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Diamond Turning Background

Diamond turning (DT) has proven to be a cost effective optical fabrication technique for both aspherical and spherical/flat figures when precise geometrical tolerances are important[1]. Diamond turning accuracy and capabilities have been steadily advancing. Our Large Optics Diamond Turning Machine (LODTM) offers state-of-the-art capability for sizes up to 1.6 m diameter. Large optics have been turned to better than 300 Å rms figure accuracy and small non-rotationally symmetric optics have been made to $\lambda/10$ in the visible[2]. Our Precision Engineering Research Lathe (PERL II) has achieved a surface finish of 7 Å rms on electroless Ni[3].

We are interested in the DT of crystals for several reasons. DT has been very effective to insure requisite accurate geometrical orientation of optical surfaces to crystalline axes for frequency conversion applications. Also, DT can achieve figure up to the edge of the crystal. Another key DT benefit is enhanced laser damage threshold, which we feel in part is due to the freedom of the surface from polishing impurities.

Several important issues for diamond turning optical crystals are the tool wear, associated surface finish, and laser damage properties. We have found that careful selection and control of diamond turning parameters can yield production techniques for crystals previously considered incompatible with diamond turning.

Crystalline Optical Materials

Table 1 lists the materials we have studied, grouped according to their applications. The group of frequency conversion materials contains both high temperature and aqueous solution grown crystals. All the other materials are inorganic crystals grown at high temperatures.

A. Frequency Conversion Crystals

The use of nonlinear crystals to convert near-infrared, solid-state laser light to the visible or near ultraviolet is of a particular interest at LLNL for large aperture solid-state lasers used for laser driven inertial confinement fusion (ICF) experiments. Diamond turning was a crucial technology in the fabrication of the 27 x 27 cm plates of potassium dihydrogen phosphate (KDP) currently used to frequency convert the 120 kJ NOVA glass laser system.[1] As part of an effort aimed at finding higher efficiency alternatives to KDP for the next generation of fusion drivers, we investigated the diamond turning of LAP and other series of organic nonlinear crystals[4].

Deuterated L-arginine phosphate (DLAP), L-arginine acetate (LAAc), diammonium tartrate (DAT), and lithium formate (LF), are potential high performance frequency convertors for fusion lasers. Like KDP, LAAc appears to be less susceptible to the tool fouling problem than LAP.

We also investigated two materials, urea and barium metaborate (BBO), which were not of direct interest to ICF but are of some interest in commercial frequency conversion applications. Because of its softness, urea has long been considered a difficult material to polish to high precision by conventional means. Small pieces (< 2 x 2 cm) of BBO can be polished conventionally without problems. However relatively thin (2-3 mm) BBO optics are required for efficient harmonic conversion[5]. This might lead to

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fabrication problems for large aperture plates because BBO has weak basal cleavage plane.

B. Lithium Niobate for Electro-optic Applications

Lithium niobate ($LiNbO_3$), currently available in large boules, has generated interest in its use for Q-switching large aperture, high average power lasers. However, optical surface damage has proved a limiting factor for conventionally polished material. Because laser surface damage is generally correlated with the presence of contaminants and polishing debris, we undertook a study to see if diamond turning could produce high optical quality surfaces with enhanced damage thresholds.

C. Laser Crystals

Two key concerns regarding laser crystals are 1) the development of a cost effective finishing technology for large numbers of large aperture slabs, and 2) laser surface damage. Lithium calcium aluminum fluoride ($LiCaAlF_6$, or LICAF) doped with chromium has been proposed as a pump laser material for a multimegajoule fusion driver. Neodymium-doped calcium fluoride (CaF_2) has been considered as an amplifying medium in that design.

Laser damage has been a recurrent problem in polished yttrium orthosilicate (Y_2SiO_5 or YOS) which is used as a host for neodymium in a ground-state depletion laser designed at LLNL.

As indicated in Table 1, the materials we have studied cover a range of properties, but can be classified roughly into two classes. The first includes, water soluble and low melting temperature crystals like KDP, DLAP and urea. These are relatively soft and easy to machine, but may have a tendency to show large degrees of plastic deformation and adhere to the cutting tool. Also, the effects of cleavage planes on the orientational dependence of surface finish are generally smaller in these materials. The second class is the hard, high temperature materials like YOS, $LiNbO_3$, and LICAF. Tool wear can be a significant problem, and shear cutting is obtainable over a much narrower range of cutting conditions.

D. Diamond Turning

The turning was carried out on either the Pneumo Precision MSE-326 machine, in a fly-cut mode or our PERL-II using poly-olefin oil as the cutting fluid.

The basic finish machining parameters, are given in Table 2, 2.5-5 μm/revolution feed rate, 45° negative rake angle, using a tool nose radius of 0.100 or 0.125 inch and a spindle rotation speed of 1000 or 1900 RPM. All tools had a nominal 83° angle between the rake and clearance faces. For roughing and semifinishing the depth of cut was increased (2 to 20 times) and the feed rate doubled. Based on diamond turning studies of single crystal Si and other brittle materials[6,7] the cutting parameters were chosen to produce smoother mechanically damage-free surfaces. The studies showed that feed rate and tool rake angle were more important parameters than depth-of-cut, in controlling the material removal behavior and the finish of the machined surface. In the future we hope to study rake angles effects[8] on surface quality and tool wear in more detail.

High power optical microscopy (up to 1000X) and SEM were used to examine tools and wear patterns. A separate new resharpened tool was used in each finishing operation. Some finishing tools, with no detectable wear, were reused in roughing and semifinishing cuts.

The samples which were fly cut on the Pneumo machine exhibited reasonable surface finish. We like to point out that our study has been limited (size of sample, range of cutting parameters, etc.) and care should be exercised before extrapolating our data to other situations. The best surface finish we report here, 0.75 nm rms, was on KDP, which showed no detectable tool wear, when spirally cut on PERL-II. The tool was chipped when

LAAc was rough cut on PERL-II. However, we feel this may be due to a defective tool edge, because chipping was not observed when LAAc was cut on the Pneumo machine. It should be noted that the LAP chipping occurred after a cutting distance (32 Km) about an order of magnitude greater than our other experiments reported here. A shorter cutting distance may have yielded better tool performance. Both $LiNbO_3$ and CaF_2 exhibited crater type tool wear, which may be due to chemical-mechanical abrasion. In terms of our present fly-cutting experiments, a continuously applied cutting fluid may have reduced tool wear. On the other hand, PERL-II, which is a superior machine, presented challenges for chucking and cutting fluid application.

We have had some very encouraging laser damage results. The diamond turned LAP was tested for laser damage with 10 nsec pulses in an N-on-1 format. LAP exhibited a surface-damage threshold >50 J/cm^2 at 1.06 µm and 25 J/cm^2 at 0.355 µm. Diamond turned $LiNbO_3$ had a 2-3 times improvement in laser damage threshold over polished surfaces when tested at 1.06 µm (polished: 2-3 J/cm^2, 16 ns, 30 Hz versus DT: 4-6 J/cm^2, 10ns, 10 Hs). LAAc, which is also limited by bulk damage, had a surface damage threshold of 10 J/cm^2 for 10 ns 0.355 µm pulses.

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TABLE 1. Properties of Crystals Studied

Material	Melting Temperature (°C)	Young's Modulus (TPa)
KDP	253 (d)	4.9×10^{-2} ($\dot{z}$)
DLAP (h)	120 (d)	1.3×10^{-2} ($\dot{b}$)
LAAc	245 (d)	
DAT (h)		
Li Formate (h)	94 (d)	2.9×10^{-2} ($\dot{b}$)
Urea	135 (d)	1.6×10^{-2} ($\dot{z}$)
BBO	925 (p)	2.7×10^{-2} ($\dot{z}$)
$LiNbO_3$	1250	20.0×10^{-2} ($\dot{z}$)
LICAF	810	
CaF_2	1423	9.0×10^{-2} (1 1 1)
YOS	2080	25.0×10^{-2} ($\dot{b}$)
h = hydrated	d = decomposition p = phase change	symbol in parenthesis indicates orientation of crystal surface

TABLE 2. Machining parameters and experimental results for study on diamond turning of optical single crystals.

Crystal	Cutting direction or mode	Cutting conditions DOC* (μm)	FR* (μm/rev)	Cutting distance* (km)	Tool wear	Surface* finish (nm rms)	Comments
$LiNbO_3$	Spiral cut	20 10 20 25	2.5 6 2.5 2.5	0.22 0.85	Rake face cratering and edge thermal cracking	5 2.6-9.7 (T)	• Rainbow finish
LAP	Parallel to cleavage plane	50 25 12.5 5 2.5	5 5 2.5 2.5 2.5	31.8 5.2 7.1 7.8 1.4	Chipping and material buildup	0.65-3.43 (W)	
KDP	Spiral cut Parallel to a-axis	50 25 12.5 50 25 12.5	5 5 2.5 5 5 2.5	3.2 4.7 3.0 2.5 5.1	No detectable wear	0.75-1.98 (W)	• Excellent finish • Very forgiving for different cutting conditions
LAAc	Parallel to (110)	5 2.5	2.5 2.5	7.6 0.8	See text	5.19-11.2 (W)	• Needs larger and better quality crystals
CaF_2	Spiral cut 1	25 5 2.5	5 2.5 2.5	 4.0 3.2	Detectable cratering and edge cracking	1.75-3.14 (T)	• Threefold symmetry in surface finish
$LiCAF_6$	Parallel to a -axis	10 2.5	5 2.5	1.1	No wear detected	1.2-8.2 (T)	• Needs larger and better quality crystals

* DOC = depth of cut: FR = feed rate: Cutting distance is per tool: Finish measured after final cut
W=Wyko 1000P, 20X; T=Talystep

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