ISSN 1340-8763

The Japan Society of Mechanical Engineers Vol.16, No.2 December 2005

Jsme News

URL http://www.jsme.or.jp/English

Nano and Micro Machining Technologies and Their Application

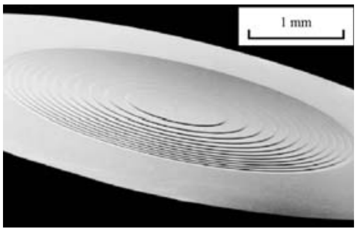
Ultraprecision micro machining of hardened die steel by applying elliptical vibration cutting

Eiji Shamoto

Professor
Nagoya University

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.



Continued on page 2

Advanced Desktop Ultraprecision Machining System for Micro-Mechanical Fabrication

Hitoshi Ohmori

Ohmori Materials
Fabrication Laboratory
Discovery Research Institute
RIKEN

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 micro-manufacturing on the desktop machines with ELID (ELectrolytic In-process Dressing), are demonstrated.

Continued on page 4

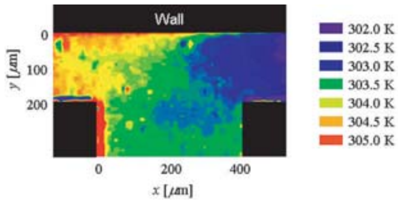
Plenty of Inspiration for the Next Generation of Microfluidic Device

Yohei Sato

Associate Professor
Department of System
Design Engineering
Keio University

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



Continued on page 6

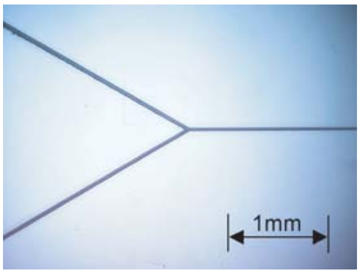
Glass Machining with Micro End Mills

Takashi Matsumura

Professor
Tokyo Denki University

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.



Continued on page 8

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

Eiji Shamoto
Professor
Nagoya University

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.

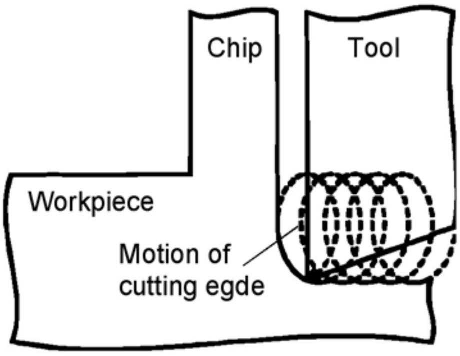


Figure 1: Elliptical vibration cutting process

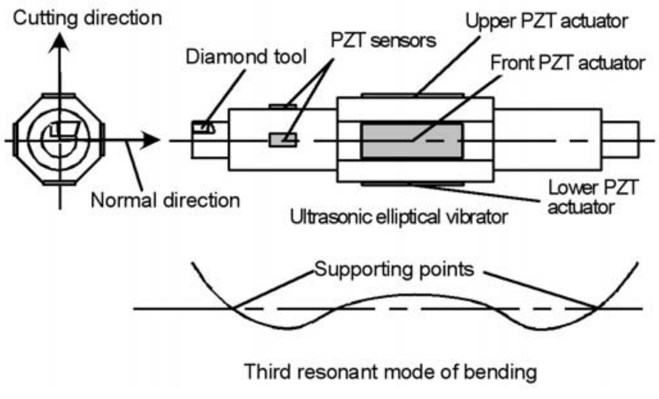


Figure 2: Developed ultrasonic elliptical vibrator

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

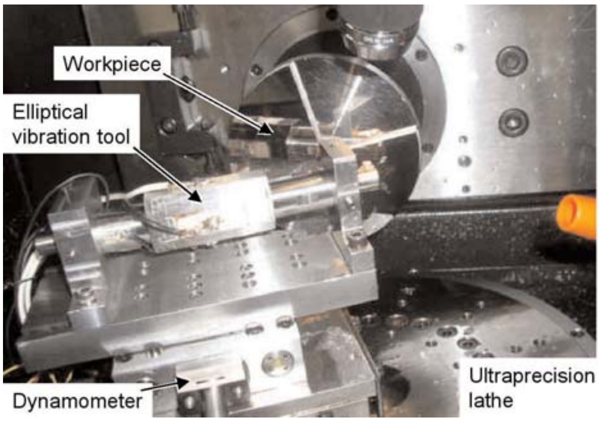
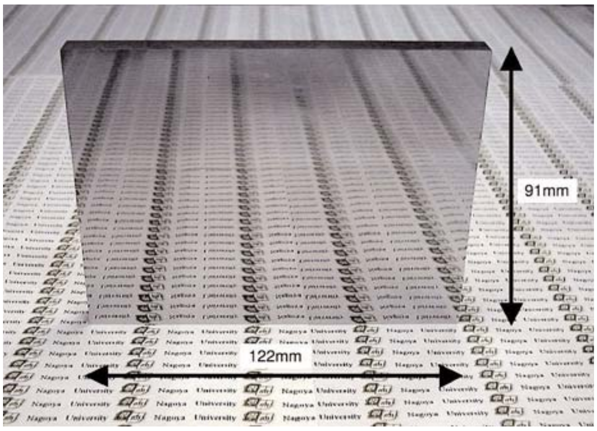
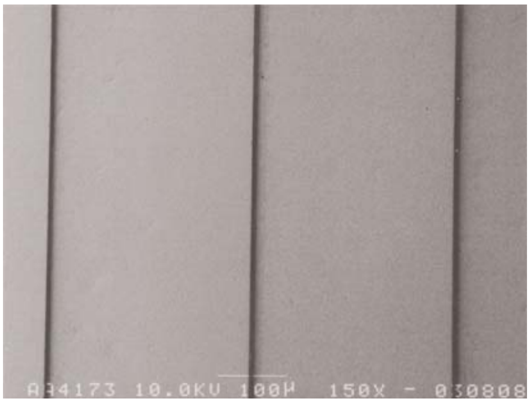


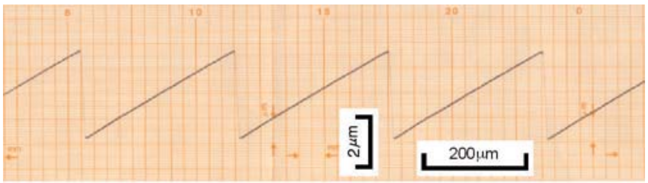
Figure 3: Set up for ultrasonic elliptical vibration cutting



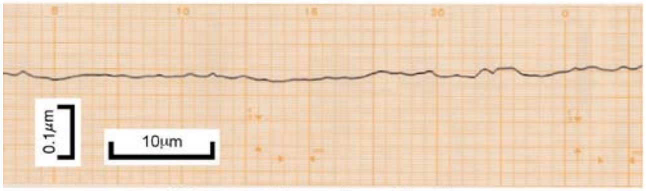
(a) Photograph of mirror surface



(b) SEM photograph of micro grooves



Measured in feed direction



Measured in cutting direction

(c) Profiles of finished surface

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

[Conditions] Workpiece: hardened die steel (JIS: SUS420J2), HRC53. Depth of cut: 3 μm. Feed rate: 300 μm. Cutting speed: 0.25 m/min. Tool: V 107 deg. Circular vibration, Radius: 3 μm, Freq.: 20 kHz.

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-

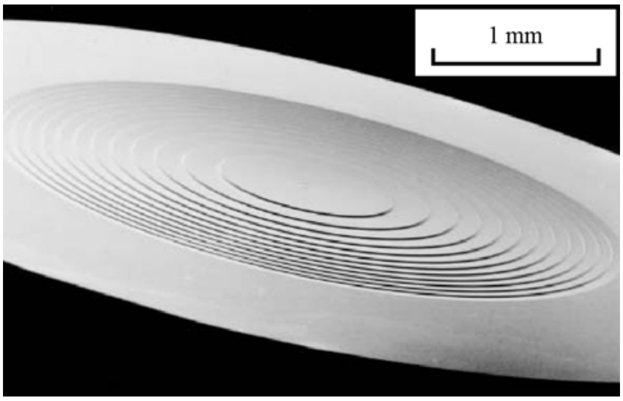


Figure 5: Hardened steel mold of micro fresnel lens finished by elliptical vibration cutting

[Conditions] Workpiece: hardened die steel (JIS: SUS440C), HRC55. Depth of cut: 2 μm. Feed rate: 2 μm/rev. Rotational speed: 20 rpm. Tool: R 25 μm, Rake angle: 0°. Circular vibration, Radius: 1.35 μm, Freq.: 20 kHz.

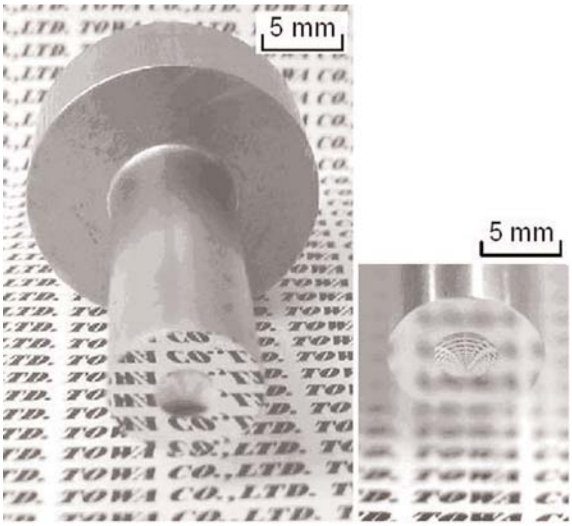


Figure 6: Hardened steel mold of small pick up lens finished by elliptical vibration cutting

[Conditions] Workpiece: hardened die steel (JIS: SUS420J2), HRC48. Depth of cut: 3 μm. Feed rate: 3 μm/rev. Rotational speed: 60 rpm. Tool: R 1 mm, Rake angle: 0°. Circular vibration, Radius: 3 μm, Freq.: 20 kHz.

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

[1] Klocke, F., Dambon, O., 2003, Precision Machining of Glass for Optical Applications, International Progress on Advanced Optics and Sensors: 185-193.
[2] Shamoto, E., Moriwaki, T., 1994, Study on Elliptical Vibration Cutting, Annals of the CIRP, 43/1: 35-38.
[3] Shamoto, E., Moriwaki, T., 1999, Ultraprecision Diamond Cutting of Hardened Steel by Applying Elliptical Vibration Cutting, Annals of the CIRP, 48/1: 441-444.
[4] Shamoto, E., Suzuki, N., Moriwaki, T., Naoi, Y., 2002, Development of Ultrasonic Elliptical Vibration Controller for Elliptical Vibration Cutting, Annals of the CIRP, 51/1: 327-330.

Advanced Desktop Ultraprecision Machining System for Micro-Mechanical Fabrication

Hitoshi Ohmori
Ohmori Materials Fabrication Laboratory
Discovery Research Institute
RIKEN

Continued from page 1

1. 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.

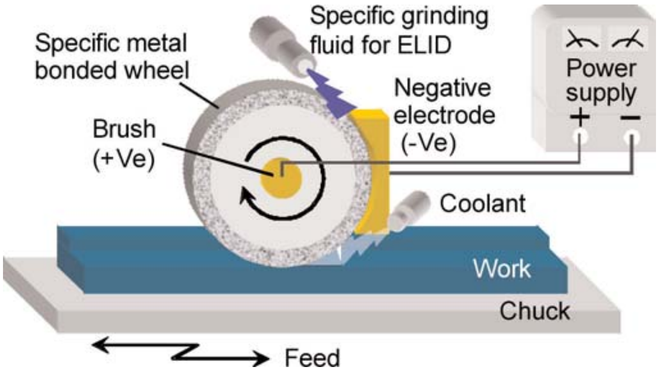


Fig.1 Principle of ELID-grinding

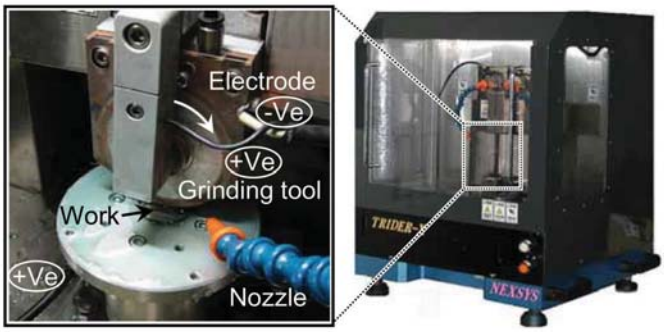


Fig.2 Example of desktop ELID-grinding machine

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 2μm*2μm 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 in-feed, 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.

Fig.3 Desktop ultraprecison 4-axes machine

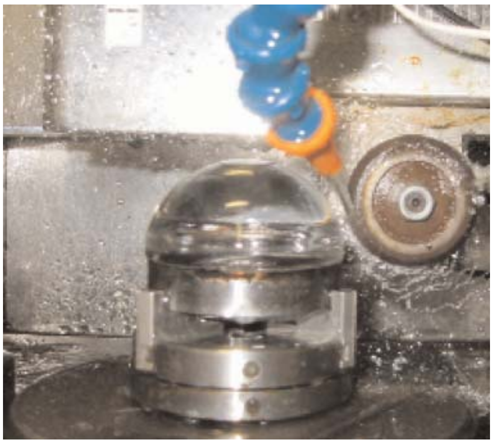
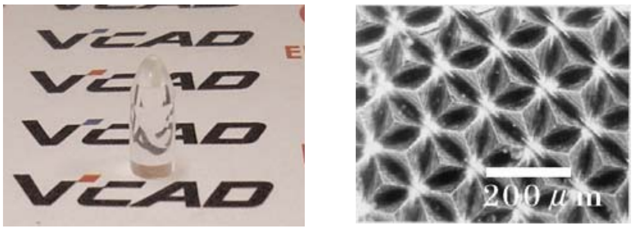


Fig.4 Mirror surface grinding of aspheric lens

4. Conclusions

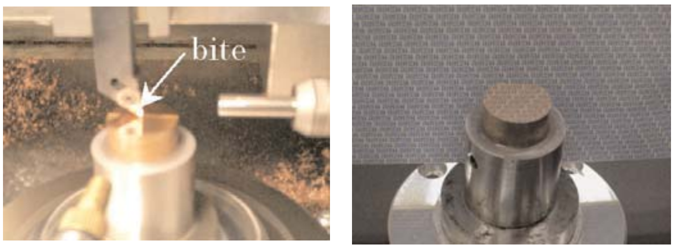
The author expects that the developed ultraprecision desk-

(a) Lens mold (b) Aspheric lens(1)



(c) Aspheric lens(2) (d)Reflector die

Fig.5 Examples produced by ELID-grinding



(a) Turning operation (b) Mirror surface obtained

Fig.6 Mirror surface cutting (turning)

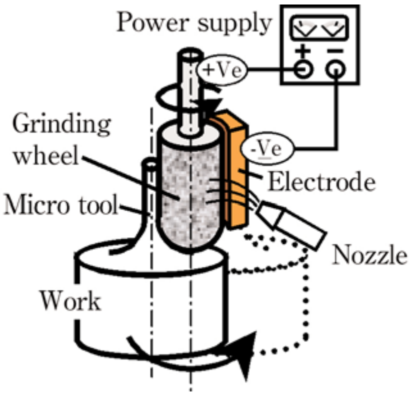
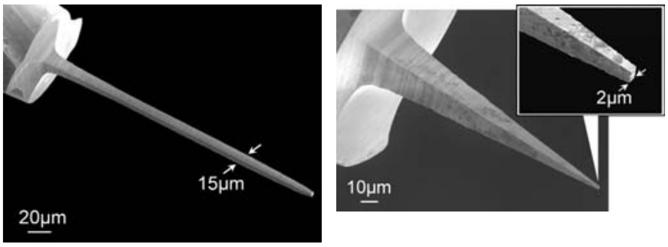
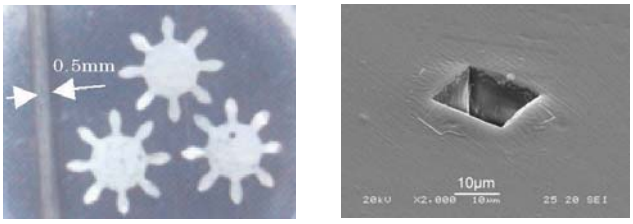


Fig.7 Micro-tool grinding principle



(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.

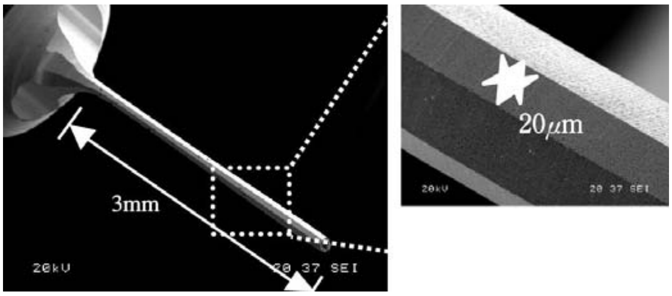


Fig.10 Example of octagonal micro-tool

References
(1) H.Ohmori, et al: Mirror Surface Grinding of Silicon Wafer with Electrolytic In-Process Dressing, Annals of the CIRP, 39, 1 (1990), 329-332.
(2) H.Ohmori, et al: Improvement of Mechanical Strength of Micro Tools by Controlling Surface Characteristics, Annals of the CIRP, 52, 1 (2003), 467-470.
(3) H.Ohmori, et al: Advanced Desktop Manufacturing System for Micro-Mechanical Fabrication, Laser Metrology and Machine Performance Ⅶ, Lamdamap 2005, euspen (2005), 16-29.

Plenty of Inspiration for the Next Generation of Microfluidic Device

Yohei SATO
Associate Professor
Department of System Design Engineering
Keio University

Continued from page 1

system, which may be called as the next generation of microfluidic device, analyzing, chemical reaction, migration, mixing and separation will be innovatively synthesized. Further insight into the flow structure in micro- and nanospace will advance our inspiration that is of importance for the reintegration of essential technologies developed in the 20th century. This article focuses on how the author challenged the development of optical sensing techniques of microchannel flow.

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

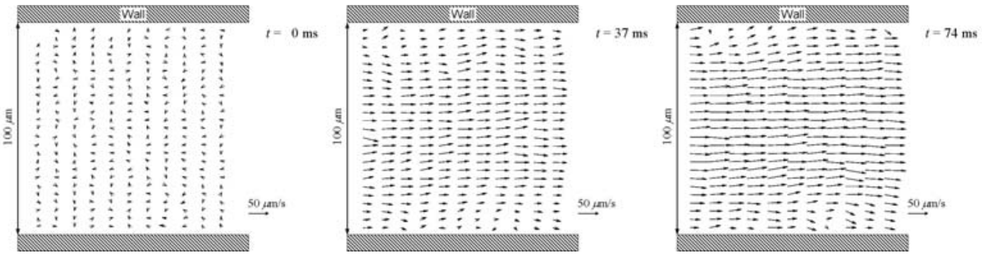


Fig. 1. Temporal evolution of velocity vector field of the pulsating flow in the microchannel with the EK pump operating at 5 Hz. The applied electric field was 60 V/cm. The time interval of each vector map was 37 ms.

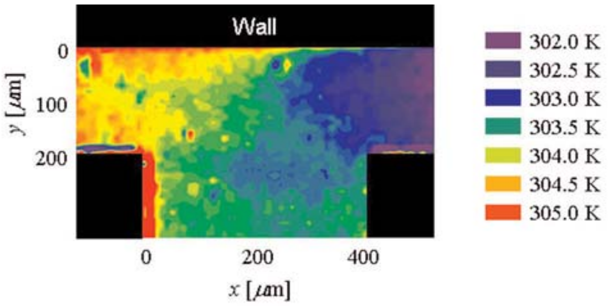


Fig. 2. Two-dimensional temperature distribution in the junction area of the T-shaped microchannel.

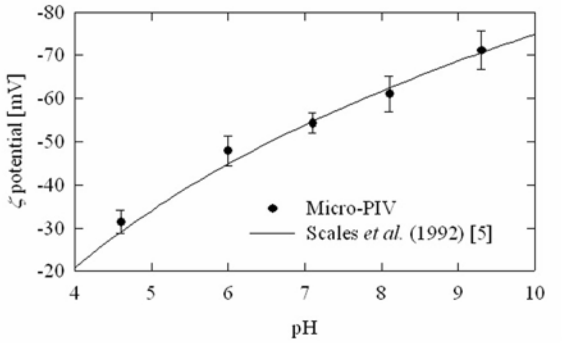


Fig. 4. Zeta-potential at the silica glass of microchannel versus pH, which was obtained by micro-PIV mea surements.

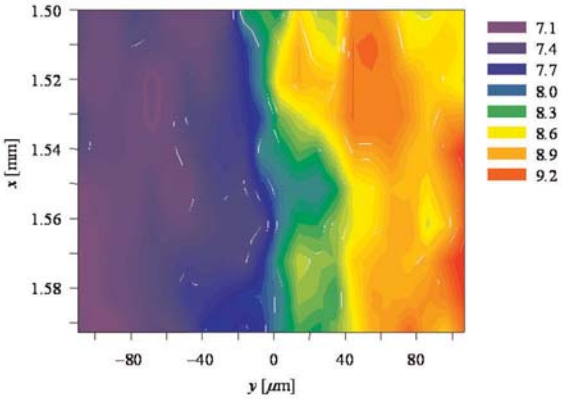


Fig. 3. Two-dimensional pH distribution in the downstream region of the T-shaped microchannel.

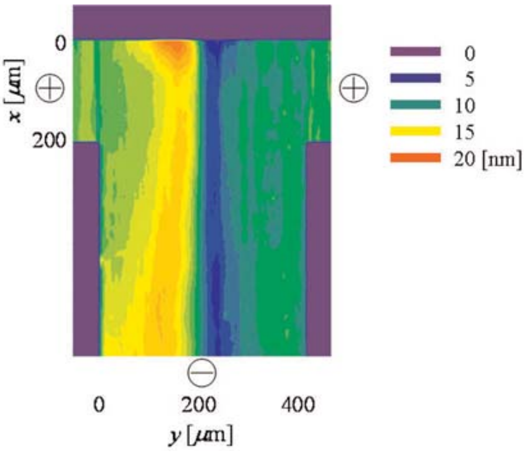


Fig. 5. Two-dimensional distribution of Debye length in the T-shaped microchannel on application of 300V.

micro-PIV. Time-series velocity measurement of unsteady microchannel flow was accomplished by using spatially averaged time-resolved particle tracking velocimetry (SAT-PTV)[1]. 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)[2] 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 μm × 5 μm and a temperature resolution of 0.26 K were achieved by using a cooled CCD camera and a 10× 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)[3] 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 micochannel 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 fluorescent 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

[1] Sato, Y., Inaba, S., Hishida, K. and Maeda, M., "Spatially averaged time-resolved particle-tracking velocimetry in microspace considering Brownian motion of submicron fluorescent particles," Experiments in Fluids, Vol. 35, pp. 167-177 (2003).
[2] Sato, Y., Irisawa, G., Ishizuka, M., Hishida, K. and Maeda, M., "Visualization of convective mixing in microchannel by fluorescence imaging," Measurement Science and Technology, Vol. 14, pp. 114-121 (2003).
[3] Ichiyanagi, M., Sato, Y. and Hishida, K., "Evaluation of electroosmotic velocity and zeta-potential in microchannel using submicron fluorescent particles," Transactions of JSME, Series B, Vol. 71-709, pp.2316-2323(2005).
[4] Kazoe, Y. and Sato, Y., "Formation and transient process of electric double layer between electrolyte-glass interface measured by evanescent wave light illumination," Micro Total Analysis Systems 2004, Vol. 1, pp. 255-257 (2004).

Glass Machining with Micro End Mills

Takashi Matsumura
Professor
Tokyo Denki University

Continued from page 1

The 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 micro-scale 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 15μm-20μm deep and 150-175μm 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-

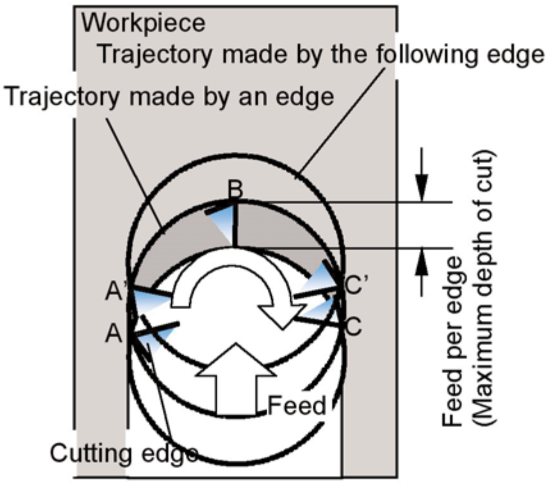


Fig. 1 Milling process

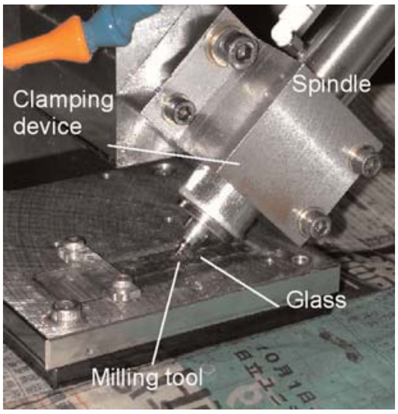


Fig. 2 Cutting operation

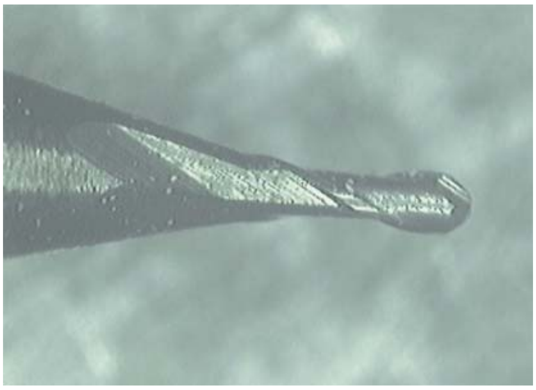


Fig. 3 Micro ball end mill

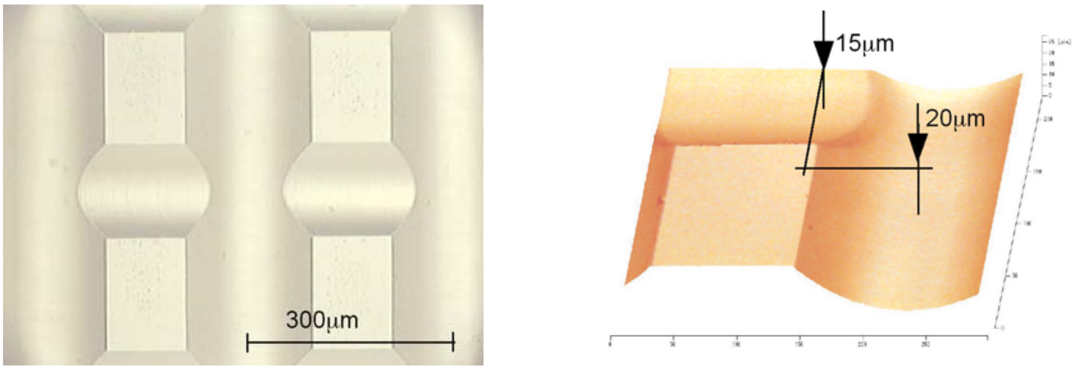


Fig. 4 Orthogonal micro channels

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 1mm 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 0.4mm and 0.5mm. The depth of the horizontal channels is 15μm; and that of vertical ones is 20μm 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 18μm deep and 77μm wide are machined with a ball end mill, where the diameter of the tool is 0.1mm. Fig. 6 shows a set of character patterns machined on the glass plate, where the depth and width of the grooves are 20μm and 175μm. The pattern is expressed as a set of bitmap data,

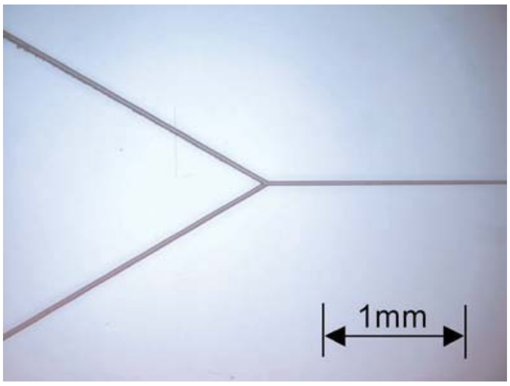


Fig. 5 Y-shaped micro channel

which is converted to the cutter location data. The machining process can be controlled by the cutter location data as usaual 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 of 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.

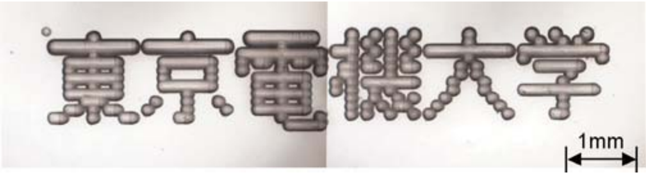


Fig. 6 Micro characters on glass plate

References

[1] Bifano, T. G., Dow, T. A. and Scattergood, R. O., (1991), "Ductile-Regime Grinding: A New Technology for Machining Brittle Materials", Transactions of ASME, Journal of Engineering for Industry, Vol. 113, pp. 184-189.

[2] Ogura, I. and Okazaki, Y., (2000), "Ductile-Regime Machining of Optical Glasses by Means of Single Point Diamond Turning," Journal of the Japan Society for Precision Engineering, Vol. 66, pp. 1431-1435.

[3] Moriwaki, T., Shamoto, E. and Inoue, K., (1992), "Ultra-precision Ductile Cutting of Glass by Applying Ultrasonic Vibration," Annals of CIRP, Vol. 41/1, pp.141-144.

[4] Nakatsuji, T., Kodera, S., Hara, S., Matsunaga, H., Ikawa, N. and Shimada, S., (1990), "Diamond Turning of Brittle Materials for Optical Components," Annals of CIRP Vol. 39/1, pp.89-92.

[5] Puttick, K. E., Rudma, M. R. Smith, K. J. Franks, A., and Lindsey, K., (1989), "Single-Point Diamond Machining of Glasses," Proc. R. Soc. London, Ser. A., Vol. 426, pp. 19-30.

[6] Yoshino, M, Aoki, T. and T. Shirakashi, (2001), "Scratching Test of Hard-brittle Materials under Hydrostatics Pressure, Transactions of ASME, Journal of Manufacturing Science and Engineering, Vol. 123, pp.231-239.

[7] Takeuchi, Y., Sawada, K., and Sata, T., (1996), "Ultraprecision 3D Micromachining of Glass," Annals of CIRP, Vol. 45/1, pp. 401-404.

[8] Matsumura, T. and Ono, T., (2005), "Glass Machining with Ball End Mill," Transactions of NAMRI/SME, Vol. 33, pp.319-326.

[9] Komanduri, R., Lucca, D. A. and Tani, Y. (1997), "Technological Advance in Fine Abrasive Processe" Annals of CIRP, Vol. 46/2, pp. 545-596.

JSME News Vol. 16 No. 2

Editors: Yoichiro Matsumoto, Chisachi Kato,
Toujirou Aoyama
International Activities Committee
Published by The Japan Society of Mechanical Engineers
Shinanomachi-Rengakan Bldg, Shinanomachi 35,
Shinjuku-ku, Tokyo 160-0016, Japan

Fax:81-3-5360-3508

URL http://www.jsme.or.jp/English