Micromachined silicon electrodes for electrochemical micromachining

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Abstract

Piracy and counterfeiting as well as retraceability demands of products such as plastic parts or tablets require new and innovative methods for unique product identification. An opportunity is the placement of microstructured codes in moulding tools. These tools are often made from materials that do not allow for highly precise micromachining by traditional technologies. Electrochemical machining (ECM) is a method for structuring construction materials such as steel or titanium. The current paper presents a new technology for the fabrication of microstructured tool electrodes for electrochemical machining by using highly doped silicon as electrode material. A simple and low priced fabrication of microstructured silicon electrodes with locally isolated areas is demonstrated by using well-established silicon processing technologies. Prototypes based on this new tool electrode technology are fabricated. Therewith electrochemical machining of microstructures in stainless steel is successfully demonstrated. Machining gaps down to 10 µm and average surface roughness of 60 nm are achieved. Typical rates of removal between 60 - 240 µm/min are reached. The local isolation of electrode areas advances the machining accuracy.

Keywords: electrochemical machining, micromachining, microstructure

1. Introduction

Microtechnological applications in medical devices, tooling for micro injection moulding or aviation as well as automotive industry demand the usage of construction materials such as steel or titanium. Electrochemical machining offers an interesting way for machining these materials [1].

ECM enables the machining of metals independent of their mechanical properties and achieves high material removal rates. Compared to electro-discharge-machining (EDM) tool wear is extremely low and the surface layer is not damaged. Additional advantages of ECM are:
- no contact between tool electrode and workpiece
- no burr formation
- no finishing process necessary
- smooth surface
- batch processing possible

Size and shape of machined microstructures are affected by tool size and shape as well as the machining gap. For the fabrication of microstructures by ECM it is essential to have a small working gap. This is achieved on the machine side by using the techniques of oscillating tool-electrodes [1] or ultra short voltage pulses [2].

The accuracy of machining is improved in addition by providing an electrically isolating layer on the electrode at the area where current passage is undesired. If the machining operations should meet high accuracy requirements, this isolating layer must be as thin as possible, for example 10 µm or less.

Different types of insulating materials have already been proposed. The metal core of the electrode is covered by isolating polymer layers or compounds of inorganic compound networks [3]. These approaches suffer from water or hydrogen absorption of organic layers with subsequent decomposition and detachment.

The drawback of inorganic compounds is that owing to the high coating process temperatures only refractory metals can be used as the electrode material. As well, the use of different materials promotes the detachment of the insulating layer due to mechanical stress and hydrogen formation during the electrochemical machining process. A further disadvantage is the thickness of the isolating layer of considerable more than 1 µm. This leads to a larger machining gap and therefore less reproduction accuracy.

Vargas Llona et al. [4] demonstrated uniform electroplating on highly doped silicon wafers. These substrates conduct sufficiently well without the use of an additional seed layer. Gianchandani et al. [5] described a process of utilizing silicon array electrodes for micro-electro-discharge machining. Our approach now uses micromachined, highly doped silicon as tool electrode material. Silicon is a well-established material in the MEMS-field that can be formed by conventional silicon processing techniques with high accuracy and reproducibility at low cost. By these techniques a simple integration of electrically conductive silicon and isolating silicon oxide areas is possible.

2. Experimental

2.1. Electrode design

The utilization of silicon as electrode material requires a low resistivity \( \rho \) that is achieved by highly doped silicon wafers \( (\rho = 1 \cdot 10^{-3} \ \Omega \cdot \text{cm} \ [6]) \). This corresponds to an electrical conductivity \( \sigma \) (Eq. 1):

\[
\sigma = 1/\rho = 1 \cdot 10^3 \ \text{S} \cdot \text{cm}^{-1}
\]

The typical conductivity of metals at room temperature is larger than \( 1 \cdot 10^4 \ \text{S} \cdot \text{cm}^{-1} \). As a consequence, the applicable electrode area has to be
kept smaller compared to metal electrodes due to the
tenfold higher resistivity of the silicon.

In addition, it’s advantageous in terms of a low
electrode resistivity to fabricate only the microstructured
part of the electrode in silicon and attach it for instance
to a metal carrier.

Typical working voltages for electrochemical
machining are between 5 and 50 V. The dielectric
strength $E_{bd}$ of thermally grown silicon dioxide is larger
than $1 \times 10^7$ V cm$^{-1}$.

For a maximum voltage $U_{\text{max}}$ of 50 V a silicon oxide
layer thickness $d$ of:

$$d = \frac{U_{\text{max}}}{E_{bd}} = \frac{50 \text{ V}}{1 \times 10^7 \text{ V cm}^{-1}} = 50 \text{ nm}$$

is sufficient (Eq. 2).

2.2. Fabrication process

The fabrication process of the electrodes is based
on standard silicon MEMS processing techniques. Fig.
1 illustrates the process flow.

![Process flow of electrode fabrication process.](image)

Fig. 1. Process flow of electrode fabrication process.

Highly doped ($\rho = 1-5 \times 10^{-3}$ $\Omega$·cm) 4"-silicon wafers
are used as substrate. The wafers are structured with
100 µm deep pits with vertical sidewalls by advanced
silicon etching (ASE®, Surface Technology Systems
plc, UK). Afterwards the structured silicon wafer is
completely coated with 200 nm silicon dioxide (SiO$_2$)
isolation layer by thermal oxidation.

Following, the silicon oxide layer is locally removed
on the front face side by chemical mechanical polishing
(CMP) or anisotropic reactive ion etching (RIE)
process. These kinds of removal leave the side walls
covered with an isolating SiO$_2$-layer. The silicon oxide
on the backside is completely removed by RIE.

Finally, the electrode dies of size 6 mm·6 mm are
cut out of the 4"-wafer by a dicing saw. Fig. 2 shows
such a microstructured silicon electrode die.

The silicon dies are fixed to the tip of a square-cut
(6 mm·6 mm) brass rod with a length of 100 mm by
soldering or electrically conductive epoxy adhesive (see
Fig. 3).

![Different electrode assemblies, the cross
section dimension of the brass rod is 6 mm·6 mm.](image)

Fig. 3: Different electrode assemblies, the cross
section dimension of the brass rod is 6 mm·6 mm.

2.3. ECM set-up

The electrochemical machining die-sinking
experiments are performed on a PEM 1360 (PEMTec
SNC, F). This machine works with a vibrating tool
electrode with constant frequency of 50 Hz and
amplitude of 200 µm. Details of the process control are
found in [1]. Fig. 4 gives an overview of the set-up of
the ECM experiments.

![ECM set-up.](image)

Fig. 4: ECM set-up.

Aqueous NaNO$_3$ solution (10 %wt) is used as
electrolyte. Workpieces of DIN 1.4108 (CRONIDUR 30,
Firth AG, CH) and DIN 1.4441 (316 LVM, Frücht-Kronos
GmbH & Co. KG, D) stainless steel were used
for the experiments.
3. Results and discussion

3.1. Surface roughness

Fig. 5 displays a microstructure that was electrochemically machined in stainless steel by a silicon electrode with isolated sidewall. Minimal feature dimensions were 200 µm wide bars. Tab. 1 shows important machining parameters.

Tab. 1: Parameter settings for surface roughness experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation</td>
<td>200nmSiO₂</td>
</tr>
<tr>
<td>Workpieces material</td>
<td>DIN 1.4108</td>
</tr>
<tr>
<td>Working voltage</td>
<td>11 V</td>
</tr>
<tr>
<td>Pulse width</td>
<td>7 ms</td>
</tr>
<tr>
<td>Rinsing pressure</td>
<td>3,7 bar</td>
</tr>
<tr>
<td>Depth machined cavity</td>
<td>60 µm</td>
</tr>
<tr>
<td>Machining time</td>
<td>27 s</td>
</tr>
</tbody>
</table>

Average surface roughness Ra has been considerably smoothed by the ECM-process compared to the non machined surface (Ra = 700 nm). At the bottom of the cavity Ra was about 60 nm. The silicon electrode had a mirror finish at the front face side. That has been largely transferred during the ECM-process.

3.2. Sidewall shape

One of the advantages of using silicon as electrode material is the simple integration of isolating areas. Fig. 5 and Fig. 6 compare a cuboid structure machined by an electrode with 200 nm SiO₂ sidewall isolation fabricated by CMP versus an electrode without isolation.

The images were taken by an optical profiler based on scanning white-light technology (NewView 5000, ZygoLOT GmbH, D). Tab. 2 overviews important experimental parameters.

Tab. 2: Parameter settings for sidewall shape experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation</td>
<td>200nmSiO₂</td>
</tr>
<tr>
<td>Workpiece material</td>
<td>DIN 1.4108</td>
</tr>
<tr>
<td>Working voltage</td>
<td>14 V</td>
</tr>
<tr>
<td>Pulse width</td>
<td>6 ms</td>
</tr>
<tr>
<td>Rinsing pressure</td>
<td>3,7 bar</td>
</tr>
<tr>
<td>Depth machined cavity</td>
<td>71 µm</td>
</tr>
<tr>
<td>Machining time</td>
<td>19 s</td>
</tr>
</tbody>
</table>

The sidewall angles of the cuboid in Fig. 6 are steeper compared to these in Fig. 7.

The cuboid machined without isolated electrode (see Fig. 7) features considerably rounded edges. All sides including the top surface have been machined, which is indicated by a smoother surface compared to the original one.

3.3. Machining accuracy

The accuracy of ECM with silicon electrodes was tested by machining a parallel bar structure (see Fig. 8). On tool side the channels were 50 µm wide and 100 µm deep. The distance between the channels was 80 µm. The SiO₂-isolation on the electrodes front face side has been removed by CMP.
Fig. 8: SEM-picture of machined parallel bar structure.

Fig. 9 displays a cross-sectional profile of one of the machined bars measured non-destructively by an optical profiler based on scanning white-light technology. This experiment was performed with DIN 1.4441 steel. Machining parameter settings are shown in Tab. 3.

The width at the base of the bar is about 30 µm. This means that the machining gap at the bottom is about 10 µm for the isolated electrode. The waviness at the right shoulder of the cross-sectional profile reproduces the surface roughness of the machined material.

Tab. 3: Parameter settings for experiments testing the machining accuracy of ECM with silicon electrodes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation</td>
<td>200nmSiO₂</td>
</tr>
<tr>
<td>Workpiece material</td>
<td>DIN 1.4441</td>
</tr>
<tr>
<td>Working voltage</td>
<td>15 V</td>
</tr>
<tr>
<td>Pulse width</td>
<td>7 ms</td>
</tr>
<tr>
<td>Rinsing pressure</td>
<td>3,7 bar</td>
</tr>
<tr>
<td>Depth machined cavity</td>
<td>65 µm</td>
</tr>
<tr>
<td>Machining time</td>
<td>62 s</td>
</tr>
</tbody>
</table>

Moreover the removal rates of the DIN 1.4441 steel are about four times lower compared to that of DIN 1.4108. Therefore a continuative process optimisation concerning flushing conditions and machining parameters is necessary.

3.4. Electrode assembly

During machining of the samples the current was measured by an inductively coupled current probe connected to an oscilloscope. Typical current densities of soldered silicon electrode dies were between 0.5 and 0.8 A/mm², of fixed with adhesive dies between 0.3 and 0.5 A/mm².

The differences originate from the varying non-isolated silicon surface as well as the contact resistance of the assembly technique. The contact resistance of fixing the silicon dies by epoxy adhesive is about twice as much as by soldering.

4. Conclusion

The application of a new electrode concept using highly doped silicon with locally isolated areas was successfully demonstrated in the case of micromachining stainless steel.

ECM with such electrodes achieves working gaps down to 10 µm and average surface roughness up to 60 nm at typical rates of removal for the machined stainless steel materials between 60 - 240 µm/min.

Machining accuracy is advanced by local sidewall isolation with silicon dioxide.

Acknowledgements

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References