Micro Milling of High Aspect Ratio Micro Structures in Ceramics

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Abstract
Micromachining is a very flexible and universal technique, compared to EDM (electrical discharge machining) or ECM (electrochemical machining). There are nearly no limitations in design. Also 3D-structures can be easily machined. The material removal rate is high and surface roughness in the submicron range can be obtained. With micromilling in contrast to EDM not only electrically conductive materials but a wide range of materials like polymers, metals and alloys as well as some sorts of ceramics can be microstructured. Manufacturing of microstructures made of several kinds of ceramics with different processing routes exhibiting specific advantages and disadvantages are discussed in this paper.

Keywords: micromilling, microcutting, micro slotting, micro structure, ceramics, ceramic materials

1. Introduction
In micromilling some effects have to be taken into account, which are negligible in the macroscopic world. Different hard metal substrates cause different cutting edge sharpness and machining results. For nonferrous materials mono crystalline diamond tools with perfect cutting edges can be used giving burr free microstructures. Cutting edges of hard metal tools, however, are jagged since hard metal is a composite material consisting of hard tungsten carbide grains in soft cobalt binder matrix (Figure 1).

Figure 1: Cutting edge of a hard metal end mill of 100 µm diameter (top) and a 200 µm diameter tool made of monocrystalline diamond (bottom)

Also the coating of micro tools to decrease the wear has an impact on machining results. The rounding of the cutting edges determines the cutting force and hence also the tool deflection of small diameter-tools (Figure 2).

Figure 2: Rounding of cutting edge of a DLC-coated end mill, d=0.4 mm by KARNASCH (top), TH45+-Coating (TiSiN) of a 30 µm-end mill by HITACHI with formation of some droplets (bottom)

The recommendation for the speed for micromachining ranges up to 160,000 or even 250,000 rpm [1] to achieve reasonable cutting speed and is far away of conventional milling. However, for small details the dynamic limitation of machine has to be taken into account to maintain a minimum feed per tooth and to prevent the tool from squeezing. Big attention has to be paid to the run out of the tool to prevent overload of single cutting edges when using two flute tools. Anyhow, the miniaturization is limited by physics due to
stability problems of the tools. The moment of inertia decreases by the fourth order with decreasing diameter (Eq. 1).

\[ I_z = I_z = \frac{\pi}{4} R^4 \]  

(Eq. 1)

To access smaller dimensions micro slotting was developed. Since the tool does not rotate the shape offers more stability.

Smallest trenches of approximately 15 µm in width and with an aspect ratio of ten [2] were demonstrated in PMMA up to now (Figure 3).

![Figure 3: Trench made by microslotting with a width of app. 15 µm and a depth of more than 150 µm, made in PMMA](image)

All microstructures presented in this paper were machined at a “HSPC 2522” by “KERN Micro- & Feinwerktechnik”, Murnau with a spindle “Precise VSC4084” with a maximum speed of 40.000 rpm. Micro end mills were thermally shrunken into chucks guaranteeing a run out within two microns.

2. Ceramic materials

Table 1 gives an overview over ceramic materials accessible for micromachining. There are several kinds of materials available with different processing routes exhibiting specific advantages and disadvantages. For example, ceramic microparts can be made very easily out of graphite and MACOR™. However, the mechanically properties of graphite are limited.

MACOR™ consists of a matrix of approximately 45% borosilicate glass and 55% mica crystals causing micro cracks when machining (Figure 4).

![Figure 4: Microstructure of MACOR™](image)

However, the chemical resistance of MACOR™ is not suited for all applications.

Shrinkage free ceramic is based on the intermetallic phase ZrSi₂. By using a low loss binder with a high ceramic yield for compaction and zirconia as an inert phase, ZrSi₂ is transformed to ZrSiO₄ during the reaction sintering process (Figure 5).

![Figure 5: Reaction sintering of shrinkage free ceramic based on ZrSi₂](image)

A prerequisite for this is a sufficient access of oxygen limiting the maximum wall thickness. This ceramic provides better mechanical and chemical properties than graphite and MACOR™ and no shrinkage has to be taken into account.

However, the mechanical and chemical properties of alumina and zirconia are superior. Micromilling of these materials is only possible between the formation of sinter necks and compaction. On the other hand, the presintered materials are subjected to shrinkage when sintering to full density after micromachining (Figure 6) and it is difficult to meet very tight tolerances.

In the final state, however, only grinding with diamond tools is possible causing 60 to 80 % of the total costs [3].

![Figure 6: State of sintering of ceramics.](image)

In general, machining of ceramics is not as challenging like chipping of difficult to machine materials e. g. nickel base alloy and tantalum, which tend to weld with the cutting edge. The tool life is reasonable when machining ceramics. A sharp cutting edge of uncoated tools is favourable to attain sharp edges of ceramic microstructures despite tool wear is higher.

A very practicable way is the micromachining of cured resins, the preliminary product of glassy carbon. The chipping is comparable with machining of polymers. The tool wear is negligible. During high temperature pyrolysis organic constituent escapes and shrinkage of about 15 % occurs. Like for the shrinkage free ceramic, a certain maximum wall thickness has to be met or venting channels must be added. After high
temperature pyrolysis glassy carbon has excellent chemical and corrosion resistance, however, it is very brittle and can be finished only by grinding. The material is biocompatible. For example heart values were made out of glassy carbon [4].

3. Machining of ceramic microstructures

Figure 7 shows a micro heat exchanger made of MACOR™. It was machined with a speed of 15,000 rpm, an infeed of 0.05mm and a feed of 600 mm/min using an end mill of 0.4mm in diameter and a length of 4 mm by Karnasch.

![Figure 7: Heat exchanger microstructure made of MACOR™. Trench width 0.4m, Depth 2.9mm at the beginning and 0.6 mm at the end. Speed 15,000 rpm, infeed 0.05 mm, feed 600 mm/min, DLC-coated tool by KARNSCH](image)

For shrinkage free ceramic several test microstructures like narrow walls, columns and micro gearwheels where machined to investigate the stability of the edges. The samples in green and sintered state are displayed in Figure 8.

![Figure 8: Test microstructures made of shrinkage free ZrSi2-ceramic. Top: green state, bottom: reaction sintered](image)

In Figure 9 a dispersion nozzle made of zirconia is shown. This material was chosen due to its excellent wear resistance. Two holes of 100 µm in diameter meet under 60° and at a distance of a few hundreds microns.

![Figure 9: Dispersion nozzle in sintered state made of presintered zirconia with two holes with 100 µm diameter under an angle of 60°](image)

By thermal shrinking ceramic components can be combined with metallic housings. An example is given in Figure 10. This possibility is important, since joining of ceramics is mostly very difficult. For example, glassy solder will decrease chemical or thermal properties of devices considerably.

![Figure 10: Ceramic test components made of alumina joint with Hastelloy C-22 by shrinking](image)

By using glassy carbon these obstacles can be avoided. Microstructured procured resin sheets can be glued with resin to complex parts and subsequently pyrolysed to obtain joint apparatuses of glassy carbon like displayed in Figure 11.
To prove the corrosion resistance of the material the v-mixer was stored in concentrated sulphuric acid (95-97%) at a temperature of 100 °C for two weeks. No traces of corrosion could be observed.

4. Summary and outlook

There is a wide range of very different ceramics with different properties accessible to mechanical microstructuring.

Ceramic materials are very interesting for microsystem technology and offer interesting properties. Especially for chemical and high temperature application as well as for applications subjected to wear ceramics are well suited. However, the design has to be changed compared to design rules for metallic parts and to be adapted to typical properties of ceramics like brittleness. New technologies to improve joining have to be developed. For example, in [5] laser welding of alumina is reported. The material is preheated by a CO₂-laser and subsequently welded with a Nd:YAG-laser. This procedure avoids a large temperature shock so crack formation can be avoided. The question is, if also very complex shapes can be welded.

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References


Table 1: Overview over machinable ceramic materials

<table>
<thead>
<tr>
<th>Machining State</th>
<th>final state</th>
<th>pressed</th>
<th>presintered</th>
<th>before ceramization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Graphite</td>
<td>ZrSi₂</td>
<td>ZrO₂</td>
<td>glassy carbon</td>
</tr>
<tr>
<td></td>
<td>MACOR™</td>
<td></td>
<td>Al₂O₃</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminiumsilicate</td>
<td></td>
<td>Aluminiumsilicate</td>
<td></td>
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<tr>
<td>Advantage</td>
<td>No thermal treatment, easy to clean</td>
<td>no sinter shrinkage after reaction sintering, green equal to sintered dimension</td>
<td>good chemical resistance</td>
<td>low tool wear, good chemical resistance, joining possible</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>tool wear (Graphite), chemical resistance? (MACOR™)</td>
<td>due to binder no cleaning in US &amp; organic solvents in green state, limited wall thickness</td>
<td>shrinkage during sintering</td>
<td>very brittle, limited wall thickness due to degassing during pyrolysis</td>
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