CUT IT OUT. SHAPING THE MICROMETER

Thomas Schaller¹, Wilhelm Pfleging¹, Marcus Hlavac²
¹ Forschungszentrum Karlsruhe, Karlsruhe, Germany
² Braunschweig Tech. University, Braunschweig, Germany

ABSTRACT

This contribution gives an overview of material removing, maskless microfabrication techniques such as micromanufacturing (drilling, turning, grinding, milling, slotting), electro-discharge machining (EDM), laser machining (drilling, cutting, ablation) and focused ion beam machining. Feasibility and commercial relevance of the techniques – including combining manufacturing technologies – will be shown by examples of microstructures and applications.

INTRODUCTION

Using a tool for shaping bulk material is nothing new, but one of the oldest arts of manufacture. An artist sees his sculpture in a block of marble or wood while he is cutting it out with a chisel or a drawknife. Splinters or chips are covering the floor, and finally a masterpiece is finished.

Nowadays, nothing has changed in principle, only techniques have changed a little: The workpiece can be seen virtually as a CAD model, and the structure is cut out of a block by modern CNC machining centers and laser systems. It is production rather than art, but knowledge and experience still are the key to excellent results, particularly in microcutting of hard-to-see structures, using a variety of tools. Shaping the micrometer means to touch the limits of technical feasibility, and sometimes there seems to be no difference between microstructures and artwork.

Due to the wide range of available techniques, tools, machines, materials, structure geometries, process variants, and individual adaptations, the overview of techniques cannot be complete. Although they may be material removal processes, some techniques are missing, e.g. electrochemical machining, lithography (developing irradiated structures), and etching techniques; our exclusion criterion is the absence of a “tool” for cutting, even in a broad sense. It could be worth the effort to compare several microfabrication techniques with respect to workpiece materials, structure dimensions and accuracy, industrial relevance, and others.

TOOLS & TECHNIQUES

The use of tools for material removal is not restricted to “real” cutting tools, such as end-mills, profiled cutters or grinding wheels. We also consider a laser or ion beam a cutting tool, as well as sparks for electro-discharge machining. Due to the different nature of the tools, applicability of the methods covers a wide range of workpiece materials, material removal rates, surface finishes, structure geometries, structure detail dimensions and aspect ratios, and more. To be counted as a microfabrication technique here, the only precondition is that the tools and structures are in sub-millimeter range, typically some tens or hundreds of micrometers.

Each microfabrication technique has its own advantages and disadvantages. In order to achieve best results for a specific microstructuring problem, you have to pick the most suitable and economical technique or, if needed, to combine several techniques. None of the techniques is "good" or "bad", but you can make a good or a bad choice. Table 1 is listing some characteris-
<table>
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<th>Technique</th>
<th>Cutting</th>
<th>Machining principle</th>
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<th>Laser Machining</th>
<th>Focused Ion Beam Machining (FIB)</th>
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<tr>
<td>Machining principle</td>
<td></td>
<td>mechanical ablation (defined cutting edge)</td>
<td>mechanical ablation (undefined cutting edges)</td>
<td>plasma ablation by electric sparks</td>
<td>thermal / chemical ablation</td>
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<td>Tool type</td>
<td>D: drilling (T,F)</td>
<td>grinding wheels and pins</td>
<td>wires or shaped electrodes</td>
<td>pulsed or continuous wave laser radiation</td>
<td>ion sputtering</td>
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<tr>
<td>Tool material</td>
<td>tool steel (D,T)</td>
<td>abrasive coatings/grains (CVD diamond, CBN, …)</td>
<td>copper, tungsten, and alloys</td>
<td>photons</td>
<td>ions</td>
</tr>
<tr>
<td>Min. tool size</td>
<td>30…50 μm (D)</td>
<td>&gt; 15 μm (wheels)</td>
<td>&lt; 5 μm (focus diameter)</td>
<td>&lt; 1 μm (focus diameter)</td>
<td></td>
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<tr>
<td>Min. tool size</td>
<td>&lt; 50…100 μm (T,F)</td>
<td>&gt; 60 μm (pins)</td>
<td>&lt; 50 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. tool size</td>
<td>&lt; 50…100 μm (M)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Workpiece material</td>
<td>ductile materials: polymers, copper &amp; aluminum alloys, graphite, green ceramics, steel</td>
<td>brittle or hard materials: glass, ceramics, silicon, tungsten carbide, steel</td>
<td>conductive materials: metals, ceramics, glass, (almost any material)</td>
<td>PMMA, brass, aluminum, steel, tungsten carbide, …</td>
<td></td>
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<tr>
<td>Removal rate / Machining time for typical applications</td>
<td>medium…low / hours…days</td>
<td>fast…medium / minutes…hours</td>
<td>medium / hours</td>
<td>fast…low / seconds…hours</td>
<td>low / minutes…hours</td>
</tr>
<tr>
<td>Min. structure details</td>
<td>&gt; 5 μm (sub-μm for SPDTb) limited by tool geometry</td>
<td>&gt; 10 μm limited by tool geometry</td>
<td>&gt; 10 μm limited by tool geometry</td>
<td>&lt; 5 μm limited by beam diameter and shape</td>
<td>&lt; 5 μm limited by beam diameter and shape</td>
</tr>
<tr>
<td>Max. aspect ratio</td>
<td>typically 10</td>
<td>&gt; 10</td>
<td>&gt; 100</td>
<td>&lt; 50</td>
<td>≈ 2</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1…3 μm (sub-μm for SPDTb)</td>
<td>&lt; 5 μm</td>
<td>1…3 μm</td>
<td>1…5 μm</td>
<td>&lt; 1 μm</td>
</tr>
<tr>
<td>Surface finish (R_a)</td>
<td>&lt; 0.1 μm (=10 nm for SPDTb)</td>
<td>&lt; 0.2 μm</td>
<td>&lt; 0.1 μm</td>
<td>&lt; 0.2 μm</td>
<td>&lt; 0.1 μm (estimated)</td>
</tr>
<tr>
<td>Microstructure application examples</td>
<td>prototyping and molds for fluidics, sensors, and actuators (optical surfaces for SPDTb)</td>
<td>prototyping, punching tools, molds</td>
<td>prototyping, molds, vias, gratings, etching, membranes</td>
<td>mask repair, diagnostic tools, direct ablation, micro cutting tools</td>
<td></td>
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<tr>
<td>Academic / commercial use</td>
<td>academic / commercial</td>
<td>academic</td>
<td>commercial</td>
<td>academic / commercial</td>
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</table>

Notes:

a  Microslotting is a new, kind of “exotic” technique under development. By steering the cutting edge of profiled tools to the actual cutting direction, the relative robustness of profiled tools is combined with the versatility of milling and the ability of cutting arbitrary structures. Features are trenches less than 20 μm wide, cutting of steel using diamond tools, and machinable structure details, such as sharp inner edges.

b  Single-point diamond turning (SPDT) is an ultra-precision cutting technique for optical surfaces and of nanometer accuracy, but limited geometric variability. Workpiece material limitations (usually no ferrous materials when using diamond tools) and structure limitations (rotational symmetry, large radius of diamond tool) can be reduced by using ultrasonic tool excitation and a fast-tool servo, respectively.
tics of micro “cutting” techniques. It should not be understood to be a ranking of competing techniques, but a representation of the state of the art.

All techniques (except for FIB) are well-established in the “macro” world, and for specific products considerable knowledge exists in industry, pushing production processes with high yields at simultaneously small tolerances. An obvious example is producing thousands of square meters of microstructured reflector foils by the 3M company (and others) using an elaborate diamond flycutting process and microreplication technologies. Other techniques are adapted and perfected by specialized companies according to the needs of a market for microstructured devices, such as microcutting (e.g. by KERN [1]), EDM (e.g. by CHRISTMANN [2] or ROLLA Micro-Synthetics AG [3]), and laser machining (e.g. by LPKF Laser & Electronics AG [4], BARTELS [5] or EUROFLEX SCHUESSLER [6]). Further progress is made by academic institutions (e.g. IMF-1 Karlsruhe [7], IWF Braunschweig [8], and many others all over the world) developing new techniques [9] and providing understanding of machining principles, such as cutting steel using diamond tools, grinding of microstructures, improving accuracy in laser ablation, or fabrication of cutting tools by FIB machining.

Many micromachining problems require more than one technique, not to forget the measurement equipment. A combination of techniques in a process chain can be established by cooperation and mutual support of industrial and academic partners. The growing networks of excellence, e.g. to be promoted within the Sixth Framework Program of the European Union, is an obvious sign of the need for collaboration. In Germany, an industrial forum (FIF) has been established at the Forschungszentrum Karlsruhe to close the gap between research and industry: The forum is open to companies, provides networking in the microfabrication scene, and renders consultancy and technical support for specific microfabrication problems [10,11].

EXAMPLES

The following examples of structures and microfabrication techniques cover directly fabricated parts and mold making for mass replication of microstructures and components. No matter if you want to have machined just one prototype or if you want to start a mass production: It’s always a good choice to cut it out.

Milling

Figure 1 shows three micromilled turbine wheels for micro fluid pumps, machined into ceramic and vespel®. Sample diameters are 7/4/2 mm. In 5-axes machining, a circumference tolerance of 2 µm is achieved. These parts are commercially produced, which demonstrates that even tough material and dimension specifications can be met in a production environment.

But there are many combinations of structure size, material choice, and surface quality that require further investigations on tools, materials and processes [12], e.g. cutting of steel or burr removal. And there is still a gap to be closed between high-precision machining in the micrometer range and ultra-precision cutting of optical surfaces with nanometer accuracy.
Grinding

Figure 2 shows a test structure ground into hardened steel (X 155 CrVMo 1 2 1). The tool used is a CBN micro grinding wheel B15 (hard resin bond), cutting width 100 µm [13]. Grinding wheels are available with various grain materials and bonds. They can be used for machining of microstructures with high aspect ratios. The smallest cutting width is 15 µm.

Arbitrary structures can be machined by using grinding pins which are available in various shapes. Best surface qualities are achieved with CVD coatings due to their small grain size. The smallest pin diameter is 60 µm.

A characteristic effect of grinding brittle materials is the appearance of chipping, which is a factor limiting the the size of structure details (cf. burrs in milling): By applying optimum cutting parameters, chipping can be reduced to 1 µm and less.

EDM

Figure 3 shows two parts of a micro gear pump, and a dandelion pollen for comparison. The parts are cut out of tungsten carbide by wire-EDM. The wire diameter is 100 µm, structure tolerance is ± 1 µm, and the roughness of the machined surface is < 0.1 µm.

In the fabrication of EDM parts, micrometer accuracy can be achieved using commercial EDM machines. For complex geometries, plunge-EDM can be applied which requires electrodes with the inverse structure. The electrodes can be machined by any microfabrication technique: EDM, milling, laser machining or others. For some types of microstructures, even elaborate LIGA microstructures may be suitable for use in a production environment [14].

Laser Machining (and Combination with Other Microfabrication Techniques)

It is impossible to give an impression of the variability of laser drilling, cutting, and ablation in just one paragraph. There is hardly any material, geometry or microfabrication task that could not be done with laser machining [15]. Another benefit of the broad application range is the easy combination with other microfabrication techniques. Figure 4 shows a bioreactor (left) for growth of three-dimensional cell cultures in tissue engineering [16,17]. The process chain of fabrication...
starts with micromilling and flycutting of a brass mold, followed by micro injection molding for mass replication of the structure. The molded polycarbonate parts accommodate approximately 300 container structures per square centimeter (middle). The bottom of each container is microstructured with pyramidal pits (right). In a final process step, the bottom has to be perforated by excimer laser machining to ensure nutrient supply to the cells in the containers. Specifications of the pores: diameter < 3 µm, length < 100 µm, pitch 15 µm.

FIB

FIB is commonly used as an analysis and machining tool, mainly in electronic and electro-optic device fabrication. Besides direct machining, FIB proved to be a suitable technique for fabricating ultra-small cutting tools [18].

Profiled tools and end-mills can be used for turning [19] and milling trenches less than 20 µm wide. Figure 5 shows a profiled tool made of tungsten carbide [20].

CONCLUSION

Many techniques are available for maskless material removal on a micrometer scale. Most of them are suitable for both fabrication of prototypes and the industrial production of microstructured components. Part of research and development should be the implementation of new techniques and solutions in industrial processes. The growing number of networks of excellence is a sign of the need for interdisciplinary cooperation which should include cooperation of research and industry.
ACKNOWLEDGEMENTS

The authors are grateful to all colleagues and companies who contributed information, figures and all kind of support. Success in microcutting depends on teamwork, and we feel that we are part of a powerful “micro” community.

LITERATURE & WWW REFERENCES