MECHANICAL MICROMACHINING OF HIGH ASPECT RATIO MICRO-STRUCTURES

Hans H. Gatzen, Caspar Morsbach, Alexey Karyazin
Institute for Microtechnology, Hanover University, Germany

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Abstract: The investigations presented in this paper focused on the potentials of precision outside diameter grinding for the fabrication of high aspect ratio microparts. The material used was a two phase polycrystalene advanced ceramic. The goal was to create high aspect ratio parts standing freely, allowing to study how to optimize the fabrication process. Since structures with a minimal cross-section and a maximum length were desirable for the investigations, obelisk structures (i.e. columns with a square cross-section and an pyramidal tip) were selected for demonstrating the process capabilities. Subsurface damages as well as lateral cutting forces may cause a breakage of the parts therefore, the challenge was to minimize both. As cutting tools, 200 µm wide resin bonded diamond wheels were selected, their diamond grit was varied between 5 µm and 45 µm. The technology study revealed the machining capabilities of high aspect ratio outside diameter grinding. The aspect ratio achieved during the study was 27 to 1. The creation of pointed tips also shows that the process, although within stringent imitations, is capable of creating 3-D parts.

1. Introduction

Due to its high performance in regard of precision, as well as edge and surface quality, outside diameter grinding is an ideal technology for machining hard and brittle materials. An important application of this technology is the separation (or "dicing") of microelectronic components fabricated on silicon substrates. It is also used for machining glass as well as mono- and polycrystalline ceramics utilized as wafer for micro electro-mechanical systems (MEMS). For this purpose, highly accurate machines are available which allow the machining of separation cuts with a submicrometer accuracy. Dicing wheels consist of a resinoid or metallic binder which holds a matrix of abrasive grains and range from 15 µm to 1 mm in thickness. Since wafer materials usually are hard and brittle, diamond grain is the abrasive of choice. Typical grain sizes for dicing wheels are between 2 µm and 45 µm. In order to evaluate the potential of this technology for the fabrication of three-dimensional microparts, investigations were performed with the goal to maximize the aspect ratio of small footprint structures. Previous efforts centered on fabricating high aspect ratio microparts by first creating membranes and then slicing them to create resonator type structures by mechanical micromachining [1]. The work presented in this paper focused on the fabrication of column-like structures. Two factors limit the achievable aspect ratio: lateral forces exerted from the dicing wheel which cause breakage of the parts during machining and grinding induced subsurface damages. Breakage may be reduced by appropriately choosing the wheel parameters. A minimization of subsurface damages is achieved by machining in a ductile mode. Ductile machining takes advantage of the phenomenon that it is possible to plastically deform brittle materials under certain conditions. By selecting machining conditions resulting in a predominantly ductile mode machining, the formation of subsurface microcracks is minimized. As a result microstructures with very small lateral dimensions on the order of some ten micrometers may be created. Factors promoting a plastic flow during abrasive machining are a small depth of cut of the single diamond grain and a great hydrostativ pressur caused by the negative rake ankle of the cutting tool [2, 3]. A low depth of cut can be achieved by choosing suitable process parameters; while a negative rake angle is present due to the shape of the blocky shape of diamond grains. The goal of the work performed was to find process parameters to reduce both the lateral forces subsurface and the subsurface damages. To do so, a compromise between reduced forces and a ductile grinding mode had to be found.

2. Experimental Procedure and Results

2.1. Machine and Workpiece Material

For the investigations a commercial dicing machine was used. It is equipped with a precision air bearing spindle, air bearing guides of the feed axis and a highly rigid machine body. The spindle's rotational velocity is up to 40,000 RPM. A feed rate between 0.01 mm/s and 100 mm/s was chosen. The machine's pitch accuracy, i.e. the accuracy of two parallel dicing cuts, is 0.2 µm. The material for the dicing experiments was Al_2O_3-TiC (Altic), a dual phase, advanced ceramic which is commonly used for the manufacture of read/write heads in rigid disk drives. The composition of the material is 64% Al_2O_3 and 36% TiC. Due to its high density, the fine dispersion of the two phases, and the small average grain size of below 1 µm it has a rather high fracture toughness index of 4.1 MPa $m^{-1/2}$ [4]. These properties make Altic an ideal material for the fabrication of microstructures, since it exhibits a, compared to other ceramics, high resistance against brittle fracture propagation.

2.2. Minimizing the Structure Width

As mentioned above, two factors limit the dimensions of high aspect ratio parts: the extent of microcracks, that weaken the part and the grinding wheel's axial forces. In order to investigate the lower limit of structural cross section achievabe by a dicing process, the following approach was chosen: by grinding parallel slots with a regressive pitch (distance between two slots), walls were created with decreasing thickness. The distance between two cuts decreased with an increment of 5 µm from 100 µm down to 30 µm. This way, the limit in wall width that was achievable with the parameters and wheels used could be identified. Based on the results of former investigations, all parameters except the diamond grain size were kept constant. Table 1 summarizes the process parameters. By grinding a kerf in two depth steps with a depth of cut of 0.4 µm in each step, the total depth of the kerfs added up to 0.8 mm.

TABLE 1
PROCESS PARAMETERS

Parameter	Unit	Value
Wheel Parameters		
Binder		Resin
Diameter	mm	55.6
Width	mm	0.2
Diamond grain size d_g	µm	5, 15, 30, 45
Dicing Parameters		
Feed rate v_f	mm/s	0.4
Depth of cut a_e	mm	0.4
Cutting speed v_c	m/s	55
Coolant flow rate V'	l/min	1

The variation of the diamond grain size revealed a dependency of he achievable minimum structure of the grit size. The 5 µm grit wheel failed in the second depth step due to destruction. The best result in respect to wall width were achieved with a 45 µm diamond size wheel. The minimal wall width was 30 µm. The other two wheels, with a width of 15 µm and 30 µm, respectively, led to a destruction of the walls at thicknesses above 30 µm. Figure 1 shows a SEM image of the walls created using a 45 µm diamond grit. With a thickness of 30 µm and a height of 0.8 µm the aspect ratio is 27 to 1.

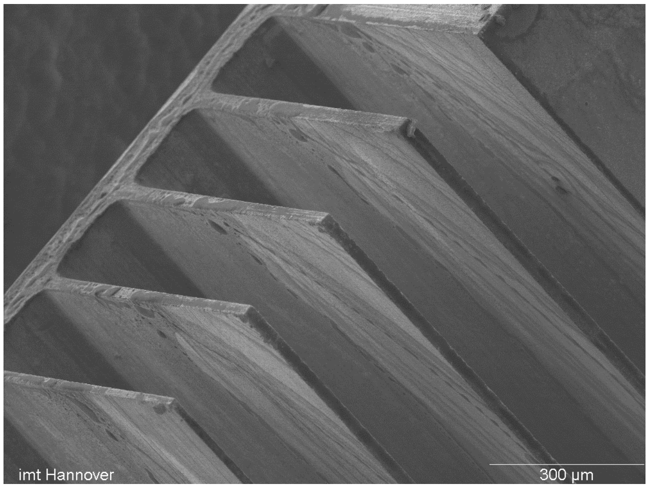

Fig. 1 Test structures machined with a 45 µm diamond grit resinoid bonded dicing wheel

The fact that a coarser grit leads to better results in regard of wall width may seem surprising, since it is known that finer grits usually yield better surface quality and reduced subsurface damages. In order to take a closer look at the damages caused by the abrasive action on the workpiece surface, investigations of the kerfs' sidewalls where performed, as described in the following chapter.

2.3. Grinding Mode Considerations

An investigation of the workpieces' sidewalls showed the diamond grit’s influence on the surface roughness. Investigations were performed using a white light interferometer. The dicing parameters were the same as documented in Table 1 but due to the early failure of the 5 µm diamond size wheel only one depth step was realized with this wheel. Therefore, in this case the total depth of cut was only 0.4 mm. The surface roughness was measured parallel and perpendicular to the feed direction. The two values vary slightly, since grooves on the sidewalls, formed by the interaction the workpiece and diamonds protruding from the wheel's sidewall have a prevailing orientation parallel to the feed direction. Therefore, the roughness value perpendicular to the feed direction was always greater than parallel to it. Figure 2 depicts the sidewall roughness as a function of the diamond grain size, with R_{ay} the roughness perpendicular and R_{ax} parallel to the feed direction.

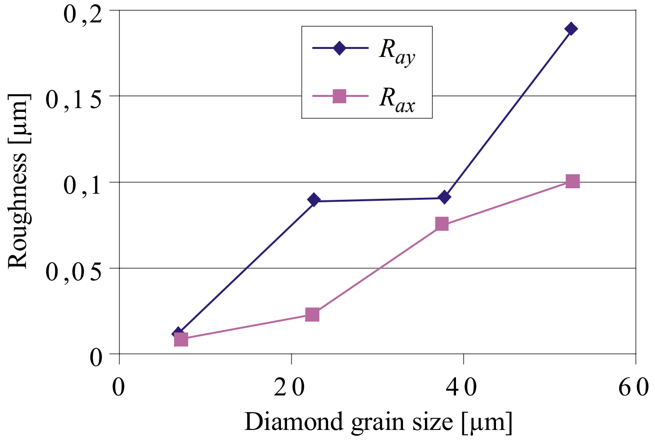

Fig. 2 Sidewall roughness as a function of the diamond grain size

The increase of the sidewall roughness is obvious. But the total values, ranging from 0.01 µm for a 5 µm grit to 0.1 µm for the 45 µm grit are indications for a predominantly ductile cutting mode. In order to verify this assumption, an analysis of the chips produced during grinding was performed. Therefore, the coolant was collected in the machine's coolant drain, and filtered with a paper fine filter with a pore size of 0.3 µm. Each filter was dried and subjected to a scanning electron microscopy (SEM). Figure 3 shows Altic chips produced by dicing with a 45 µm diamond grain size resin bonded wheel.

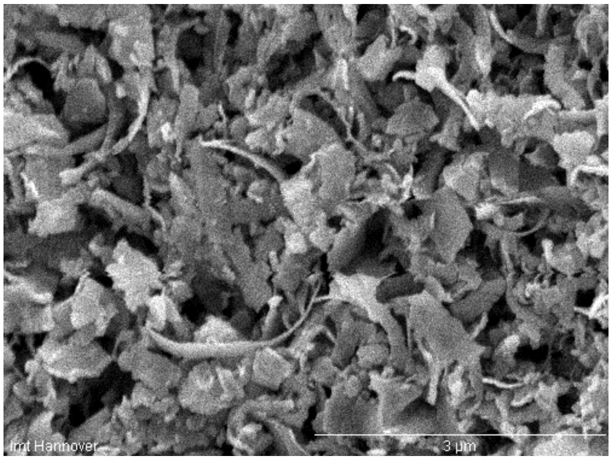

Fig. 3 SEM micrograph of Altic chips collected during machining with a 45 µm diamond grit dicing wheel.

The spectrum of chip shapes indicated a cutting mode at the transition from ductile to brittle fracture. Two types of chips could be detected: blocky chips, which are a result of a brittle fracture propagation as well as long and long and narrow chips formed by plastic deformation. The ratio in the number of both types of chips rather pointed towards a that the cutting mode was predominant brittle. Nevertheless, the partially ductile cutting mode, as indicated by the glossy surface and the presence of plastically deformed chips provided an explanation for the capability of the dicing wheel to machine rather fragile structures. On the other hand, it did not explain why the poor finer grit wheels (< 45 µm) were inferior in fabricating high aspect ratio microstructures. A potential reason was the forces exerted from the wheels on the workpiece during machining. Due to the high aspect ratio, the structures were extremely sensitive to lateral forces. These forces were a result of the stress field induced by the interaction between tool and workpiece. The stress field originated from the point of engagement of the diamond grains in the cutting zone and from frictional forces between workpiece and abrasive products squeezed in between wheel binder and workpiece surface. With respect to the latter phenomenon, wheels with a coarse grit are superior to fine grit wheels, as they provide more space between single abrasive grains due to a wider distance and larger grain protrusion. Therefore the stress field induced by coarse wheels is much lower then the one induced by fine grit wheels.

2.4. Fabrication of Microcolumns

In order to demonstrate the potential of the process described above, obelisk shaped columns with a square cross-section and pyramid like tips were manufactured applying the following process sequence. First, a desired cross section was selected. Since 30 µm was the minimum value achieved during the machining of walls, and columns yield a lower resistance against axial forces, a 40 µm x 40 µm footprint was chosen. Next, a shallow waffle pattern was ground to create the pyramid tips. The cut depth was 50 µm and a wheel with rounded edge profile was used, creating the slopes of the tips. In a third step, 800 µm deep grooves in x-direction were formed by a dual cut of 400 µm depth each, creating walls of a thickness of the desired cross section. For creating the columns, it was found necessary to backfill the grooves. This was mainly necessary due to the coolant jet directed tangentially to the wheel into the grinding zone. The forces from the coolant jet were destroying the structures during machining if they are not stabilised by backfilling. As material, the same hot glue used for mounting the workpieces to carriers was chosen. Cutting the grooves in y-direction followed the same fabrication sequence previously applied for generating the x-grooves. Removing the hot glue with acetone completed the fabrication sequence. Figure 4 depicts an array of the columns fabricated that way.

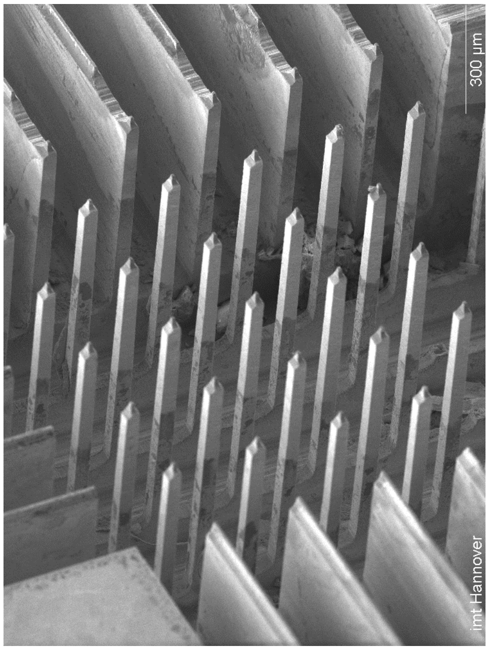

Fig. 4 SEM micrograph micro-columns with a pyramidal tip

3. Summary and Conclusions

The work presented in this paper demonstrates the potential of a modified dicing process to fabricate three-dimensional, high aspect ratio micro-parts. By using a resinoid wheel with a rather coarse grit of 45 µm, walls with a minimum thickness of 30 µm and an aspect ratio of 27 to 1 could be created. Investigations of the workpieces' sidewalls and of the abrasive product revealed, that the process parameters resulted in a partially ductile machining mode. A coarse grit proved to be advantageous because it offered sufficient space for the removal of abrasive products from the machining zone and therefore minimizes the effect of friction between tool and workpiece, which subsequently leads to high axial forces. As a for instance of high aspect ratio three-dimensional parts, obelik shaped columns with a pyramidal tip were manufactured applying the above the beforehand developed process. The footprint of these columns was 40 µm x 40 µm and with a height of 800 µm the aspect ratio is 20 to 1. For the manufacture of the columns a technique was developed to support the structures during the last machining step in order to prevent destruction caused by the impact of coolant.

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