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TECHNICAL PAPER

Design and prototyping of a ceramic micro turbine: a case study

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Abstract Within the framework of the Collaborative Research Center 499 (SFB 499) of the German Research Foundation (DFG), one task was the development of a zirconia micro turbine as a demonstrator tool to enhance the interaction of the participating workgroups. This case study describes the evolution of the demonstrator and experiences gained with the design and the manufacturing of a micro device. Although it was not the aim of this basic research project to develop a commercial product, the experiences are valuable for improving the performance of industrial product development processes for ceramic micro devices. The various parts of the zirconia micro turbine were prepared by a rapid prototyping process chain (RPPC) that allows for a fast and inexpensive manufacturing of ceramic parts with details down to the micron range. A first design concept was made to mainly demonstrate the shaping feasibility of the process in the micro range. However, some features affected the performance due to their low loading capacity. Thus, a modified design was improved for power output and durability. After optimization of the process chain, dense and homogenous ceramic micro parts could be manufactured. These parts were used for the assembling of a functional micro turbine demonstrator, which was powered by compressed air.

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1 Introduction

The Collaborative Research Center 499 (Sonderforschungsbereich 499, SFB 499) “Development, production and quality control for molded micro components made of metallic and ceramic materials” was established by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) in the year 2000. Participating research institutes come from the Karlsruhe Institute of Technology [KIT, former Universität Karlsruhe (TH) and Forschungszentrum Karlsruhe] and from the Universität Freiburg. It is the aim of the SFB 499 to work out the scientific basics for the development of a continuous and stable process chain for the mass production of molded micro components made of metallic and ceramic materials (Spath et al. 2003; Anon 2009). This includes the design, the manufacturing and an attendant quality management of micro components. The core competencies of the SFB 499 consist of the production techniques powder injection molding (PIM) and micro casting. PIM can be used for the manufacturing of complex 3-D metallic or ceramic micro components, while micro casting is used for metallic micro components, exclusively.

Demonstrator systems were defined to link the individual projects of the Collaborative Research Center. Although it was aspired to build functioning systems, one always has to bear in mind that it is not the mission of the project to develop commercial products with competitive costs and optimized functionality. The purpose of a demonstrator was rather to represent a physical interface which allows to optimize the cross-linking between workgroups and to integrate a variety of manufacturing challenges into a single system. The demonstrators should be used to demonstrate the problems which arise from assembling a complex system instead of manufacturing only individual components. With the help of the demonstrator it was possible to detect restrictions and to cross frontiers in the micro fabrication processes for ceramics and for metals.

One sub-system of the demonstrator system is a micro turbine that drives a planetary gear set. This paper is focusing only on the micro turbine sub-system. It presents a case study which summarizes the experiences which were gained with the design and the manufacturing of the turbine components by a prototyping method and the assembly of the components to the final device. Restrictions and problems which were identified in the manufacturing and handling of a first design concept lead to a design evolution and to progresses in the manufacturing processes.

2 Design of the micro turbine demonstrator

Designing micro parts is different from macroscopic design tasks. From the macroscopic point of view, the detailed design is usually one of the last steps. The design of micro parts deals from the beginning with the question what is feasible with available manufacturing methods. Even more than in other design tasks the limitations and restrictions for the design possibilities come from downstream process steps (Albers et al. 2007a, b; Albers and Metz 2006). Therefore, it is important to stay in close contact to the other process disciplines and to start testing and simulating very early. First concepts are needed to validate the details in the design of the parts.

Design guidelines that might support the development process of the fluidic components of a turbine are generally known for large systems, but lacking for the micro range. Although it is not certain that it will be valid for the aspired size range, the design is mainly based on experience gained in the macro range. Another aspect that influences the design is the specific purpose of the demonstrator. The integration of demanding features was necessary to reveal manufacturing limits and to demonstrate deficits in the practicability of assembling strategies.

Figure 1 shows a design scheme with the demonstrator components. The system consists of a perforated plate with media inlets and outlets, the rotor, nozzle plate and a gear wheel for power output. All rotating components should be fixed on a central shaft. An outer diameter of 4 mm was intended for the final, air-driven system.

Two concepts of the demonstrator device are presented. In concept 1 especially the micro dimensions of the rotor wings and nozzle channels were challenging for the molding process. The single parts of the micro turbine were

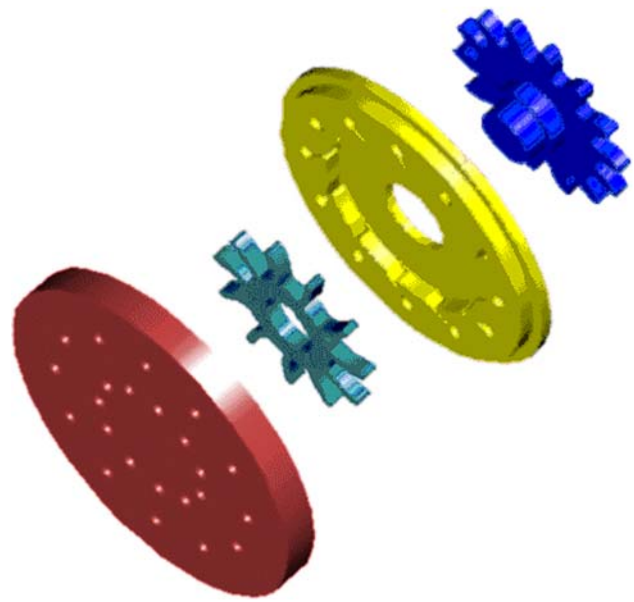

Fig. 1 Exploded assembly drawing of the micro turbine demonstrator device consisting of perforated plate, rotor, nozzle plate and a gear wheel that is already merged with the shaft

manufactured individually and were assembled afterwards. For this reason a shaft-hub joint connecting rotor and gear wheel's shaft was needed enabling torque transmission. A cylindrical interference fit was used to explore its possibilities in micro system design and because of its very simple geometry that is quite easy to manufacture. Nevertheless, subsequent development phases posed grave problems that inhibited to use this kind of shaft-hub joint further on and lead to a re-design of the demonstrator, see concept 2.

A cylindrical interference fit transmits torque by friction forces in its working surface pair by radial pre-tensioning of shaft and hub. In order to produce this type of joint, two challenging demands had to be fulfilled. On the one hand, if the hub is made up of brittle materials like ceramics, very small geometrical tolerances must be maintained to avoid disruption. On the other hand, shaft and hub demand a complex handling during assembly; either a high axial force must be applied to fit both parts or thermal expansion is utilized by heating up the hub or cooling down the shaft, respectively. The comparatively small thermal expansion coefficient of ZrO_2 would lead to very hot or very cold parts which makes handling even more complicated. The difficulties of both demands were underestimated in the beginning and they could not be satisfied.

In concept 2 the assembling effort was reduced by combining the two separate parts "gear wheel" and "shaft" from concept 1 into one single part and by replacing the interference fit between rotor and gearwheel shaft with a form fit connection. The cross-sectional shape of the form

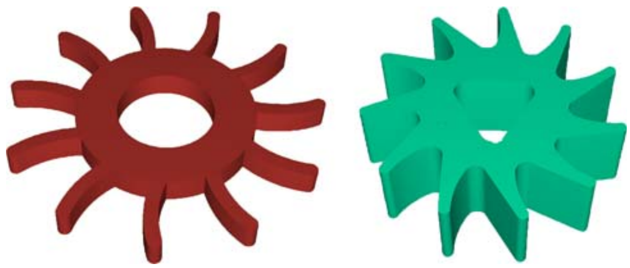

Fig. 2 CAD drawings of the rotor concepts (*left* concept 1, *right* concept 2)

fit connection used in concept 2 was an equilateral triangle with rounded edges. This shaft-hub joint is easy to manufacture because of its simple geometry and moreover it is easy to assemble because a clearance fit can be permitted without losing the joints ability to transmit torque. The main functional disadvantages of this shaft-hub joint in comparison to an interference fit connection are a higher backlash, locally higher stresses and a higher eccentricity, but with regard to manufacturing and assembly this shaft-hub joint is a much better choice.

Further improvements are expected by developing other types of shaft-hub joints for micro systems, e.g. the modification of the triangular form fit junction as a 3G-polygon. This special shape is expected to bring improvements in regard to backlash, maximum stresses and eccentricity while keeping the assembling benefits.

Additionally, the rotor wings were enlarged in width and height for improved loading and for higher torque output (Fig. 2). The exact shape of the rotor wings was determined by applying a shape optimization based on a modified finite element analysis that was adapted to be able to represent micro specific effects (Albers and Enkler 2009). This optimization considered anisotropic material characteristics as well as deviations of the rotor wing's geometry caused by the manufacturing processes to make the design more robust against these statistical effects.

Results and experiences gained during the (re-)design of the turbine were abstracted, formulated in design rules and stored in a wiki-based knowledge management system to support the development of micro products in future (Albers et al. 2007a, b).

3 Manufacturing by ceramic injection molding

Ceramic injection molding (CIM) was established as a standard process for the manufacturing of complex micro patterned ceramic parts (Piotter et al. 2000; Haupt 2009). There are two variants of ceramics injection molding, the widely used high-pressure injection molding (HPIM) process (Piotter et al. 2001) and the less common low-pressure injection molding (LPIM) process. While the potential of high-pressure injection molding lies in cost-effective mass production, low-pressure injection molding is predestined for the fast manufacturing of small production lots (Bauer et al. 2002; Bauer et al. 2005). One reason for the positioning of HPIM for mass production is the high costs associated with the manufacturing of the molds. This makes the process only profitable when a large number of parts are molded. On the other hand, LPIM can work with simple and inexpensive molds and is even economically for small series. Both variants complement each other in an ideal manner and cover the entire range from one-off prototype to mass production.

A central objective of SFB 499 is the development of a processing technique adapted to the manufacturing of middle and large series. Therefore, HPIM takes up a central position in the project. On the other hand, the demonstrator systems consist of a large number of individual parts. Manufacturing the complete demonstrators by HPIM would produce large costs for the required molds. Thus, it was decided to limit the application of HPIM to the molding of specific parts, mainly for the planetary gear set, and to establish a prototyping project based on LPIM for the other parts, including the manufacturing of the complete micro turbine.

4 Prototyping of ceramic micro components

During the last 20 years a variety of different rapid prototyping (RP) or solid freeform fabrication (SFF) methods for the fast manufacturing of models and prototypes were developed in the macro world. They are mainly generative methods, like stereolithography or laser sintering, enabling the production of 3-D parts directly from the 3-D CAD data. Originally developed for polymer materials, meanwhile, numerous methods also exist for the production of large ceramic models (Heinrich 1999; Tay et al. 2003). On the other hand, SFF of ceramic micro parts is still limited with regard to accuracy and materials variety. The principle feasibility of expanding SFF methods to the manufacturing of small ceramic parts was demonstrated for stereolithography or ink jet printing (Bertsch et al. 2004; Wang and Derby 2005), but difficulties in the preparation of suited dispersions limit the applicability to a few materials only. The missing availability of commercial equipment additionally prevents a wider proliferation of the technique.

The current restrictions of RP methods in the micro range can be overcome by a rapid prototyping process chain (RPPC), where a primary model is manufactured from a polymer or metal material and then replicated into the requested ceramic material (Fig. 3; Knitter et al.

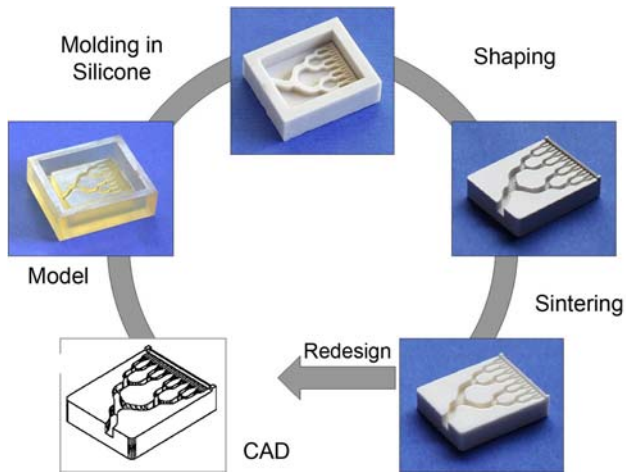

Fig. 3 Schematic representation of a rapid prototyping process chain (RPPC) for the production of ceramic parts

2001). While most of the replication was done using LPIM, the shaping step can also be performed by centrifugal casting or by hot casting (Bauer and Knitter 2002). Micro stereolithography is particularly suited for the fabrication of micro patterned polymer models. Primary models can also be manufactured by micromechanical machining of polymers or metals which is described later in this paper.

The second step of the process chain is the fabrication of a mold suited for LPIM. Using molds from silicone rubber has proven to be advantageous as silicone rubber is characterized by an excellent reproduction ability of the finest structures; even details in the sub-micrometer range are replicated. The elasticity of the silicone rubber is not only favorable for the extraction of the primary model but also for the subsequent removing of the soft green body. This makes it possible to de-mold also fragile details and vertical walls with high surface roughness, as they are often characteristic for RP methods. Even undercuts can be removed without a complex tool design due to the compliancy of the material. However, this compliancy makes some demands on the control of the LPIM process. To avoid discrepancies in the dimensions of the part, it must be guaranteed that the molding process ends in a stress-free state. Deformations may also occur due to the weight of the green body, but this problem is usually negligibly for micro parts. Another challenge is the high thermal expansion of the silicone rubber. For the production of precise parts there are high demands with respect to temperature control during hardening of the silicone rubber as well as during the shaping process. On the other hand, varying the curing temperature enables an uncomplicated size adjustment for individual parts. Silicone rubber molds can withstand a large number of moldings, as long as the mechanical loads remain in a moderate frame. According to experience, a minimum batch of some 100 turbine parts can be manufactured by a single mold without problems.

Zirconia (ZrO_2) is proposed as the most promising ceramic material for micro components. It offers a fine grained microstructure and excellent mechanical properties. Additionally, for micro parts the high costs of the material only play a minor role. For the micro turbine the zirconia powder TZ-3YS-E from TOSOH (Tokyo, Japan) was used. The starting powder has a mean particle size of less than 400 nm and a BET surface of 6–7 m^2/g. The powder was dispersed at a solid content of 52 vol.% in a commercial binder system (Siliplast LP 65, Zschimmer & Schwarz, Lahnstein, Germany) or at 50 vol.% in a mixture of a paraffin (TerHell 6403, Sasol Wax, Hamburg, Germany) and a dispersant (Hypermer® LP1, Croda Lubricants, Wilton, Redcar, UK). The dispersant was added to the paraffin with an amount of 2 mg/m^2 of the particle surface. The commercial Siliplast system already contains unpublished dispersing ingredients. Melting temperature of the binders is located at ~65°C. The preparation of the LPIM feedstock was performed in a heatable dissolver mixer (VMA Getzmann, Reichshof, Germany), resulting in a viscosity of 17 Pa s (at 85°C and a shear rate of 100 s^{-1}) for the Siliplast binder and a viscosity of 23 Pa s for the paraffin/Hypermer system.

For the manufacturing of the molds a two-component silicone rubber NEUKASIL® RTV 20 with a shore A-hardness of 50 from Altropol Kunststoff GmbH (Stockelsdorf, Germany) was used. At a temperature of 40°C cross-linking took place within 6 h, enabling the manufacturing of additional molds within short time.

The molding of the micro parts was performed in a piston-driven injection molding machine GC-MPIM-2-MA-X from GOCERAM Ltd. (Sweden). With this machine it was possible to work at injection pressures as low as 0.1–0.3 MPa to prevent distortion of the compliant silicone mold. A feedstock temperature of 95°C and mold temperature of 40°C was used. Prior to injection, the air was removed from the mold to prevent incomplete filling by entrapped gas. De-molding was performed manually. The process is promoted when the micro parts are molded on a base plate. This supports the mold-filling as the plate creates additional heat storage and thus reduces the risk of premature freezing of the feedstock. Furthermore, it works as a support to facilitate the de-molding of the fragile micro parts. The plate was removed by grinding before final sintering took place. At the beginning of the project, the micro parts were recast with wax or paraffin to protect them during machining. Later, they were pre-sintered for 1 h at 1,080°C. Thereby the strength of the parts was sufficiently increased to improve the handling without significantly aggravating the machining. In particular, the yield of the rotor parts was considerably increased by the pre-sintering procedure.

Standard de-binding procedures were performed up to 500°C at a rate of less than 1°C/min and dwell times at 150 and 240°C. For sintering a 3°C/min ramp up to 1,450°C and a dwell time of 1 h was used. For the thermal treatment, the micro parts were placed on a porous alumina substrate which could be heated up to 1,450°C, thus it was not necessary to transfer the sensible parts to another support after de-binding.

5 Prototyping of the micro turbine (concept 1)

Polymer models for concept 1 of the micro turbine were manufactured by the so-called RMPD® method, developed by microTEC (Duisburg, Germany; Götzen and Reinhardt 2005). This process allows the prototyping of polymer micro parts down to the micro range. In the RMPD technique thin layers of photo curable acrylic or epoxy resins are exposed via a mask. By stacking the layers, a 3-D micro part is formed. The layer thickness can be reduced down to a few micrometers, resulting in very smooth vertical surfaces (Fig. 4). But for reasons of time and effort usually a layer thickness of 25–50 μm is preferred. Lateral resolution is in the range of some micrometers.

The Siliplast binder system was used for the replication of the ceramic parts. Examples of sintered zirconia micro parts are shown in Figs. 5, 6 and 7. All structural details of the turbine design could be manufactured with the described method. The high precision of the replication process is evidenced by a complete replication of the layer characteristic of some polymer models into the ceramic micro parts (Fig. 5). However, at a closer look surface defects are revealed arising from insufficient feedstock homogeneity.

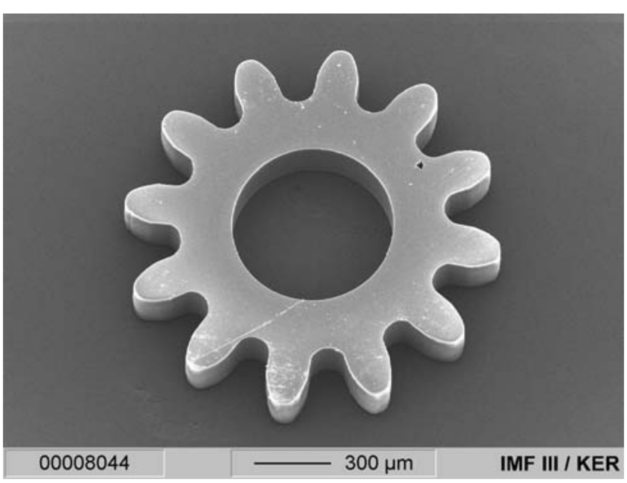

Fig. 4 Scanning electron microscope (SEM) micrograph of a polymer gear wheel made by the RMPD process

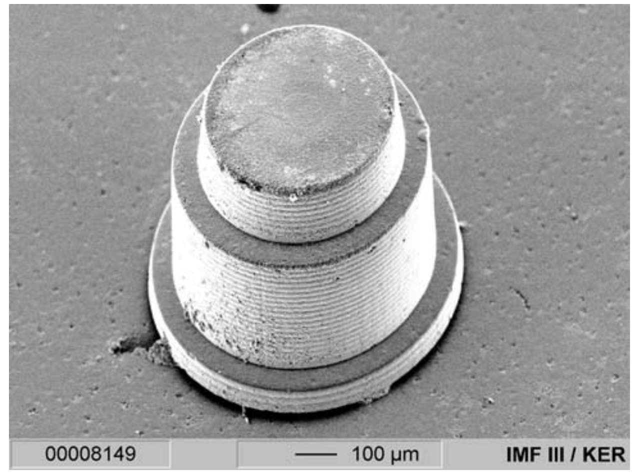

Fig. 5 SEM micrograph of the sintered zirconia turbine shaft

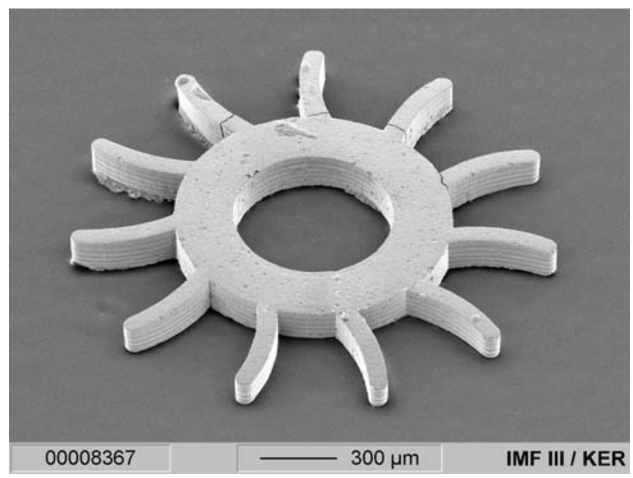

Fig. 6 SEM micrograph of the zirconia rotor. The cracks in the wings were introduced during SEM preparation

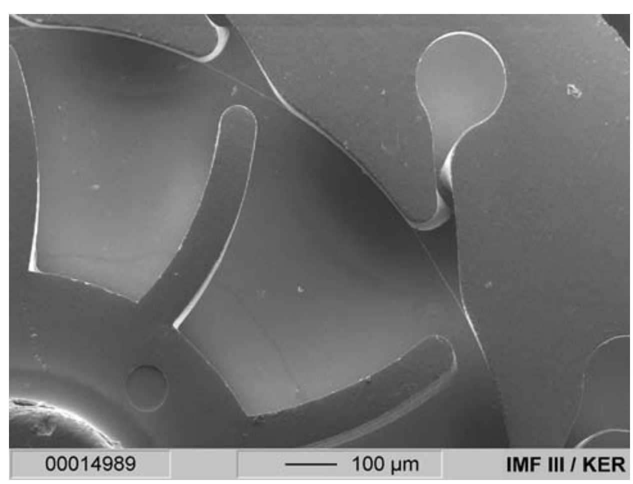

Fig. 7 SEM micrograph of the zirconia rotor within the nozzle plate. The twisted shape of the nozzle is caused by a distortion of the silicone mold during the filling with the high viscous feedstock

Table 1 Measurements of sintered ZrO_2 micro gear wheels

	Mean (μm)	Standard deviation (μm)
d_i	491	5
d_a	1,158	6
h	155	17

Direct measuring of the sintering density was not feasible with sufficient accuracy due to the low weight of the micro parts, but could be performed with parts where the base plate was not removed. The result was a mean sintering density of 97% of theoretical density (at a theoretical density of 6.10 g/cm^3) confirming the remaining porosity.

The precision of the micro parts is exemplarily demonstrated by the sintered gear wheel part. The shaft diameter (d_i), the addendum circle diameter (d_a) and the height (h) of the parts are given in Table 1. All values were measured on a dozen samples with an optical microscope.

With the exception of the height, a precision of better than 10 μm can be obtained by LPIM with silicone molds. Comparable values were achieved for the precision of the other components. For all samples, the relative precision seems to become lower for the small features. This is mainly due to the error of measurement, which was identified to be in the range of 3–4 μm for the used measuring equipment. Additionally, for very small features limitations will be caused also by the discrete grain size of the sintered ceramic (400–500 μm for the used zirconia). The lower precision of the height of the gear wheel has another reason. It results from the grinding of the base plate that was performed manually without precise process control.

All components were produced with a yield of more than 90%. The only exception is the rotor part (Fig. 6). Here problems arose from the sensitivity of the wings with a cross-section of only 150 × 80 μm. During de-molding, grinding of the base plate and other handling steps, wings broke off easily. This reduced the yield of this part to less than 20%.

The components were tested for assembly as described in chapter 2. However, even a small scattering of the diameters led to an insufficient fit of the components. For thin parts like the rotor even the overcoming of the wall roughness produced tensile stresses which were high enough to break the central ring. Due to this, the cylindrical interference fit could not be used for the assembly of the micro turbine. Alternatively some rotors were fixed on smaller axes with glue and turned from the outside via the gear wheel. The vulnerability of the design was so high that even a slight contact with the surrounding parts caused failure of the wings.

All components of the concept 1 were also prepared with the paraffin/Hypermer binder system. In this system the homogeneity of the feedstock is obviously improved as an enhanced sintering density of more than 99.6% of theoretical density and a reduced surface roughness were obtained. The linear sintering shrinkage was 20.6%. However, the viscosity of this feedstock is near the upper limit compatible with silicone molds. Although all structural details are replicated in the sintered micro part, frequently deformations can be seen at specific features like the channels in Fig. 7. During the filling of the mold, the silicone walls for the 40 μm wide channel structure were distorted by increased shear stresses within the feedstock, but this deformation does not affect the functional capability of the device.

6 Turbine design optimization (concept 2)

In concept 2 the design was optimized for better performance and for higher torque output by a new rotor profile and by increasing the height of the rotor from 150 to 800 μm. Gear wheel and shaft are a single unit and the connection between rotor and shaft was designed as a triangular form fit junction (Fig. 8).

All parts of concept 2 were prepared by the paraffin/Hypermer binder system only, due to the improved homogeneity and surface quality arising from this feedstock.

Models of the rotor and the nozzle plate for the concept 2 were manufactured again as polymer parts by the RMPD process. A challenge due to the new design was the increased height of the parts. With the layer based RMPD technique thick layers and an undulated vertical surface were produced for this sample height (Fig. 9). This aspect aggravated the de-molding of the parts drastically. Although the rotor could still be de-molded due to the

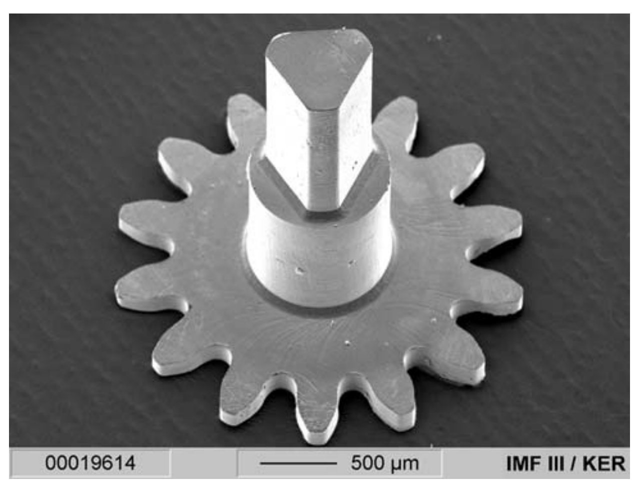

Fig. 8 SEM micrograph of the zirconia shaft/gear wheel combination (concept 2). The model was fabricated by micro milling of brass

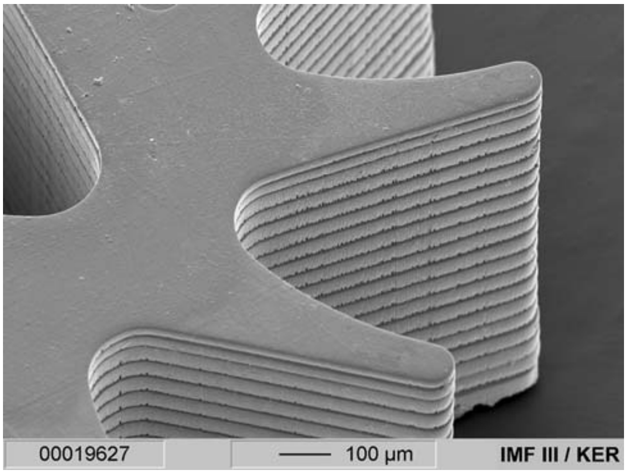

Fig. 9 SEM micrograph of the zirconia rotor (concept 2). The polymer model was made by the RMPD® process

flexible nature of the mold material, the de-molding of the nozzle plate was rendered impossible by the roughness inside of the channels. For that reason, a micromachining method for brass, which is described in detail in the next chapter, was chosen alternatively to produce this component with a smoother surface.

7 Micro structuring of metal models

For the structuring of the geometry of the nozzle plate, micro milling and micro electrical discharge machining (micro-EDM) have been used. Micro milling enables the manufacturing of metal models with accurate geometrical tolerances in the range of a few microns and smooth surfaces with an attainable roughness as low as a R_z of 0.3 µm. It is possible to achieve aspect ratios of 10 with cutter diameters of 100 µm, at bigger diameters up to an aspect ratio of more than 30. The highest machinable hardness by the usage of cemented carbide cutting tools is limited to a value of around 64 HRC (Weule et al. 2001; Hesselbach et al. 2004; Dornfeld et al. 2006). Brass was selected as work piece material featuring a very good machinability while still being quite wear resistant.

The most complex part of the turbine was the nozzle plate with thin channels and a high aspect ratio in order to guarantee the proper functioning of this fluidic part. The width should be as small as possible while maintaining a total depth of 1,000 µm (corresponding to approximately 800 µm after sintering).

The smallest commercial available tool diameters in micro milling with a sufficient reproducibility rate are 30 µm wide. At the Universität Karlsruhe (TH) a 20 µm tool with improved geometry was developed and successfully used to machine steel (Schulze et al. 2009). However, these tools currently only allow machining of aspect ratios of up to three. To reach the desired depth, a 100 µm tool had to be used with a flute length of 1 mm and therefore an aspect ratio of 10. The process parameters employed with this tool were 24,000 rpm, a feed per tooth of 2 µm and an axial feed of 2 µm.

For smaller nozzles, EDM has been used as an additional machining step. The complete geometry has been machined by milling except for the narrow channels. Subsequently this work piece was clamped to a Micro-EDM machine tool (SX 100, Sarix SA, Losone, Switzerland). Cylindrical electrodes with a diameter smaller than 10 µm can be produced by WEDG (wire electro discharge grinding), but the electrode wear is very high resulting in uneven surfaces (slopes) at the bottom of the work piece. In a second approach small feeler gauges, commercially available as electrodes with a thickness of 30 µm, were successfully employed. The used process parameters were: pulse frequency 180 kHz, pulse width 2 µs, gap-voltage 70 V, pulse peak 1.5 A, idle voltage 90 V.

In first tests, a nozzle plate was manufactured by EDM-milling with a channel width of 100 µm. The used parameters are an open circuit voltage of 100 V, discharge current 1 A, a frequency of 120 kHz and a pulse-on time of 2 µs. This cavity had a depth of 1 mm (Fig. 10). It could be proved that EDM-milling is a very flexible and precise way to machine micro molds in hard materials with high aspect ratios.

Due to the optimization of the EDM process and smaller electrode diameters, the slots of the nozzle plate could be scaled down. A 50 µm cylindrical tungsten carbide electrode was used to manufacture a minimal slot width of

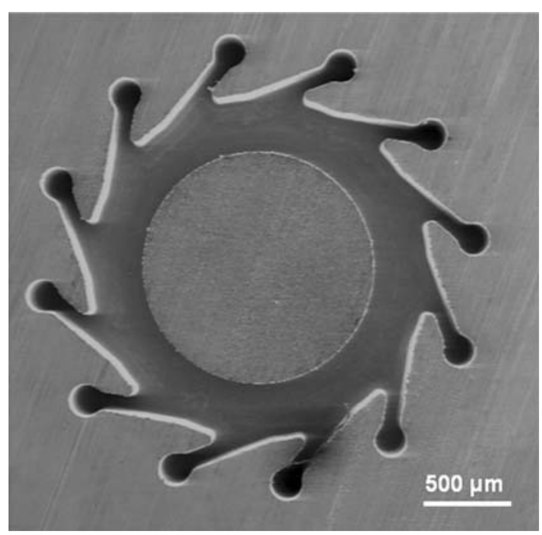

Fig. 10 SEM micrograph of a 1 mm deep nozzle plate with 100 µm channels, completely made by EDM in 30CrMo6

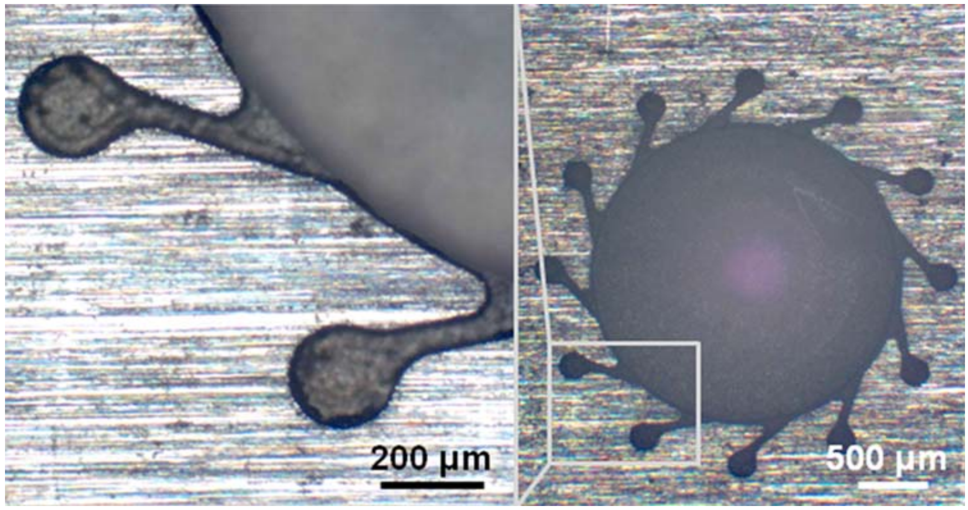

Fig. 11 Optical micrograph of a nozzle plate with 60 µm slots made by EDM in 30CrMo6 with a depth of 500 µm

60 µm (Fig. 11). In this example a total depth of 500 µm could be achieved. By using very thin electrodes to manufacture narrow slots there are some problems with the flushing of the dielectric in the working gap. This is just one of the challenges research has to deal with in order to increase the depth of this micro part.

Due to the smooth vertical surfaces of the micro machined model the zirconia nozzle plates with 100 µm nozzles could be de-molded from the silicone molds without problems. After sintering a nozzle width of approximately 80 µm is achieved. With the 60 µm nozzles, a slot width of less than 50 µm at a depth of 800 µm will be expected for the sintered nozzle plate.

8 Assembling of the micro turbine

In concept 2 the mechanical strength is high enough to handle all parts without specific care. The parts of the micro turbine were assembled manually and fixed by instant adhesive (Fig. 12). In the original demonstrator design the planetary gear drive acts as an end support for the shaft. Without the planetary gear drive the rotor has to be glued onto the shaft, otherwise the air flow would press the shaft out of the turbine. The application requires special care to prevent the good wetting adhesive migrating into the bearings of the rotor.

The most challenging step was to position the perforated plate onto the nozzle plate. The alignment of the holes could slightly be supported by the insertion of thin metal wires, but further design optimization steps are required to facilitate the assembling process. In general, assembling aids like positioning features or pockets for adhesives should already be considered in the design guidelines of micro devices.

The assembled micro turbine was inserted into a polymer housing that supplied the outer ring of holes in the perforated plate with compressed air. Usually an air pressure of 50–80 kPa was applied to move the rotor at a few thousand RPM. At higher pressures the efficiency is reduced, probably due to the deflection of the 240 µm thick perforated plate.

Fig. 12 Comparison of the sintered zirconia parts with a needle pin (*left*) and SEM micrograph of an assembled turbine without the perforated plate (*right*)

9 Summary

The micro turbine has proven itself as a valuable demonstrator for the improvement of the design and the micro manufacturing processes. It was successfully used to identify deficits on a system level that would not be gained with the particular components only. For example, the feasibility of various connection strategies for shaft-hub joints was demonstrated in a ceramic micro system. With the help of the components of the micro turbine a prototyping process chain was established that allows the manufacturing of ceramic micro components within a few days, using e.g. micro milling and micro electrical discharge machining as efficient technologies for the structuring of 3-D geometries in the micro range.

The accuracy of the manufactured components was found to be sufficient to demonstrate the functionality of the turbine. However, for a technical application further optimization of the design is required to improve the performance. Besides performance, pending problems are related mainly to the development of assembling and positioning aids and their integration into the design process. In general, a big challenge for the future is, to extend the turbine specific experiences to a broader level of micro devices and to transfer the whole process chain, including the knowledge of development, manufacturing and assembly of small and functional systems, at a good price performance ratio to industry.

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