Nano and Micro Machining Technologies and Their Application

Ultraprecision micro machining of hardened die steel by applying elliptical vibration cutting

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Introduction
Ultraprecision micro machining is needed to produce many of electronic and optical parts used for information communication equipment and devices, such as front and back light panels for LCD, glass substrates with barrier ribs for PDP, holographic optical elements and optical wave-guides [1]. The demands for ultraprecision dies and molds made of hardened stainless steel are increasing for mass production of those devices.

Plenty of Inspiration for the Next Generation of Microfluidic Device

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Introduction
Micro- and nanotechnologies will be expected to microminiaturize the present large medical equipments, e.g., artificial dialysis and plasma exchange equipments, which will bring about drastic changes in our lives. These technologies will be based upon the development of a micro- and nanoscale multiphase flow system that is comprised of liquids as continuous phase and molecules, protein and submicron particles as dispersed phase. In this novel

Advanced Desktop Ultraprecision Machining System for Micro-Mechanical Fabrication

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Introduction
Advanced desktop ultraprecision machine-tools have been developed for an advanced production shop, which is a new micro-mechanical fabrication system for manufacturing variety of advanced micro-components. The author introduces the concept and the features of the developed fabrication system and also results achieved by the system. Practical performances for micromanufacturing on the desktop machines with ELID (ELEctrolytic In-process Dressing), are demonstrated.

Glass Machining with Micro End Mills

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Introduction
The demand for fabricated glasses has been increasing to make diversified functionalities on testing plates such as micro TASs (Total Analysis Systems), which have micro scale channels to test a small amount of samples. In manufacturing of the glass chips, chemical etching has been applied to micro fabrication on glass so far.
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Continued from page 1. Machining, i.e. cutting and grinding, and chemical etching have been applied to micro machining. However, conventional ultraprecision diamond cutting can not be applied to machining of die steel due to rapid tool wear [2-4], while ultraprecision grinding and chemical etching are not suitable to machine such ultraprecision micro structures especially with sharp edges. Thus, the ultraprecision micro machining of die steel can not be realized by the conventional methods.

The authors have developed a new cutting method named ‘Elliptical Vibration Cutting’ and clarified that ultraprecision diamond cutting of hardened steel can be realized by applying this method [2-4]. The method, a developed ultrasonic vibration device and its applications to ultraprecision micro machining of hardened die steel are introduced here.

Elliptical vibration cutting process and device

Figure 1 shows a schematic illustration of elliptical vibration cutting process. The tool is vibrated elliptically and fed in the nominal cutting direction relatively to the workpiece at the same time, so that the chip is formed intermittently and pulled out in each vibration cycle. Since the friction between the chip and the tool rake face is reduced or reversed, the shear angle is increased and consequently the cutting force and the cutting energy are reduced significantly.

It should be noted that deviation of the elliptical vibration locus, especially the vibration in the thrust direction, causes machining errors on the finished surface. It is, therefore, necessary to control the vibration locus precisely during machining.

Figure 2 shows a schematic illustration of the developed ultrasonic elliptical vibrator, whose resonant frequency is 20 kHz. The vibrator has 4 large piezoelectric plates as actuators and 2 small plates as sensors. The diamond tool tip is set at the end of the vibrator and vibrated elliptically by exciting the bending modes in the cutting and normal directions with some phase shift. The two directional vibrations are detected by the two sensors, and the sensor signals are utilized for feedback control of the vibration amplitudes and their phase shift. The resonant frequency is also chased automatically by the control system. The developed vibration tool is mounted on an ultraprecision cutting machine as shown in Figure 3.

Application to micro machining of hardened die steel

Figure 4 shows a mirror surface with fine micro grooves machined by the developed system. It is made of hardened die steel, whose hardness is HRC53. As shown in the figures, the surface roughness is less than 0.04 μm Rz, and the ultraprecision micro grooving of hardened die steel was successfully realized by the ultrasonic elliptical vibration cutting.

Figure 5 shows a mold for micro fresnel lenses, while figure 6, for small pick up lenses. The both molds are made of hardened stainless steel and finished by the elliptical
vibration cutting. It is difficult to machine those molds by the conventional abrasive processes, because the fresnel lenses have fine micro grooves and the concave for the small pick up lenses is too small and deep for grinding wheels.

Summary
The new machining method has been proposed, which is named 'Elliptical Vibration Cutting'. The ultrasonic elliptical vibration cutting system has been developed, and it has been successfully applied to ultraprecision micro machin-

![Figure 5: Hardened steel mold of micro fresnel lens finished by elliptical vibration cutting](image)


![Figure 6: Hardened steel mold of small pick up lens finished by elliptical vibration cutting](image)


Figure 4: Hardened steel mirror surface with micro grooves, machined for mold of front light panel of LCD

(a) Photograph of mirror surface

(b) SEM photograph of micro grooves

(c) Profiles of finished surface

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ing of hardened die steels with fine grooves and small deep concaves, which is difficult for the conventional machining methods. It is expected that ultraprecision micro machining of difficult-to-cut materials will be realized in practice in the near future by the present method.

References


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Continued from page 11. ELID-grinding technique
ELID grinding was developed in 1987, and a number of reports describing this process have been published. The principle of ELID-grinding is shown in Fig.1. The wheel serves as the positive electrode. The negative electrode is installed opposite the grinding surface of the wheel. The clearance between these two electrodes is set at 0.1 to 0.3 mm. DC-pulse voltage is supplied between the two electrodes in order to electrolytically remove only the metal bond of the wheel, allowing efficient and automatic dressing of the wheel. This dressing is continued even during grinding a work in order to prevent reduced wheel sharpness from wear, thereby realizing highly efficient mirror-surface grinding.

2. Concept of Desktop Fabrication System
The developed desktop fabrication system employed with ELID-grinding process is composed of the following machines/units:
  a. Desktop slicing machine
  b. Desktop lapping machine
  c. Desktop multi-axes grinding/ cutting machine
  d. Desktop micro-tool grinding machine
  e. ELID and truing devices for micro-grinding
  f. Measuring and evaluation function/unit

These machines/units can work as each machine and also can work harmoniously. Each desktop machine can mount an ELID-grinding unit efficiently to enable high quality surfaces with fine mesh sized wheels for hard-to-machine materials. The features of the developed desktop machines are as follows.
  a. Compact body as desktop
  b. Lightweight
  c. Easy operations with PC based NC controller
  d. Equipped with ELID mirror surface grinding unit
  e. 100V AC input power
  f. On-machine measuring capability

Through the use of the developed desktop machines, wider ranges of materials micro-mechanical fabrications for semiconductors, optical elements, ceramic/carbide-alloy tools, bio-implant materials, were carried out for the first time on desktop. For these purposes, the systems must employ ELID-grinding process and the related mechanical processing to attain ultraprecision mirror surface finishing for hard and brittle materials at nano-level with low machining resistance and low tool wear. Fig.2 shows an example of developed desktop machine.

Fig.1 Principle of ELID-grinding

Fig.2 Example of desktop ELID-grinding machine
3. Development of Desktop Fabrication System

Fig.3 shows the latest ultraprecision desktop 4-axes machine. Aspheric lenses can be finished into mirror surface quality only by this machine (Fig.4). A specific CAM system to generate NC programs for this desktop machine is also supplied. Fig.5 shows examples of ELID-grinding on this machine. Consequently, curving, engraving, grooving, and profiling can be carried out by cutting and/or milling, and after these procedures, ELID-grinding for mirror surface finish can be applied on the same system without detachment of the workpiece. Applications to micro-aspheric lenses/ molds and micro-parts fabrication can be looked forward to. The rotary index table, serving as the fourth axis, can be continuously rotated and angularly controlled at the same time, and thus used for axis-asymmetrical machining. Not only ELID-grinding, but also mirror surface cutting can also be realized on the same machine (Fig.6).

To realize further desktop micro-machining features, the development of micro-tools is indispensable. Fig.7 shows the schematic illustration of the first developed micro-tool ELID-grinding principle. The developed machine to produce micro-tools uses a mist coolant supply for ELID. Fig.8 shows the examples of micro-tool ELID-grinding results. High aspect and very sharp micro-tools could successfully be fabricated without crack origin by the mirror finish grinding feature. A pyramidal micro-tool with top square of 2 μm*2 μm was successfully achieved (Fig.8(b)). Fig.9 shows examples of micro-gears and micro-stamping by the fabricated micro-tools.

The second developed micro-tool grinding machine has the new principle for grinding micro-tools, which uses two grinding wheels plunging into a workpiece for a micro-tool at the same time. By avoiding deformation of a workpiece of small diameter by each grinding wheel infed, extremely high aspect ratio micro-tool can be produced. Fig.10 shows an example of octagonal micro-tool obtained by this new method, which has about 30 times efficiency of the above first method.

4. Conclusions

The author expects that the developed ultraprecision desk-
(a) High aspect square tool   (b) Fine pyramidal micro-tool

Fig.8 Grinding results of micro-tool

(a) Micro-gears   (b) Micro-stamped hole

Fig.9 Examples produced by micro-tools

top machine-tools are to be utilized widely and practically for effective manufacturing increasing variety of advanced micro-functional components.

References

Plenty of Inspiration for the Next Generation of Microfluidic Device

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Micron-resolution particle image velocimetry (micro-PIV) is a powerful tool for measuring velocity fields, in which the effect of Brownian motion of submicron particles on velocity detection is reduced by ensemble averaging. However, most transport processes in micro total analysis system (micro-TAS) applications are unsteady phenomena. For temporal changes in velocity fields, it is hard to distinguish temporal variations of fluid flow from velocity fluctuations associated with Brownian motion using

Fig. 1. Temporal evolution of velocity vector field of the pulsating flow in the microchannel with the EK pump operating at 5 Hz. The applied electric field was 60 V/cm. The time interval of each vector map was 37 ms.
micro-PIV. Time-series velocity measurement of unsteady microchannel flow was accomplished by using spatially averaged time-resolved particle tracking velocimetry (SAT-PTV)\(^9\). Figure 1 shows measurement results of a pulsating flow with an electrokinetic pump.

Quantitative temperature measurement in microspace is also strongly required, because a precise temperature control is a key issue of most chemical processes in micro-TAS. Sato et al. (2003)\(^9\) developed a two-dimensional measurement technique in time series utilizing a fluorescent dye whose fluorescent intensity is strongly dependent on temperature. The fluorescent dye was applied to the bottom surface of a cover glass, that served as the upper boundary surface of a flow channel. A spatial resolution of 5 \(\mu\)m \(\times\) 5 \(\mu\)m and a temperature resolution of 0.26 K were achieved by using a cooled CCD camera and a 10 \(\times\) objective lens of a microscope. Figure 2 depicts two-dimensional distribution of temperature in the junction area of a T-shaped microchannel.

Most chemical phenomena in microchannels are sensitive to a change in pH, so that researchers are eager to know two-dimensional distribution of pH in microspace, especially with a high spatial resolution. Moreover, pH of buffer solution is related to zeta-potential of microchannel wall. Ichiyanagi et al. (2005)\(^9\) performed both pH and zeta-potential measurements by using micro-PIV considering the electrophoretic velocity of submicron particles. Figure 3 illustrates two-dimensional distribution of pH in the downstream region of the T-shaped microchannel and figure 4 shows zeta-potential of silica cover glass in terms of pH. Both of the experimental results will contribute to the development of a novel control technique for chemical process by only changing zeta-potential of microchannel wall.

From a viewpoint of nanoscale, zeta-potential is closely related to the ion layer formed in the vicinity of wall, i.e., the electric double layer (EDL). The flow structure in a microchannel is governed by the formation of EDL, thus the spatial and temporal formation of EDL will extend our knowledge for designing multifunctional microchannels and suppressing the loss in transport, such as hydrodynamic dispersion is minimized and residence-time broadening is avoided. However, it is impossible to measure the EDL thickness, a.k.a., Debye length, using a far-field optical system, because the EDL thickness is on the order of 10-100 nm, i.e., less than the wavelength of conventional laser system. The evanescent wave generated by total internal reflection at a refractive index surface has the ability to penetrate into the EDL, since the evanescent wave decays exponentially with the distance from the interface, with a characteristic penetration depth of 10-100 nm. Kazoe and Sato (2004)\(^4\) established a large-area evanescent wave light illumination technique utilizing flu-
orescent dye with a depth-wise spatial resolution of a few nm and investigated the two-dimensional structure of EDL between the electrolyte and the wall surface of microchannel in time series. Figure 5 depicts two-dimensional distribution of EDL thickness in the T-shaped microchannel. The experimental results obtained by using the nanoscale measurement will enable us to reconstruct the theory of EDL considering the ion convection.

About five years of experience in the development of sensing techniques has brought inspirations that will yield novel technologies in the future, which will be integrated in the microfluidic device.

References

Glass Machining with Micro End Mills

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Continued from page 1The etching process consists of mask making with lithography and chemical reaction in fluorine acid. Chemical etching, therefore, requires a long time for the process with hazardous operations. Other approaches, then, are required to manufacture glass products at a high production rate with easier operations. Glass machining with a cutting tool is one of the potential manufacturing approaches. Several investigations have already been performed on glass machining [1]-[6] Most of them have tried to machine glasses in the shaping processes with single crystal diamond tools and have focused on the transition from a ductile to a brittle mode. According to earlier works, glasses can be machined in a ductile mode when the undeformed chip thickness is less than a micrometer. However, the glass machining processes have yet to achieve high removal rates. On the other hand, only a few investigators have been studied glass milling. Takeuchi et al. made an excellent work to fabricate microscale structure on the glass [7]. They investigated a ductile-brittle transition with the cutting conditions; and then showed a three-dimensional glass mask within 1mm square. This article describes the machining process with ball end mills to manufacture micro grooves on glass plates [8]. The grooves 15 µ m-20 µ m deep and 150-175 µ m wide are machined in a feed of the tool to improve the machining rate, which is impossible to machine in shaping as earlier researches have done. Most of the researches have used diamond tool to machine glasses so far. On the other hand, cemented carbide tools are applied to cutting operations because large edge roundness makes a large hydrostatic pressure under the cutting edge [9]. It also reduces the cost for glass machining.

2. Milling Process of Glass
The milling process removes materials with rotating cutting edges, where the tool moves the specified paths according to the pre-determined NC code. Figure 1 shows the trajectory of cutting edges in a cross section of a rotating cutter in the milling process. The shaded area shows the material to be removed by a cutting edge. The cutting process starts at Point A and ends at Point C. The unde-
formed chip thickness is small in the beginning and the end of the cut. Crack-free machining of glass is performed in an undeformed chip thickness of less than a micrometer. Brittle fracture, therefore, does not occur in the beginning of the cut around Point A and in the end of the cut around Point C. Point A’ and C’ are the engagement and the disengagement points of the following edge. The surface of the groove can be made in the cutting process from Point A to Point A’ and from Point C’ to Point C. Even if brittle fracture occurs in the process from Point A’ to Point C’, the fractured area can be removed during the subsequent cut. The cutting edges cannot practically trace the ideal trajectory given by the cutting conditions and the tool geometry because the spindle and the milling tool have runout during machining. The undeformed chip thickness, however, changes with cutter rotation in the above manner. As long as the cutting process from Point A to Point A’ and from Point C’ to Point C can remove the glass in a ductile mode, no brittle cracks are left on the surface. The mechanism can be also applied to machining with ball end mills. The radius of the cutter trajectory reduces with the cutter height, where the radius at the bottom of the cutter is zero. All cutting area can follow the above manner. Crack-free surface, therefore, can be machined on the inside of the groove if the glass can be removed without brittle fracture in A-A’ and C-C’ in Fig. 1. The mechanism does not depend on the axial depth of cut. The glass can be machined without brittle fracture even if the axial depth of cut is much larger than a micrometer, which is the advantage of milling over shaping.

3. Application
The orthogonal micro channels are machined on the glass plate in the milling process as shown in Fig. 2. The 1 mm thick plates of the glass are machined with the ball end mills made of cemented carbide as shown in Fig. 3. The diameters of the tools used in the cutting tests are 0.4 mm and 0.5 mm. The depth of the horizontal channels is 15 μm; and that of vertical ones is 20 μm as shown in Fig. 4, where those channels can be machined in a feed of the cutter. The application is made to improve the inspection accuracy of DNA tests with controlling the DNA mounted area on the flat surface. The etching process in fluorine acid has been usually applied to manufacturing of the micro channels on the glass plates. On the other hand, the machining process does not require chemical liquids and the mask making process for etching. The micro channels can be made in a short time with safety. Fig. 5 shows the Y-shaped channels working as a micro reactor, which is usually fabricated on the micro TAS. The grooves 18 μm deep and 77 μm wide are machined with a ball end mill, where the diameter of the tool is 0.1 mm. Fig. 6 shows a set of character patterns machined on the glass plate, where the depth and width of the grooves are 20 μm and 175 μm. The pattern is expressed as a set of bitmap data,
which is converted to the cutter location data. The machining process can be controlled by the cutter location data as usual machining operations.

4. Conclusion
The article describes glass machining with ball end mills to manufacture micro channels. The cutting mechanism with ball end mills is effective to machine grooves 15-20 μm deep and 150-175 μm wide on the glass in a feed of the cutter, whose the removal volume is much larger than that of shaping. Carbide tools can be also applied to glass machining. A large hydrostatic pressure is expected to suppress crack propagation to the machined surface with a large edge roundness of the carbide tools. The above advantages lead to a high machining rate at a low cost. Although the presented approach is not suitable for the mass production, the presented approach can be applied to manufacturing prototypes of micro TASs because of no mask-making process and chemical reaction in fluorine acid.

References

Fig. 5 Y-shaped micro channel

Fig. 6 Micro characters on glass plate


