seen in the ceramic part as well. These pores were produced during the stirring of the feedstock in an open, non-evacuated beaker. They cannot be removed from the feedstock even by multiple evacuation prior to and after the centrifugation. Moreover the buoyancy forces during the centrifugation are too weak to effect a rising of the bubbles as the high yield point of the viscous feedstock prevents their movement. Applying higher rotational speeds may enhance the buoyancy forces but will also cause sedimentation of the particles, which would result in warped parts after sintering. In contrast to that, a low viscous feedstock can be better homogenized and released from agglomerates and bubbles. Such feedstocks show a high surface quality and sharp edges (Fig. 4b). The replication ability is so excellent that even the surface scratches of the metal model were reproduced on the sintered ceramic.

Another aspect that becomes considerable for high aspect ratio microcomponents is the softening behavior during the binder burnout. A high strength at this stage is necessary to prevent the distortion of exposed details by gravity or surface tension forces. In Fig. 5a the alumina sample shows an overturning wall due to softening during the debinding step. Deformation cannot be seen in the corresponding zirconia sample (Fig. 5b), although this feedstock has the lower solid content. Both feedstocks show comparable viscosities due to the



(a)

Figure 8 Zirconia replications of silicon etched models: (a) nozzle and (b) gear wheel. (*Continued.*)



(b)

Figure 8 (*Continued*).

lower particle size of the zirconia powder. At the moment an explanation for this behavior cannot be given, a quantitative description must therefore be part of further investigations.

8. Precision and limits of the shaping process

As a whole, the replication steps of the rapid prototyping process chain exhibit a high precision and accuracy in the micrometer range. Measurements with regard to the reproducibility of the dimensions of structural details yielded a standard deviation of 0.2% to 0.3% for parts with a typical specimen size of approximately 15 mm if a feedstock with a solid contents above 60 vol% is used. For solid contents of about 50 vol% the standard deviation is still between 0.5% and 1%.

Of decisive importance for the accuracy of the process is the quality of the RP model. The achievable resolution and surface quality are mainly limited by the layer structure of the RP part, where each inclined area

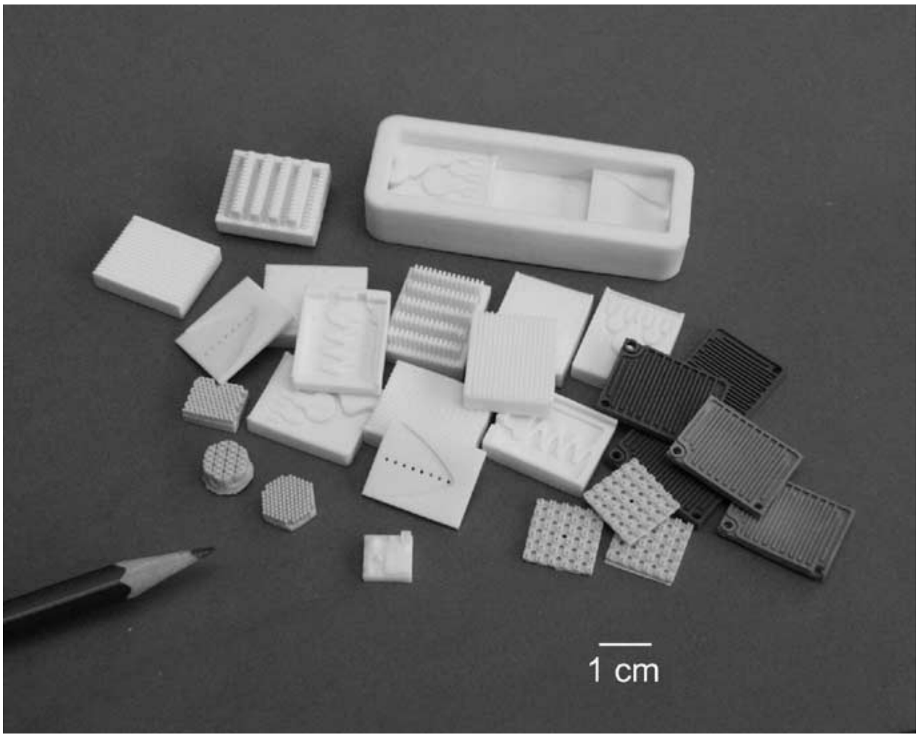


Figure 9 Examples of ceramic microcomponents.

of the component is approximated by steps. In addition, the layered structure of the original mold is reflected by periodic depressions on the vertical walls and inclined regions (Fig. 6a). The higher the selected layer thickness is, the coarser is the reproduction of contours in the ceramic component. Reducing the layer thickness, as can be performed by microstereolithography, may improve the surface and the contours but this will also increase the building time and the cost of the model (Fig. 6b). As compared to the layer structure, the grain size in the sintered ceramic part can be neglected.

The STL data format, which is the standard format for rapid prototyping, approximates the contours of the volume model by triangles. With improved resolution the number of triangles increases and, hence, the multitude of data. If the number of triangles is chosen too small, the resolution is low and curves are represented by polygons, as can be seen in Fig. 7.

The potential of the molding process is demonstrated by using high resolution models, prepared by LIGA or by silicon etching techniques. Details in the range of 10 μm can be shaped with this technique (Fig. 8). The aspect ratios that can be achieved, depend on the original model used. When using models of high surface quality, e.g., LIGA components, aspect ratios of more than 10 can be reached. In contrast to this, the much rougher surfaces resulting from the layered structure of rapid prototyping models considerably aggravate demolding at vertical walls with aspect ratios of >5 due to the relatively high friction forces. Even when silicone molds are used, the demolding of high aspect structures is still a risk for wall thickness below 100 μm. Due to the elasticity of the material the mold is in intimate contact to the shape even after some shrinkage of the green body. During the separation of the mold tensile or bending stresses are applied to the green body. For small cross sections this load may lead to damage of the structure. Since the demolding step is carried out manually, experience and skill also influence the performance. For cross sections below 100 μm and aspect ratios in the range of 10 and above, the use of suited sacrificial molds may be a more promising approach.

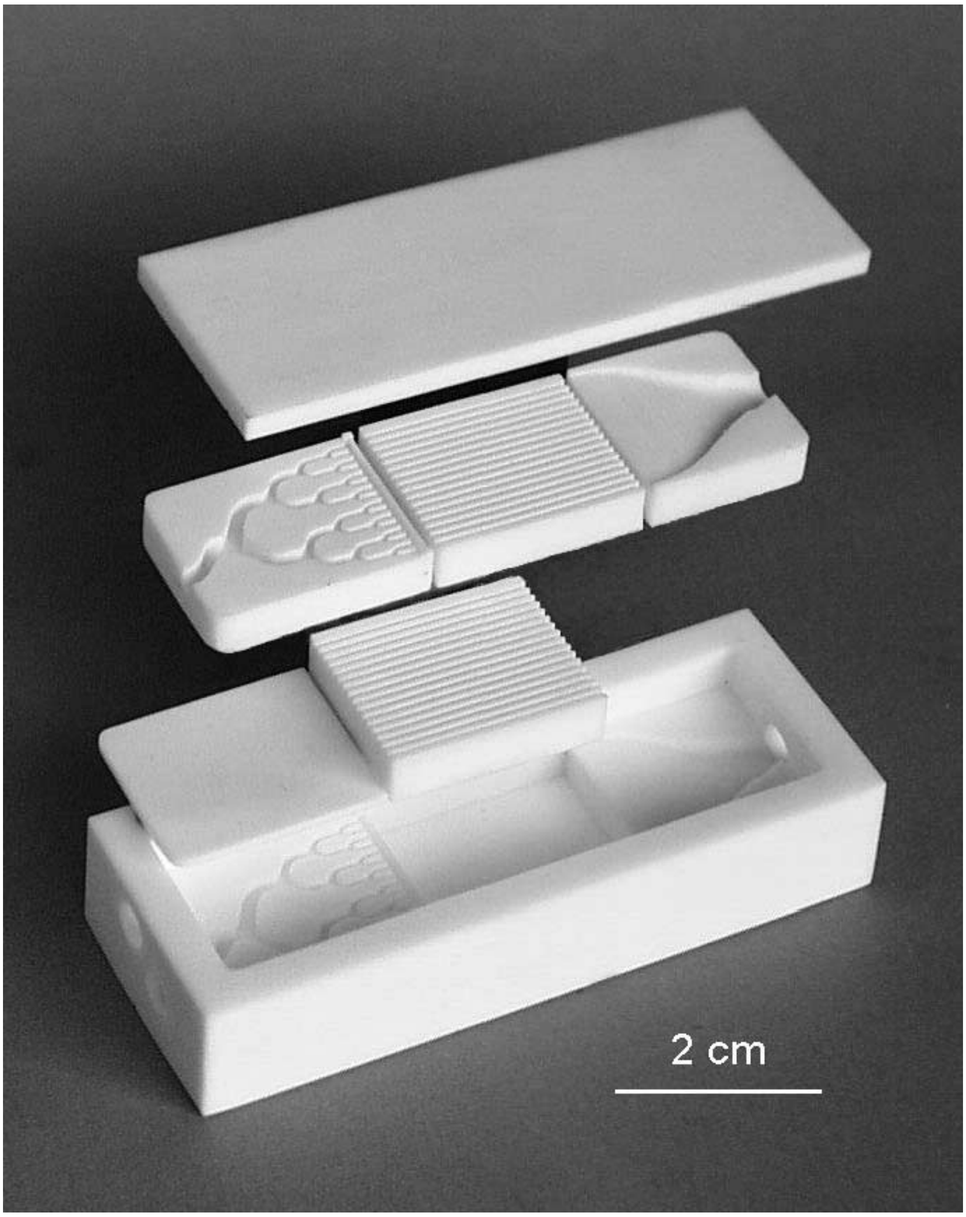
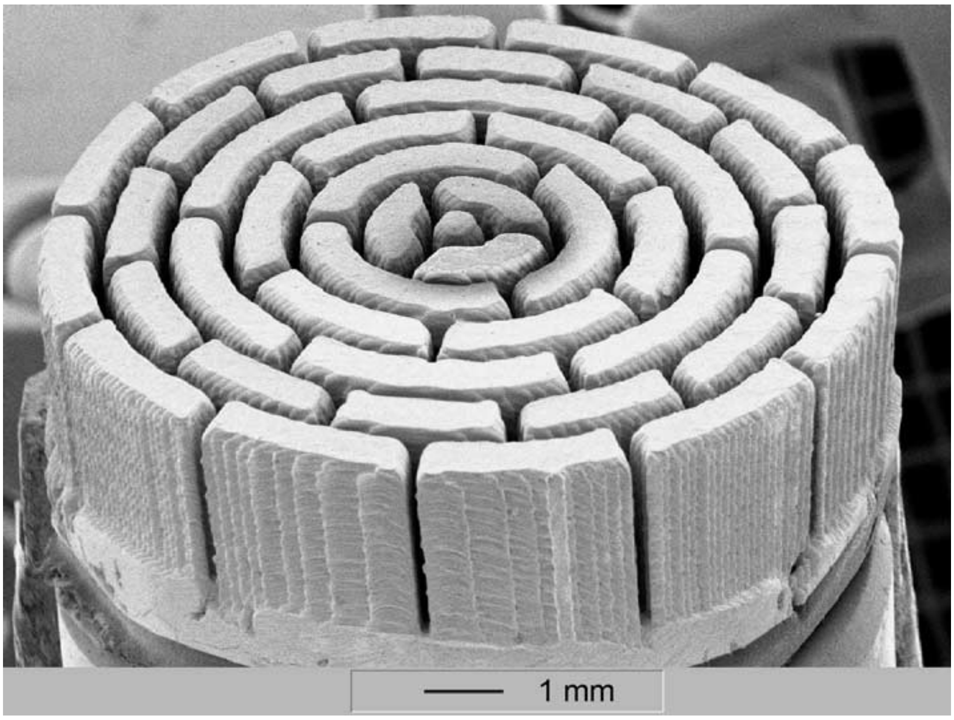


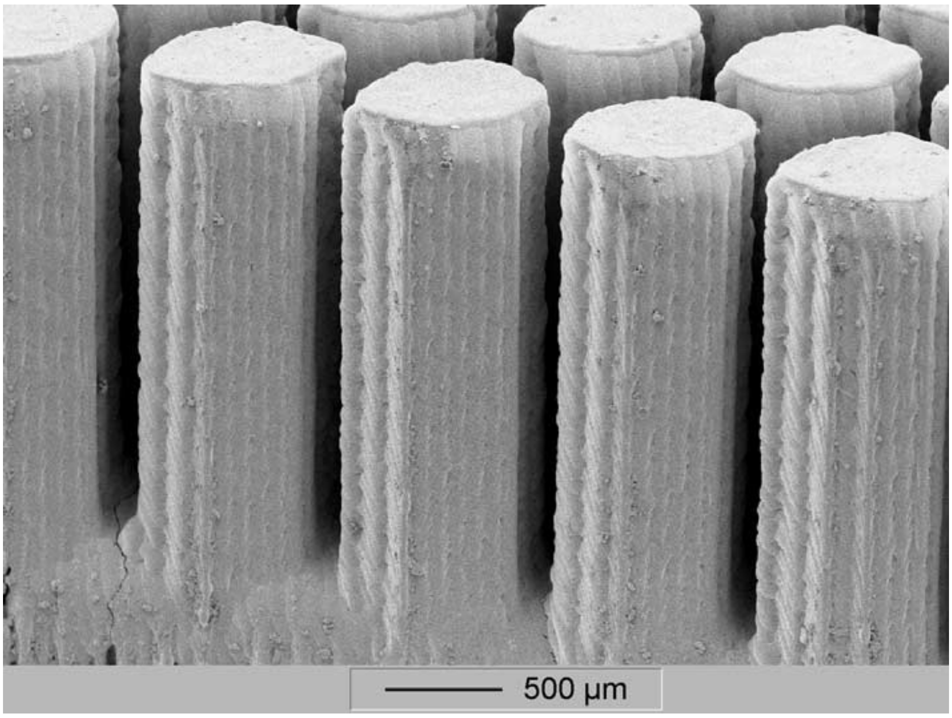
Figure 10 Modular ceramic microreactor. Individual parts are made from alumina, shaped by a RPPC. (The reactor housing has a length of 68 mm).

9. Examples

A variety of ceramic components were fabricated from different materials and for various applications (Fig. 9).The advantages of the RPPC, i.e., the rapid and flexible fabrication of master models, can be illustrated by a ceramic microreactor for use in microreaction technology (Fig. 10) [39]. Whereas metal microreactors have already proved to work successfully, comparable ceramic components for very high temperatures or corrosive conditions are still lacking, and a novel, material appropriate design had to be established. For the design development and due to the desired modular character of the reactor, a variety of molding tools was needed. As the final design cannot be verified on design models, but only under operating conditions, the manufacturing of functional models was indispensable. Moreover, a fabrication technique had to be chosen that met the requirements for the molding of the relatively large reactor housings as well as of the micropatterned details of the modular components. Without the use of



(a)



(b)

Figure 11 PZT transducer preforms, developed for a biometric system (fingerprint detection).

the rapid prototyping process chain, this development had not been possible within a reasonable period of time and at acceptable costs.

Another example for the beneficial use of the RPPC was the development of piezoelectric transducers which are used in a fingerprint identification system. For that purpose the polish company Optel managed to create a transducer which has a completely new design. The transducer is able to emit very short pulses (in the range of 20 ns) and has very wide bandwidth as receiver (ca 4–25 MHz) [40]. For the optimization of the design various models have been fabricated by MJM and afterwards replicated in lead titanate zirconate (PZT) by hot casting. By this technique shapes could be realized which are not feasible with a standard dicing process (Fig. 11).

10. Outlook

Usually the development of ceramic products is an iterative process, characterized by the evolution of models and prototypes. If a fabrication by generative processes is not possible, for each cycle new molds are required. Additionally, the progress in the development of ceramic feedstocks may require new dimensions of the molding tool if an alteration of the shrinkage behavior takes place. While in the past, feedstock development had to be completed before an expensive molding tool was ordered, RPPC allows simultaneous adaptations of feedstock and design and allows the production of new prototypes within a period of a few days.

Further developments in the rapid prototyping of microdimensional parts can be expected within sight. The largest progress may be presumed for polymer materials and each improvement can be integrated into the RPPC immediately. If an advanced stage of resolution and reliability is reached by generative processes for the direct production of ceramic microcomponents, they may represent an interesting alternative to the process chain, which is presented here. As the time-determining step of both processes is the thermal treatment, however, time reduction will be relatively modest. Furthermore, the direct processes will have a lower flexibility for the introduction of new materials and they not always allow for economically efficient production of larger series of components.

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