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Development of a Novel Ductile-Machining System for Fabricating Axisymmetric Aspheric Surfaces on Brittle Materials

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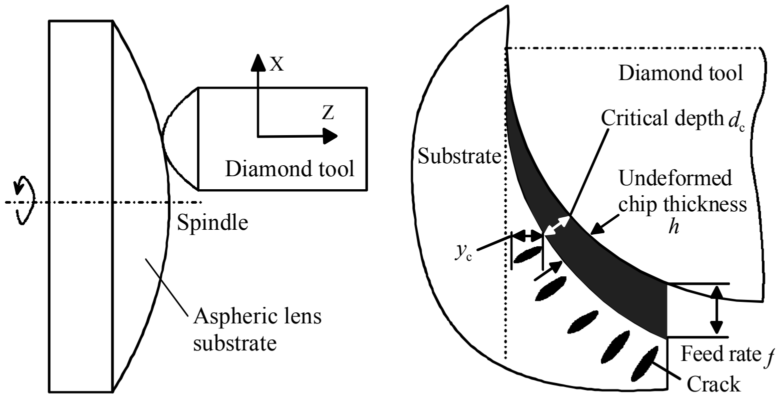
Abstract. A ductile machining system based on the straight-line enveloping method is developed for fabricating convex axisymmetric aspheric surfaces on hard brittle materials. This system enables thinning of undeformed chip thickness in the nanometric range by using a straight-nosed diamond tool on an *X-Z-B* 3-axis simultaneous numerical-control ultraprecision machine tool. The configuration of system and the test cut experiment of a large-scale single-crystal silicon aspheric lens are described. Results indicate that the developed system improves production efficiency and tool life significantly compared to the conventional method.

Introduction

Recently, various kinds of brittle materials such as single crystals, glasses and advanced ceramics are used more and more in the optical industries as substrates or molds of lenses, mirrors and windows etc. Most of these applications require crack-free surfaces. The traditional methods to obtain such surfaces are grinding, lapping and polishing. An alternate method would be to machine brittle materials with a single-point diamond tool in a ductile mode, i.e., ductile (regime) machining, which enables the fabrication of complex-shaped components including aspheric and diffractive surfaces. Ductile machining technology requires the use of a high-rigidity ultraprecision machine tool, a precisely sharpened single-crystal diamond tool with a high negative rake angle (~–40º) and cutting conditions involving an extremely small machining scale (~50 nm) [1]. Under such conditions, a high hydrostatic pressure can be formed underneath and ahead of the tool thus a brittle material will behave in a ductile mode rather than being fractured, generating continuous plastically deformed chips and smooth surfaces.

The existing ductile machining technology pioneered by Blackly at al. and Nakasuji et al. uses a round-nosed diamond tool at an extremely low tool feed rate [2-4]. On those occasions, ductile mode material removal occurs along the tool tip apex where the undeformed chip thickness is sufficiently small, thus a damage-free can be obtained. However, the use of an extremely low tool feed rate (~1 μm/rev) leads to a very long cutting length and consequently causes severe wear of diamond tools and also lowers production efficiency, especially when machining large-diameter components [5]. To solve this problem, the authors used a straight-nosed diamond tool in the ductile machining of silicon [6]. This method enables thinning of undeformed chip thickness in the nanometric range without the need for lowering tool feed rate. It has been shown that ductile machining of silicon at a tool feed up to a few tens of micrometers was possible [7]. In the present work, a prototype aspheric-surface fabricating system based on this method is developed. This paper deals with the basic concept and the configuration of the system. The test cut experiment of a large-scale single-crystal silicon aspheric lens for infrared applications is described.



(a) Arc-enveloping method (b) Machining model

Fig.1 Schematic of the existing aspheric surface cutting method

Straight-Line Enveloping Method

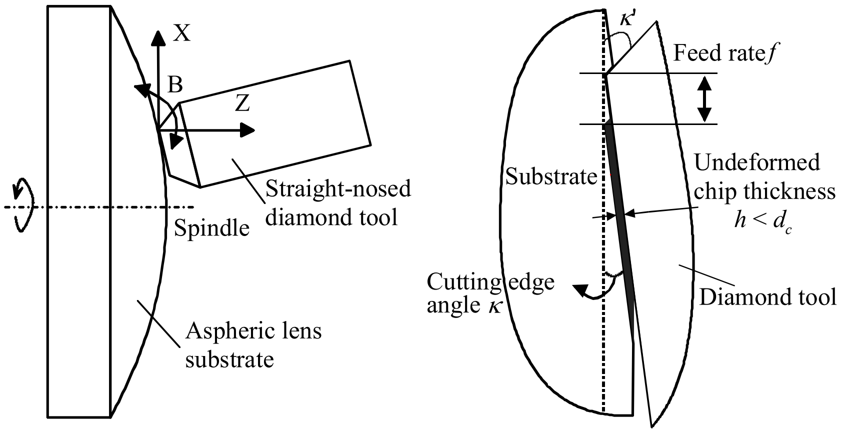
An aspheric surface is expressed as the difference between a sphere and an asphere at different heights above the optic axis [8]. An axisymmetric aspheric surface can be generally described by

$$z(x) = \frac{Cx^2}{1+\sqrt{1-(k+1)C^2x^2}} + \sum_{i=1}^{m} a_i x^i \tag{1}$$

where C=1/r, in which r is the radius of curvature of the spherical surface; x is the distance from the optic axis (Z); k is the conic constant, a parameter representing the eccentricity of the conic surface; a_i for even i are the aspheric deformation constants, and a_i for odd i are aspheric coefficients used to define other polynomial curves by setting C=0.

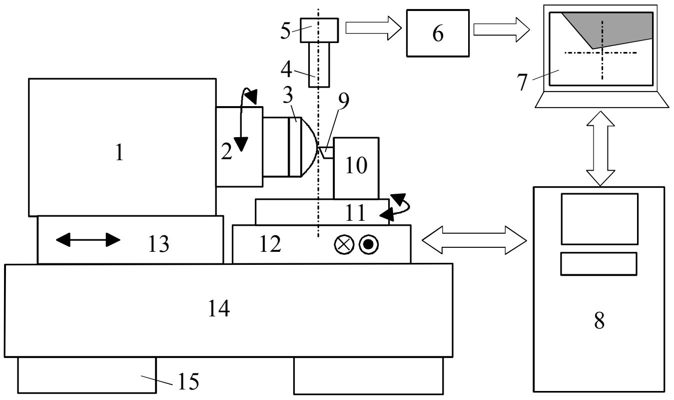
In the available literatures [9, 10], an aspheric surface has been cut using a round-nosed tool on a 2-axis (X-Z) machine, as schematically shown in Fig. 1(a). In this method, the arc of tool envelops the aspheric surface and the cutting model can be schematically shown as Fig. 1(b). In the figure, the undeformed chip thickness varies along the cutting edge. A truly ductile response only occurs along the apex of the tool tip where the undeformed chip thickness is smaller than a critical value (critical depth d_c), while the upper material is fractured. Thus for a given d_c, tool feed must be kept smaller than a critical value ($f_{\max}$) in order to obtain a crack-free surface. In previous studies, $f_{\max}$ for silicon was reported to be ~1μm/rev [3, 4]. If the area of surface to cut is constant, an extremely small tool feed will lead to a very long cutting distance, which increases tool wear and lowers machining efficiency [7]. In particular, when machining a large-diameter component tool wear will become a critical problem. Moreover, in the arc-enveloping method, expensive diamond tools with very high arc accuracy is necessary due to the fact that the resulting form accuracy is strongly dependent on the arc accuracy of tool [9].

In the present work, a new aspheric cutting method, termed the straight-line enveloping method (SLEM), is proposed. A schematic representation of the method is shown in Fig. 2(a). The tool is moved in the X and Z directions and simultaneously rotated about a B-axis that is perpendicular to the X-Z plane. The objective aspheric surface is then enveloped by the straight edge of the tool. The corresponding cutting model is shown in Fig. 2(b). In this case, undeformed chip thickness h is uniform within the entire cutting region and is determined by tool feed f and cutting edge angle κ. Theoretically, for a given d_c, the maximum tool feed $f_{\max}$ for ductile machining can be expressed by



(a) Straight-line enveloping method (b) Machining model

Fig.2 Schematic of aspheric surface cutting by straight-line enveloping method



1 : Air spindle
2 : Vaccum chuck
3 : Workpiece
4 : Mini-microscope
5 : CCD camera
6 : Adapter
7 : Personal computer
8 : Numerical controller
9 : Diamond tool
10: Adjustable tool post
11: *B*-table
12: *X*-table
13: *Z*-table
14: Machine base
15: Air mount

Fig. 3 Schematic of the system configuration

$$f_{\max} = \frac{d_c}{\sin \kappa} \, . \tag{2}$$

Therefore, by using a sufficiently small cutting edge angle κ, an extremely small undeformed chip thickness h can be obtained even at a large tool feed f. Ductile machining at a large tool feed improves both machining efficiency and tool life. In addition, the straight-nosed tool used in this method is easier to manufacture than the round-nosed tool, thus low-cost production can be expected.

System Configuration

As can be seen in Fig 2(a), the proposed method requires the use of a 3-axis (*X-Z-B*) machine tool and these axes must be simultaneous numerically controlled. In this study, a specially manufactured *X-Z-B* 3-axis simultaneous numerical-control ultraprecision lathe was used. Figure 3 shows a schematic of system configuration. The machine has an air-bearing spindle with a maximum rotation rate of 2500 rpm, two perpendicular hydrostatic slide tables along the *X*-axis and *Z*-axis respectively as well as a hydrostatic rotary table around the B-axis. The hydrostatic bearing has the advantages of high stiffness and low friction. The motions of all three axes are real-time measured by linear laser scales and numerically controlled in a closed loop. This provides the X and Z slide tables with a linear motion revolution of 10 nm per step, and the B-table with an angular motion resolution of 0.001º, respectively. The machine base was made of granite and supported by air mounts for the purpose of isolating external vibration. Figure 4 is a photograph of the main section of the machine tool.

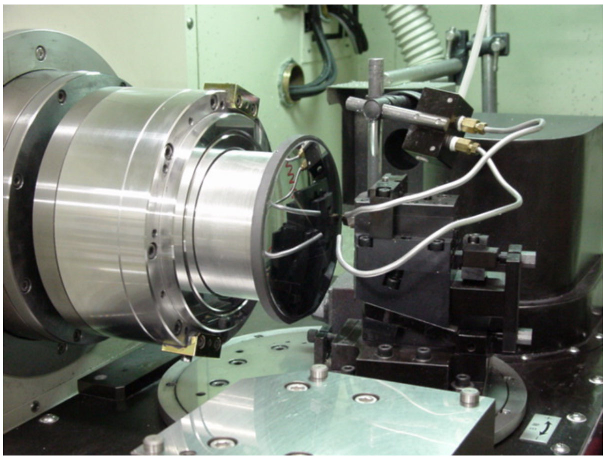


Fig.4 Photograph of the main section of the machine tool

In Fig. 2(a), the apex of the straight-nosed diamond tool should be set accurately to the centerline of B-axis in order to achieve high machining accuracy. To assist tool setting, a tool vision system consisting of a compact microscope, a CCD camera and a personal computer with monitor was used, as shown in Fig. 3. By monitoring the tool position with the vision system while rotating the B-axis for a half circle (180º), the initial tool positioning error with respective to the centerline of B-axis can be measured accurately and rapidly. The tool positioning error can be then eliminated through adjusting a three-dimensional tool post equipped on the B-table.

Experimental Results

An infrared lens substrate made of single-crystal silicon (100), 125mm in diameter and 15mm thick, was used as the workpiece for test cut. The objective is to generate a convex aspheric surface with coefficients k=0, a_1=0, a_2=0.0004, $a_{i\ (i=3\sim\infty)}$=0 on the substrate. First, one face of the substrate was contoured into a spherical surface having the same curvature radius as the objective aspheric surface by curve-generating grinding. The workpiece was then bonded onto a diamond-turned aluminum blank using a heat-softened glue and vacuum chucked on the machine spindle. Rough cuts were performed before finishing cuts for the purpose of obtaining an aspheric shape from the ground sphere and removing the ground-damaged layer.

A straight-nosed single-crystal diamond tool as shown in Fig.5 was used for the finishing cut. The tool has a 1.2 mm-long main cutting edge, a rake angle of 0º and a relief angle of 6º. A micro chamfer was fabricated on the rake face of the tool in order to obtain a smoothing edge. The tool rake angler γ, cutting edge angle κ and the smoothing edge angle κ' were set to –40º, 0.24º and 0.11º, respectively.

Two finishing cuts were performed under the following conditions: for the rough cut, depth of cut a=10 μm and tool feed rate f=50 μm/rev; and for the fine cut, a=2 μm and f=20 μm/rev. Therefore, the undeformed chip thickness h was 210 nm and 84 nm, respectively. The undeformed chip

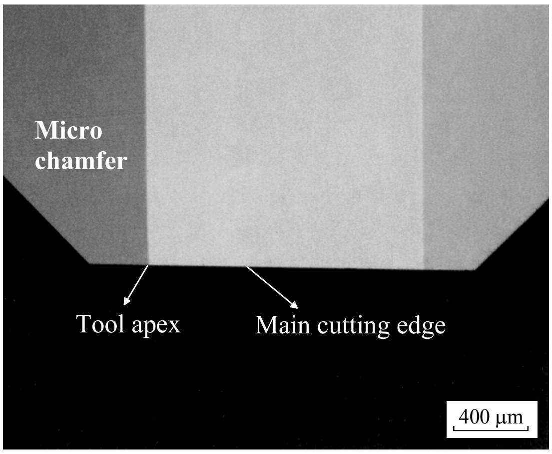
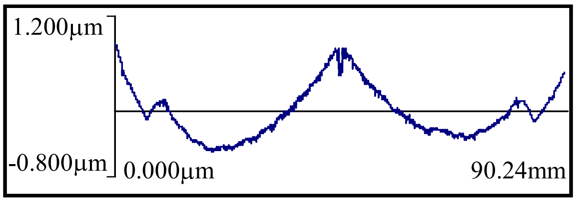
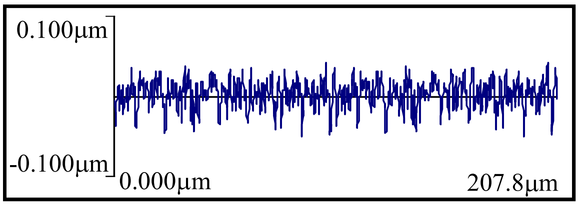


Fig.5 Photograph of a straight-nosed diamond tool with micro chamfers



(a) Form error



(b) Surface roughness

Fig.6 Form error and surface roughness of the aspheric lens

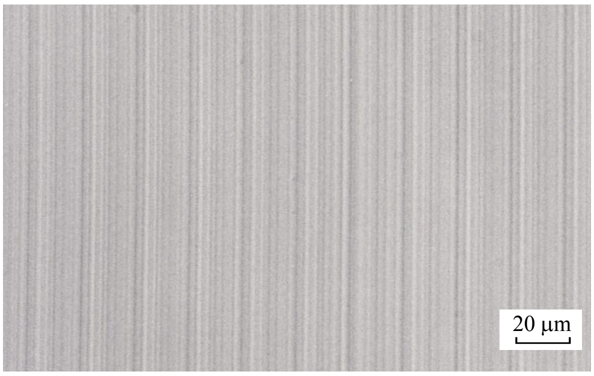
thickness of the fine cut was smaller than the critical depth for ductile machining of silicon (100) [7]. The spindle rotation rate was set to 1000rpm and kerosene mist was used as the cooling fluid.

After the fine cut, the resulting aspheric lens was measured with the Form Talysurf. Figures 6(a) and (b) show the form error and the surface roughness, respectively. The peak-to-valley value of the form error over the measured range (90 mm) is 1.36μm. The form error can partially be attributed to tool setting error and can be reduced by on-machine measurement and compensation machining, which will be described elsewhere. The surface roughness is 16nmRa and 78nmRy.

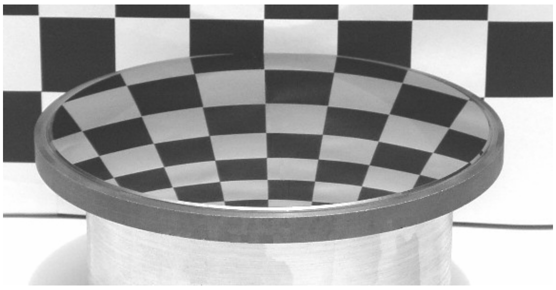
Figure 7(a) is Nomarski micrograph of the lens surface. The surface is smooth, ductile-mode machined, with periodical tool feed marks. Figure 7(b) is photograph of the lens. The entire surface is mirror-like, with no damaged area observed. Because the tool feed rate used here (20 μm/rev) was larger by a factor of ten than that of the conventional method (~1 μm/rev), the corresponding machining efficiency and the tool life have been improved significantly.

Summary

A ductile machining system based on the straight-line enveloping method has been developed for fabricating axisymmetric aspheric surfaces on brittle materials. This system uses a straight-nosed diamond tool on a 3-axis simultaneous numerical-control ultraprecision machine tool, enabling



(a) Nomraski micrograph of lens surface



(b) General view photograph

Fig.7 Photographs of the aspheric lens machined on silicon (100) substrate

ductile machining at high tool feed rate. As a test cut, a 125 mm diameter infrared-lens substrate made of single-crystal silicon was machined into an aspheric surface. Ductile cut surface having 1.36μm form error and 16nmRa surface roughness was obtained at a tool feed rate of 20μm/rev.

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