Development of numerically controlled local wet etching

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Received 29 October 2006; received in revised form 22 January 2007; accepted 6 February 2007
Available online 23 April 2007

Abstract

Numerically controlled local wet etching (NC-LWE) has been developed as a novel noncontact subaperture deterministic figuring method for fabricating ultraprecision optics or for finishing functional materials. In this method, a localized wet etching area is formed using a combined nozzle that is constructed by coaxially arranging the supply part and the suction part of the etchant. The removal volume anywhere on the workpiece surface is determined by the convolution of the removal function and the dwelling time distribution of the nozzle. The machining properties of this method are insensitive to external disturbances, such as vibration or thermal deformation, because the removal process is performed under a noncontact condition.

I applied NC-LWE to finish a 6 in photomask substrate made of synthesized quartz glass having size of 6 in, and improved the flatness of the substrate from 260 to 69 nm by only one NC-LWE correcting process.

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Keywords: Wet etching; Figuring; Ultraprecision machining; Numerically controlled machining; Optics; Photomask substrate

1. Introduction

In practical production systems, mechanical machining such as slicing, lapping and polishing, play important roles in processing various materials. These methods have a high removal rate and have also greatly contributed to industrial mass-production systems. However, since plastic deformation and brittle fracture are used as removal mechanisms in mechanical machining, subsurface damage, such as dislocations or microcracks, inevitably occurs. Moreover, the accuracy of mechanical machining is strongly affected by external disturbances, such as vibration or thermal deformation of the workpiece and the machine, because of the contact removal mechanism. Therefore, to realize ideal machining, it is necessary to satisfy the requirements of excellent productivity, controllability, and reproducibility, without spoiling the original physical properties of the workpiece material.

Numerically controlled local wet etching (NC-LWE) has been developed as a novel deterministic subaperture figuring and finishing method for any kind of optical component or functional material. In this method, removal of the material is progressed by a chemical reaction between the etchant and the surface of the workpiece, so that there is no degradation of the physical properties of the workpiece material. Furthermore, the machining properties of NC-LWE are insensitive to external disturbances because of its noncontact removal mechanism. Therefore, in this machining system, although the initial cost at the time of introduction is very low, ultraprecision machining properties are achieved very easily compared with other conventional machining methods.

2. Concept of NC-LWE

Fig. 1 shows a schematic diagram of the NC-LWE system. This machine is constructed from a workpiece holder, an XY-table driven by stepping motors, an etchant nozzle head, and an etchant circulation unit. The nozzle head is constructed from the etchant supply part and the suction part, which are arranged coaxially, and the removal area is limited to inside the suction slit. The etchant solution does not remain on the surface of the workpiece after the nozzle has passed, because both the supply and the suction of the etchant are balanced. Therefore, it is not
necessory in this machining method to stop the etching reaction by rinsing with water.

Fig. 2 shows the shape of the removal spot formed using a circular coaxial nozzle head. In this case, the diameter of the suction slit, the composition and temperature of the etchant, the machining time, and the material of the specimen were 15 mm, 22.2 wt% hydrofluoric acid and 25°C, 10 min, and synthesized quartz glass, respectively. The forced suction of the etchant realizes the formation of the localized removal area, and the size of the removal spot corresponds to the diameter of the suction slit. The cross-sectional shape of the removal spot is a simple cylinder, because the etching rate in the etchant contact area is uniform. Therefore, a removal spot with an arbitrary shape and size can be formed by adopting various designs of nozzle head.

The removal rate is controlled by composition and temperature of the etchant, and the dwelling time of the etchant supply nozzle determines the removal volume at any point on the workpiece surface. Therefore, simply controlling the speed of the scanning of the nozzle on the workpiece enables us to create various ultraprecision figures very easily. Furthermore, in this method, the machining property is insensitive to external disturbances, such as vibration and thermal deformation of the electrode, the machine and the workpiece, due to the noncontact removal mechanism.

3. Results and discussion

The removal volume at any position on the workpiece surface is determined by the convolution of the removal function and the dwelling time distribution. The removal function is derived from the shape of the removal spot formed in the unit time, as shown in Fig. 2, and the dwelling time distribution, which is calculated by a deconvolution simulation, is determined by controlling the scanning speed of the worktable. Hence, we can figure any shape by only controlling the scanning speed of the worktable. Fig. 3 shows the relationship between the inverse scanning speed of the worktable and the removal depth per scan, which is obtained by performing one-dimensional reciprocal scanning at various scanning speeds. In this case, the workpiece material and etchant solution were synthesized quartz glass and 22.2 wt% hydrofluoric acid, respectively. The removal depth during the scanning of the worktable increased proportionally with an increase in the inverse scanning speed of the worktable with high reproducibility, and was in agreement with the theoretical value. Therefore, a removal depth of nanometer level can be precisely achieved by only controlling the scanning speed of the worktable.

Fig. 4 shows the relationship between the etching rate of quartz glass and the temperature of hydrofluoric acid with a concentration of 20 wt%. The etching rate exponentially increases with the etchant temperature. Fig. 5 shows the rate of change of the etching rate (\(\Delta \text{ER}\)) of the quartz glass at around 25°C, and \(\Delta \text{ER}\) is defined by the following formula:

\[
\Delta \text{ER} = \frac{\text{ER}(T) - \text{ER}(25)}{\text{ER}(25)} \times 100.
\]

\(\text{ER}(T)\) and \(\text{ER}(25)\) represent the etching rates of the quartz glass at \(T\)°C and 25°C, respectively. It is found from this figure that the temperature of the etchant should be kept within ±0.18°C to keep the etching rate within ±1%. In our system, the etchant solution is circulated through a heat exchanger using a magnetic pump during the machining process.
operation, so that temperature of the etchant is kept within $\pm 0.2^\circ C$, as shown in Fig. 6.

We have achieved a peak to valley (p-v) figure accuracy of 3 nm in the fabrication of an elliptical mirror made of single-crystal silicon for hard X-ray focusing by applying numerically controlled plasma chemical vaporization machining (NC-PCVM) utilizing atmospheric-pressure plasma [1]. However, in the case of machining a low-heat-conductivity material such as quartz glass, the relationship between the removal rate and the dwelling time of the plasma becomes nonlinear, because the surface temperature rises from the inflow of the heat flux from the plasma [2]. Therefore, from the viewpoints of controllability and the stability of the removal volume, NC-LWE is superior to NC-PCVM.

Fig. 7 shows the machining result using a commercially available photomask substrate (152 mm x 152 mm x 6.35 mm$^3$) made of synthesized quartz glass by NC-LWE. The figure error of the substrate was measured by laser interferometer (Zygo, Mark-GPIxps), and the size of the area over which the flatness was evaluated was 142 mm x 142 mm, as required in the Semi P37-1101 standard. The p-v flatness of the substrate fabricated by conventional mechanical polishing was 260 nm before machining. For this substrate, we performed NC-LWE correcting machining, and the process parameters of the feed pitch, the concentration and temperature of hydrofluoric acid, and the diameter of the nozzle were 1 mm,
25 wt% and 25 °C, and 15 mm, respectively. In this case, the p-v flatness of the substrate was deterministically improved to 69 nm by only one NC-LWE correcting process. It seems that circular residual figure errors originate from the measurement error caused by using an interferometer; thus, an improvement in figure measuring will enable us to fabricate more precisely.

Fig. 8 shows the surface roughness of the machined substrate, measured by microscopic interferometer (Zygo, New View 200CHR). The surface roughness was the same as before machining, and its value was less than 0.15 nm rms. Thus, this figuring method does not degrade the surface roughness in the visible-light spatial wavelength region.

4. Conclusions

We proposed NC-LWE as a novel figuring method for fabricating ultraprecision optics or finishing the functional materials. In this method, a localized etching area is formed using a nozzle that is constructed from the supply part and the suction part of the etchant, and the removal volume anywhere on the workpiece surface is determined by the dwelling time distribution of the nozzle. We applied NC-LWE to finish a photomask substrate made of quartz glass using HF solution, and achieved a 69 nm p-v flatness.

Acknowledgments

This work was partially supported by a Grant-in-Aid for 21st Century COE Research (H12) from the Ministry of Education, Culture, Sports, Science and Technology, Japan, and the Industrial Technology Research Grant Program in 2005 from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

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