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# On the ultra-precision diamond machining of chalcogenide glass

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ABSTRACT

Chalcogenide glasses are important materials for components in thermal imaging systems (IR-optics). While suitable for molding, the machining characteristics of these brittle materials are largely unknown. In this paper, ultra-precision machining data for a common chalcogenide glass ($As_{40}Se_{60}$) is presented. Data acquired from orthogonal cutting experiments show a transition in cutting mechanics at an uncut chip thickness of approximately one micrometer. This data is used to identify parameters for high-speed milling, and results are used to produce a thermal imaging lens. This paper demonstrates that the milling process is suitable for prototyping and low-batch production of IR-optics in this glass.



## 1. Introduction

For centuries, optical devices have consisted predominantly of combinations of spherical and flat components due to the relative ease of manufacture. However, recent advances in manufacturing equipment and software for simulation and manufacturing of optics now make it possible to implement optimized freeform optical designs that can arbitrarily redirect light in three-dimensions. In fact, freeform optics appear poised to radically change optical designs in many areas ranging from imaging to light management, with applications in consumer electronics, night vision, surveillance, directed lighting, medical testing, etc. [1]. Advantages of integrating freeform surfaces with optics include: (1) the ability to replace multiple traditional optics with a single freeform; (2) the capability to simultaneously machine an optical surface with precision alignment features; and (3) the capability to accomplish new optical functions, such as in the Alvarez lens [2]. However, freeform optics present manufacturing and metrology challenges. Ultra-precision diamond machining and freeform milling is one path to production, particularly for infrared (IR) applications where form and finish requirements are less stringent than for visible light applications. However, to achieve this, cutting under the complex geometric and dynamic conditions encountered in freeform milling must be predicted and controlled. This requires improved understanding of the cutting mechanics of brittle IR-materials.

For decades, it has been known that brittle materials can be successfully diamond turned [3–9]. Citing the indentation literature, Giovanola and Finnie [3], Nakasuji et al. [6] and Blake and Scattergood [7] proposed that ductile chip formation will occur when the material is under high hydrostatic pressure, and when the chip thickness are below a critical value dependent upon material properties. Under these conditions, optical quality surfaces can be obtained in crystalline materials important for IR-imaging such as germanium [9,10]. Lucca et al. [8] showed that when the resultant cutting force vector rotates to produce tensile stresses behind the tool, surface fracture will be initiated. While molecular dynamics simulations elucidate possible mechanisms for the ductile behavior of brittle materials [11], the mechanics of the process is still not fully understood. Nevertheless, IR-optics can be diamond turned in brittle semiconductor materials including silicon, germanium [10], zinc selenide and cadmium telluride. Optical glasses have also been the subject of diamond turning investigations [3,4,12]. Chalcogenide glasses have more recently become important for infrared imaging. These materials, containing one of the three elements sulfur, selenium and tellurium, have numerous advantages for IR-imaging. Yet, scientific studies of their machining behavior are limited [13].

In this paper, turning and milling data for an arsenic-selenium, infrared, chalcogenide glass ($As_{40}Se_{60}$) is shown. Forces are measured for orthogonal turning and face turning. Conditions under which the material deformation becomes fracture dominated are identified and correlated to the machined surfaces. Orthogonal cutting data is combined with a mechanistic model to estimate the forces in high-speed, single crystal diamond, ball milling of the material. Milling is applied to the manufacture of a freeform surface incorporating an aspheric thermal landscape imaging lens and kinematic alignment features (lens specifications: $F/1.18$, 30 mm effective focal length, 30° field of view). While diamond turned chalcogenide glass lenses have been reported [13], it is believed that this is the first study of the mechanics of machining chalcogenide glass, and shows that freeform milling is a viable path for prototyping and small volume production of IR-optics in $As_{40}Se_{60}$.

## 2. Description of experiments

Machining experiments were conducted with arsenic selenium ($As_{40}Se_{60}$) chalcogenide glass (trade name IRG 26). Because of its

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relatively high index (2.8) and high transmittance (>60%) over wavelengths ranging from 0.85 μm to 12 μm, this material is particularly suited to IR imaging. The density, thermal conductivity and specific heat capacity are 4630 kg/m$^3$, 0.24 W/m-K, and 360 J/kg-K, respectively. The material has a fracture toughness of 0.285 MPa-m$^{1/2}$, a Knoop hardness of 1.04 GPa, and a Young's modulus of 18.3 GPa. The glass transition temperature, $T_g$, is relatively low, 185 °C, making mass producion by molding feasable. However, in this paper it is shown that diamond machining of this brittle material is also viable for prototyping and small/medium batch production of IR-optics.

Three types of experiments were conducted with single crystal diamond tools: (1) orthogonal turning; (2) face turning; and (3) ball endmilling. All experiments were conducted on a Moore Nanotechnology 350 FG machine having two air bearing spindles, a 10,000 rpm turning spindle and a 60,000 rpm milling spindle. Mineral oil spray mist coolant was used for all of the cutting experiments and lab temperature was maintained at 20 ± 0.1 °C.

Turning tools were mounted directly on a Kistler 9256C1 dynamometer as shown in Fig. 1a. Orthogonal cutting was done on the outer diameter of a 14 mm diameter cylinder with a pointed (deadsharp) tool having a 60° included angle as shown in Fig. 1b. The tool had a 0° rake angle and a 7° clearance angle, and the chip width ($a_p$) was 200 μm. The uncut chip thickness ($t_c$) was varied from 0.1 μm to 8 μm and the cutting speeds ($V_c$) were varied from 0.5 m/s to 8 m/s. To correlate cutting mechanics with surface characteristics, forces were also measured in face turning with a single crystal diamond tool having a nose radius of 0.5 mm, a 0° rake angle, and a 7° clearance angle. The feed per revolution, *f*, was varied from 0.25 μm to 10 μm while the depth of cut and cutting speed were held constant at 25 μm and 4 m/s respectively. Interestingly, a negative rake angle was not required to obtain fracture free surfaces in this material. For all turning experiments, force data was acquired using LabVIEW with an NI cDAQ-9174 DAQ board and an NI 9215 module at a sample rate of 25 kHz. For each parameter set, 80 revolutions of data were recorded, trimmed to avoid lead in and lead out effects, and mean values were calculated. The procedure was repeated three times for each parameter set. (Although DC forces were measured, the loaded dynamometer bandwidth in the thrust and cutting directions is approximately 5 kHz.)

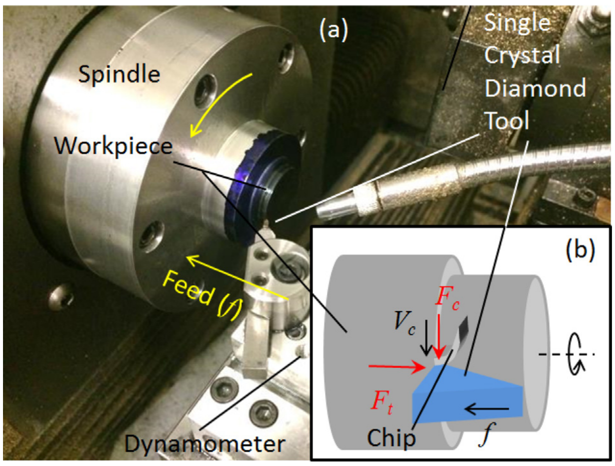


**Fig. 1.** (a) Turning arrangement and (b) orthogonal cutting.

Milling performance was also evaluated. Square patches, 2 mm on a side, were raster milled with a single-flute, zero rake, 1.5 mm diameter single crystal diamond endmill in the configuration shown in Fig. 2. The workpiece was mounted on the main spindle which was locked in place. The spindle speed was 45,000 rpm ($V_c$ of 3.5 m/s at periphery of cutter) and the axial depth was 100 μm. The feed rate ranged from 0.3 μm to 10 μm per revolution, and the stepover ranged from 12 μm to 60 μm. To examine effects of zero surface speed at the tool center, three different inclination angles between the workpiece normal and the milling tool axis ($\alpha$) were examined: 0°, 22.5°, and 45°. The feed direction was perpendicular to the plane of inclination as shown in Fig. 2. Due to bandwidth limitations of the dynamometer (approximately 5.5 kHz, unloaded), milling force data was not acquired.

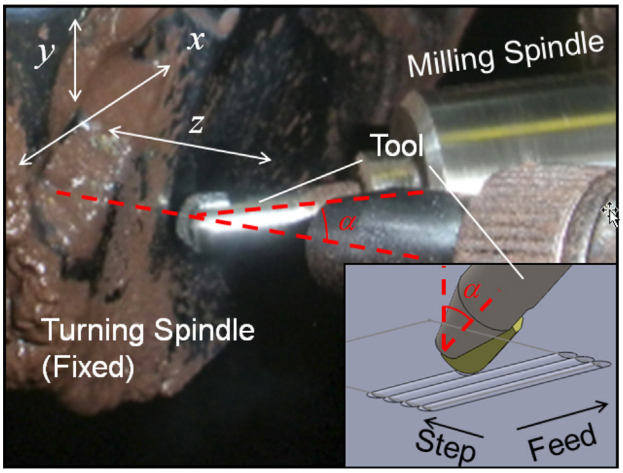


**Fig. 2.** (a) Milling arrangement and (b) tool geometry.

For the face turning and milling experiments, the machined surfaces were examined using optical microscopy and a Zygo NewView scanning white light interferometer (SWLI). Chips and tools were examined in a scanning electron microscope (SEM). Negligible tool wear was seen for all cutting configurations.

## 3. Experimental results

### 3.1. Orthogonal cutting

Fig. 3 shows the average $F_c$ and $F_t$ as a function of $t_c$ for orthogonal cutting. For the lowest value of $t_c$ (0.1 μm) $F_t$ was greater than $F_c$, consistent with the edge effects described in other work [8]. After an initial increase, a rapid decrease in $F_c$ and $F_t$ is seen at $t_c$ equal to 1 μm. Then, further increases in forces at reduced slope were seen as $t_c$ was increased up to 8 μm. For $t_c$ less than 1 μm, the chips appear to be the result of ductile deformation (inset for $t_c$ equal to 0.2 μm). As $t_c$ was increased beyond 1 μm, the chips appear fragmented (inset for $t_c$ equal to 2 μm). Despite the relatively low $T_g$ of this material (185 °C) and potential thermal softening, no measurable change in $F_c$ and $F_t$ as a function of cutting speed (up to 8 m/s) was observed.

Cutting force coefficients, $K_c$ and $K_t$, are shown in Fig. 4. For $t_c$ below 1 μm, $K_c$ decreases continuously from approximately 2.5 kN/mm$^2$ to 1.25 kN/mm$^2$, and $K_t$ decreases from approximately 2.6 kN/mm$^2$ to 1.0 kN/mm$^2$. When $t_c$ exceeds 1 μm, a sharp decrease in $K_c$ and $K_t$ to less than 0.25 kN/mm$^2$ is seen. $K_c$ and $K_t$

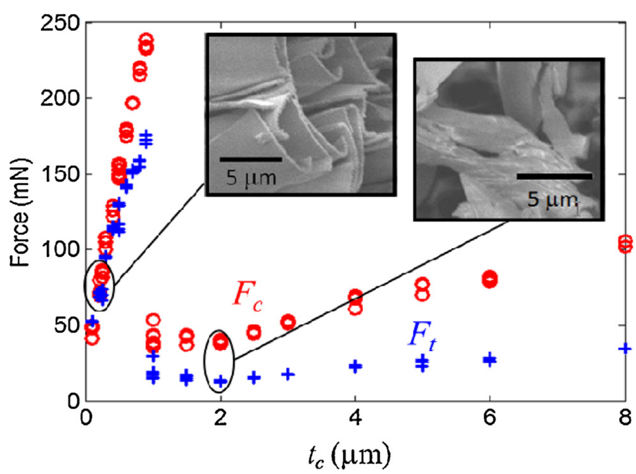


**Fig. 3.** Cutting forces and chips (insets) for semi-orthogonal cutting a function of cutting speed (up to 8 m/s) was observed.