Predicting Surface Figure in Diamond Turned Calcium Fluoride Using
In-Process Force Measurement

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Abstract
Single crystal calcium fluoride (CaF$_2$) shows significant variation in material properties as a function of
crystallographic orientation. The surfaces generated by material removal processes such as diamond turning are
influenced by this anisotropy and consequently show periodic undulations aligned with the crystal structure.
This paper explores the relationship between surface figure and cutting forces measured during the diamond
turning of single crystal calcium fluoride. The cutting forces, when mapped to the physical geometry of CaF$_2$
plano (flat) optics, show good correlation with surface figure measured by interferometry.

Introduction
Despite promising results obtained in applications such as photolithography optics, calcium fluoride is widely
considered a challenging material to work with because of its high coefficient of thermal expansion (24 × 10$^{-6}$
°C$^{-1}$) and relatively low hardness (one-seventh that of silicon). However, calcium fluoride is one of the few
visible or ultraviolet wavelength optical materials that may be machined with single point diamond tools to
obtain specular surfaces and minimal subsurface damage. A typical diamond turned workpiece might have a 3
nm $R_a$ and 18 nm peak-to-valley micro-roughness. The subsurface damage, as measured by the quasi-Brewster
angle measurement technique, ranges from 250 to 500 nanometers [1].

The surface figure and surface finish obtained in diamond turning is strongly influenced by the
crystalline structure of calcium fluoride. Yan reports that the same radial spokes of damage that are well known
in silicon can arise in CaF$_2$ with various combinations of typical diamond turning parameters [2]. Yan also
reports machining parameters that may be chosen to generate damage-free surfaces in single point diamond
turning for all crystal orientations [3]. This orientation-dependent behavior is further documented in the
extensive literature on silicon and diamond, two other crystalline materials that show the same large variations
in machinability with crystal orientation [4,5,6,7,8].

When diamond turning CaF$_2$ optics, the cutting tool encounters different orientations of the crystal
within each rotation of the workpiece. As with diamond and silicon, the orientation-dependent material
properties of calcium fluoride cause variation in the apparent material stiffness that leads to oscillatory cutting
forces and undulations in the surface figure. During the course of this work, the surface figure of plano (111)
CaF$_2$ workpieces invariably showed three-lobed (trifoil) spherical aberration with amplitudes ranging from 25
to 250 nm peak-to-valley depending on the material removal rate and the condition of the diamond tool.

Despite this lobing, single point diamond turning (SPDT), followed by magnetorheological finishing
as needed, is a good alternative to traditional grinding and polishing because the material removal rate is much
higher, the subsurface damage propagated into the workpiece is low (sub-micrometer) and aspheric shapes can
be generated and polished directly.

An essential requirement in turning brittle materials such as CaF$_2$ is the selection of cutting parameters
such that the material removal mechanism is in the ductile mode regardless of the crystal orientation [9]. This is
achieved by keeping the effective depth of cut below the critical uncut chip thickness $t_{unc}$ which varies with tool
geometry and crystal orientation. Yan studied this effect for (111) CaF$_2$ turning and found that $t_{unc}$ is 85 nm in
the hard <112> direction with flat diamond tools and -20° rake angle [2]. In our work, we used round nosed
tools and found the critical depth of cut to be somewhat larger, presumably as a result from the substantially
different geometry of the chips. A micro fracture model explaining the difference between the micro fractures
left by round and flat tools is found in Blake and Scattergood [10].
In summary, CaF$_2$ presents an interesting opportunity in optical fabrication because the material offers both favorable optical properties and the possibility of reduced manufacturing costs by replacing the traditional grinding steps with a single diamond turning setup. The remainder of this paper demonstrates the relation between crystal structure-induced spherical aberration and cutting forces that arise in diamond turning anisotropic CaF$_2$. A model for predicting the magnitude of these aberrations from in-process force measurement is presented and validated. The model enables the prediction of aberrations at various conditions by extrapolation from force measurements made during a single diamond turning operation.

**Experimental Setup**

In order to validate the cutting force model presented in the previous section, calcium fluoride turning tests were performed on a hydrostatic way, diamond turning lathe with a 10 nm programmable resolution (Moore Nanotechnology Systems AG150). An illustration of the machine and its vertical air bearing spindle (Professional Instruments Twin-Mount) is shown in Figure 1. A high resolution three-axis dynamometer (Kistler MiniDyn 9256A2) measures the three components of force on the tool.

![Figure 1 Hydrostatic way diamond turning lathe with air bearing spindle.](image)

A capacitance probe (Lion Precision C1-C with DMT 10 driver) targets the rotating workholder (not shown) in order to synchronize the cutting force data with the rotation of the workpiece. This index pulse allows accurate mapping of the cutting forces to the trifoil structure of the (111) CaF$_2$ crystal in the presence of spindle speed variations.

When machining brittle materials such as calcium fluoride, a negative rake angle is beneficial due to its mitigating effects on fracture [11]. The synthetic, monocrystalline diamond tools used in these turning experiments achieve the negative rake angle with a chamfer, or radial rake. Most tests were run with 0° rake angle or -30° radial rake angle with a -10° clearance angle, and 1.5 mm nose radius (Edge Technologies, Inc). More negative radial rake angle tools (-45° and -60°) were also used with less favorable results. The tool edge radius, which may be measured in a low voltage SEM or by AFM, is less than 50 nm [12]. The tools are chemically faceted on the rake and nose facets to remove surface and subsurface damage from the tool edge. Mineral oil coolant was used during all cutting tests.

The three components of the diamond turning cutting forces contain useful information about the state of the material removal process. Changes in the forces reflect changes in the geometry of the tool (wear) and the surface finish of the machined surface. Figure 2 shows the three components of the average cutting force as the tool progresses from the outside to the inside of a calcium fluoride workpiece. The nominal force levels remain roughly constant, despite the fact that the cutting velocity approaches zero at the center of the workpiece. In these tests, a small hole was ground into the center of the workpieces prior to cutting so the cut ends one mm from the axis of rotation. Although not shown here, the cutting force results from subsequent passes over the workpiece are very similar to the data shown in Figure 2; however, after many facing cuts, the forces eventually increase as the tool edge begins to wear. At this point, the surface of the workpiece shows visible damage in the hard machining directions of the CaF$_2$ crystal and the diamond tool must be resharpened.
Figure 2 Calcium fluoride cutting forces after filtering to remove three-lobe fluctuations.

Figure 3 shows a close-up view of the unfiltered cutting forces with fluctuations over two revolutions of the workpiece that are due to anisotropy. The three-lobe fluctuations result from the interaction of the cutting tool and the crystalline structure of the (111) calcium fluoride workpiece. The fluctuations in forces are highly repeatable and additional similarity is seen between the subsequent revolutions (first three peaks vs. the second three peaks). The three peaks in each revolution are not identical because the crystal is not perfectly aligned with the cutting plane. As a result, the diamond tool engages the crystal at a small angular offset that leads to the slight variation between the three lobes. This effect was originally documented in diamond polishing [8].

Figure 3 Two revolutions of cutting force data showing the three-lobe fluctuations on a (111) CaF$_2$ crystal.

Figure 4 shows the three components of cutting force mapped to the physical geometry of the round, flat workpieces. The three-lobe (trifoil) fluctuations in force resulting from the (111) symmetry of the crystal are clearly evident.

A series of calcium fluoride optics were diamond turned with -30° radial rake angle diamond tools of 1.5 mm radius with mineral oil coolant. Trial cuts were made at a depth of cut of 25 micrometers, feed rate of 4 micrometers/rev and two spindle speeds (600 and 1200 RPM). The three force components were measured during all tests. The finished workpiece surfaces were measured with a grazing incidence interferometer (Tropel FlatMaster 200) to quantify the height of the trifoil aberration. A 1.2 N PV normal force was measured when the CaF$_2$ workpiece was turned with a spindle speed of 600 RPM and 4 micrometers/rev feed rate. A 120 nm PV figure aberration is predicted using the measured loop stiffness of 10 N/micrometer. The actual aberration was measured to be 130 nm.
Figure 4: The cutting force components mapped to the surface of a Ø80mm plano (111) CaF₂ workpiece.

Conclusions
This paper demonstrates that trifoil aberration is predictable using in-process force measurements taken while diamond turning (111) calcium fluoride. The predictions agree with actual measurements within less than 13% error. The model also shows how the trifoil aberration can be minimized using a higher stiffness machine tool. The predictable nature of the trifoil aberration makes it possible to design a cutting process capable of generating rough-turned optics of sufficient quality for final polishing.

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References