**Accurate Tool Servo Control for Precision Diamond Turning**

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Abstract

The accuracy of precision diamond turning is limited by stage interferometers, which do not provide a direct measure of the cutting tool proximity to the workpiece or the depth of cut. When making shallow trim cuts on a previously machined part, accuracy can be greatly increased by using a proximity or depth sensor on or close to the tool for position servo control. Further improvements in both surface form and finish can be made by machining a pattern into a sacrificial layer, which is then transferred into the workpiece by a selective etch process. These techniques are particularly useful for EUV and X-ray mirrors and gratings.

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Precision Diamond Turning (PDT) is a commonly-used method for fabricating optical components. One example of a state-of-the-art PDT system is the Nanoform 1000 (manufactured by Precitech [1]), which has a 1-meter swing diameter and has a form accuracy specification of 125 nm P-V and surface finish of 1.25 nm Sa. For applications such as EUV lithography and synchrotron X-ray optics the form and finish accuracy can both be of order 0.2 nm [2], which can be achieved by post-polishing a diamond-turned part.

Some EUV/X-ray applications require blazed (sawtooth-profile) reflection gratings, which can be diamond-turned but cannot be post-polished by conventional means to achieve the requisite shape and smoothness requirements. An alternative method, anisotropic etching of silicon, can form geometrically perfect gratings with surfaces defined by the silicon crystal planes, but this method is inapplicable to gratings on curves substrates. [3]

Synchrotron gratings have been made with a mechanical ruling engine by patterning the grating in a gold layer on silicon, and then etching the gold to transfer the pattern into the silicon. The silicon etches much slower than the gold, so the grating's depth dimensions, including its form and finish errors, are scaled down by the etch process. For example, Siewert et al. used this method to reduce the grating blaze angle from 6.6° to 0.62°, and the surface roughness was reduced from 0.56 nm r.m.s. to 0.12 nm r.m.s. [4] The method could be modified to use other etch chemistries, e.g. with PMMA used as a sacrificial layer instead of gold.

In principle, Siewert's method could be used with diamond turning, but the accuracy of diamond turning is not as good as mechanical ruling and may be inadequate even with the error scale reduction of the selective etch process. The grating can be patterned in a substrate that has been machined and polished to a very accurate form specification, but the PDT machine cannot maintain the accuracy during grating formation because the tool positioning system, which relies on stage interferometers, does not provide a direct measure of either the cutting tool's proximity to the workpiece or the depth of cut.

This limitation can be overcome by mounting a position sensor or sensors (e.g., interferometric or capacitive sensors) on the tool post, or on the tool itself, to provide feedback for the tool servo control. For example, Figure 1 illustrates an adaptation of Siewert's process for PDT in which a grating is formed by the following steps: (1) Form a curved surface in an aluminum substrate by diamond turning. (2) Deposit a silicon layer on the aluminum. (3) Polish the silicon surface to correct the form error and reduce the surface roughness. (4) Deposit a gold layer on the silicon. (5) Pattern a blazed grating structure in the gold layer via diamond turning. (6) Apply Siewert's etch process to transfer the grating pattern into the silicon. In step 5 (shown in Figure 1), a single-crystal diamond tool us used to define the grating surface profile, and an interferometric proximity sensor, which is attached to or has a close mechanical coupling to the tool, monitors the tool position relative to the workpiece for servo control.

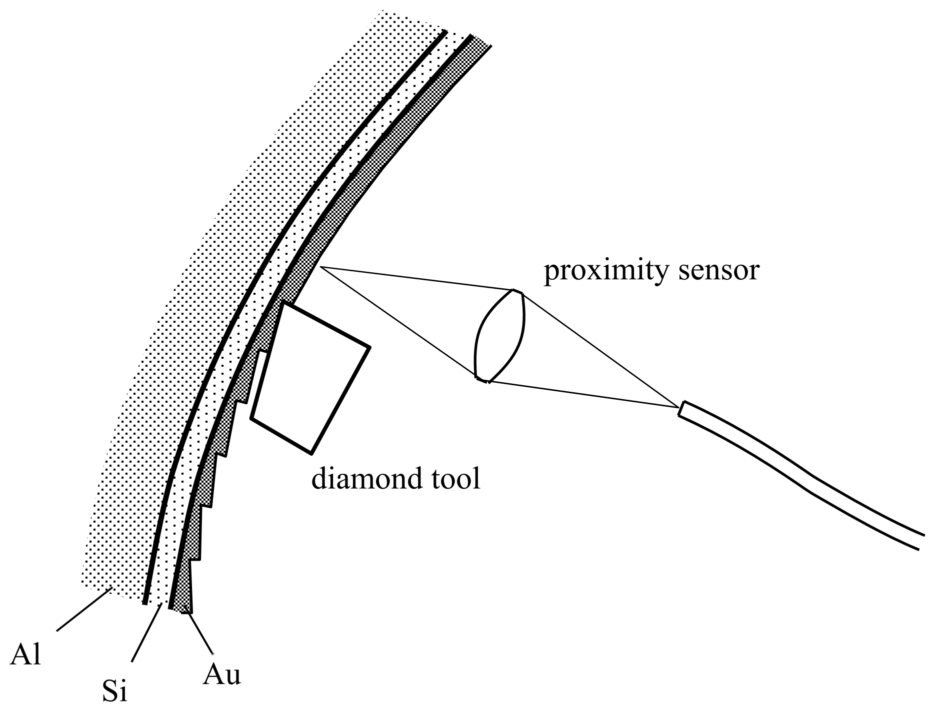


Figure 1

A variety of sensor heads and systems suitable for this application are manufactured, for example, by Attocube. [5] An optical fiber connects the sensor head to the interferometer encoder and electronics. The surface reflection from the fiber exit face provides an internal phase reference for the interferometer. The beam transmitted from the fiber is focused by a lens onto the workpiece ahead of the tool (on the uncut surface), and is retroreflected back into the fiber to form and interference signal with the reference beam.

Figure 2 illustrates an alternative position control sensor, which directly measures the PDT tool's depth of cut. In this system the reference beam is not reflected from the fiber end. Instead, the fiber output beam is split into two beams, which are both focused onto the workpiece, one in advance of the tool cutting edge and one behind the edge. The beams are reflected and recombined in the fiber to provide a direct interferometric measure of the cut depth.

Both beams follow the same optical path, except for the very slight lateral offset between the focal points, so the depth measurement will be immune to air turbulence and thermal gradients.

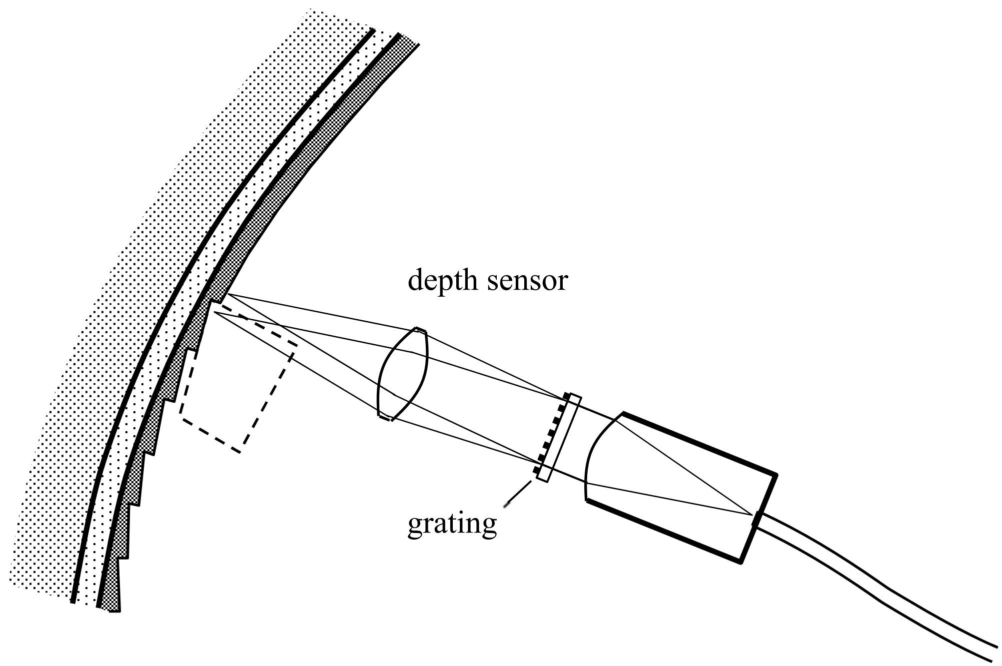


Figure 2

The sensor head could be constructed as illustrated schematically in Figure 2. The optical fiber is optically coupled to a plano-convex lens, so there is no reflection at the fiber exit face. A second lens focuses the optical beam onto the workpiece, and a diffraction grating between the two lens elements splits the beam energy into two foci and recombines the retroreflected beams.

The combination of a selective etch process such as Siewert's and workpiece proximity/depth sensors could be useful not only for grating fabrication, but also for general-purpose surface form correction. For example, Figure 3 illustrates a PDT process similar to Figure 1, except that a continuous feed is used to form a corrected surface without a grating pattern. In the illustrations the diamond-turned pattern is cut into a sacrificial layer, but proximity/depth sensors can also be used for direct cutting into the finished part.

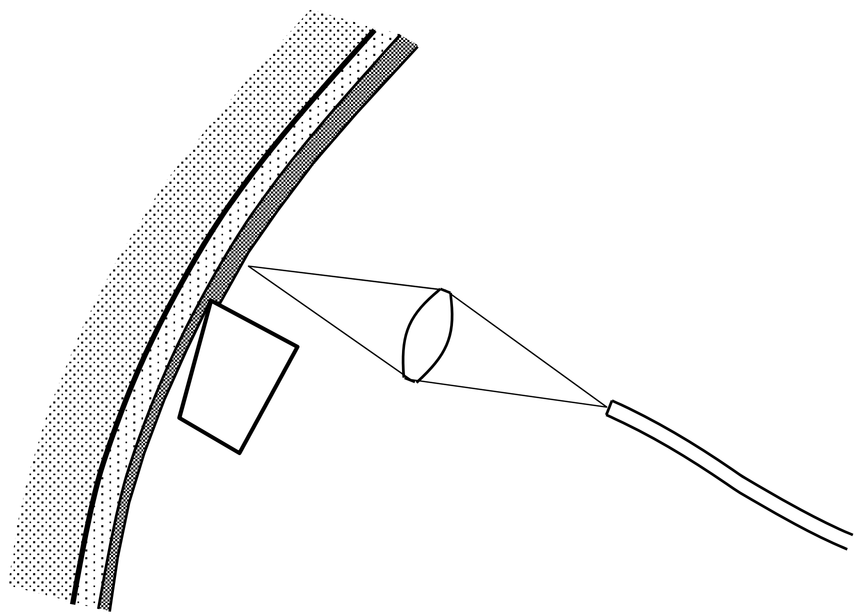

Figure 3

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