CUTTING FORCE MEASUREMENT DURING DIAMOND FLYCUTTING OF CHALCOGENIDE GLASS

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INTRODUCTION

For ease of manufacture, optical devices have traditionally been based upon flat and spherical surfaces. Recent advances in manufacturing technology have made it possible to generate arbitrary freeform surfaces. The advantages include, for example: reduction of the number of components, reduction/elimination of some of the classical optical aberrations etc.

Ultraprecision diamond machining is a viable technology for the manufacture of freeform optics particularly for IR applications, where form tolerances and finish are less stringent than for visible applications. It has been known for several decades that brittle materials such as glass can be successfully diamond turned [1]. Such materials can be machined in a ductile mode if chip thicknesses are kept below a critical value [2-4]. However, studies on the machining behavior of IR glasses are limited; a better understanding of the cutting process is necessary to improve both component quality and process throughput.

In this paper, cutting force measurements during orthogonal turning and flycutting of arsenic selenium ($As_{40}Se_{60}$, trade name IRG26) chalcogenide glass are presented. This material has a glass transition temperature of 185° C, a refractive index of 2.82 at 2000 nm and >55% transmittance from 1100 nm to 12 µm. The high index and wide transmittance make this glass attractive for SWIR-LWIR applications. In addition to subtractive methods, the low transition temperature makes this glass viable for molding.

ORTHOGONAL TURNING EXPERIMENTS

Orthogonal machining experiments similar to those presented in [5] were conducted on a Moore Nanotechnology 350 FG machine with a 10,000 rpm main spindle in a temperature-controlled lab maintained at 20 ± 0.1°C. Forces were measured while cutting the outer diameter of a 30 mm cylinder using a dead sharp (pointed) single crystal diamond (SCD) tool with 60° included angle, 0° rake angle, and 10° clearance angle. This specially-designed tool consists of a 55° carbide DCMT-style insert to which the diamond is brazed, and a corresponding steel insert holder. The specimen was held with a spindle-mounted vacuum chuck which was finish-turned in situ to eliminate runout and resultant imbalance. The experimental arrangement and force directions are shown in Figure 1.

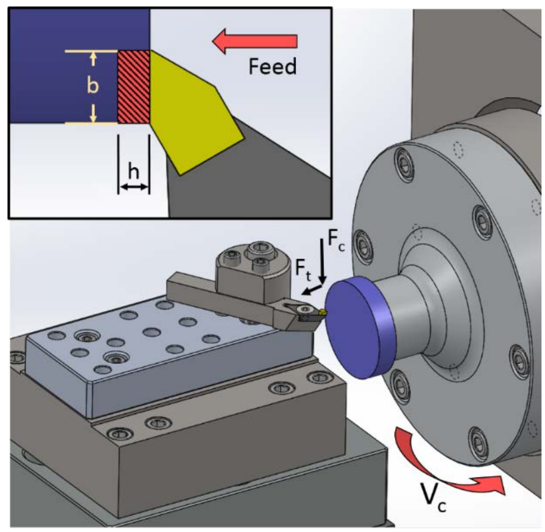

FIGURE 1. Experimental arrangement and cutting force orientation for orthogonal turning.

Cutting force (in the direction of cutting velocity) and thrust force (opposing the feed direction) were measured using a Kistler 9266C1 miniature cutting force dynamometer for a chip width (b) of 100 µm, a cutting speed (V_c) of 2 m/s, and chip thicknesses (h) from 200 nm to 2 µm. Four cutting tests were performed at each chip thickness. To reduce the effect of initial subsurface damage on subsequent tests, 250 revolutions of machining at a feedrate of 100 nm/rev were performed between each cutting experiment. To improve chip evacuation, tests were performed without lubrication, but with a gentle air blast on the tool tip. Data was acquired at 500 kHz using an NI USB-6251 device. Good agreement was seen between sets of experiments done in order of ascending and descending chip thickness.

Similar to the results presented in [5], cutting and thrust forces measured were much higher for h below 600 nm and increased linearly with h, While mechanisms are likely mixed, this is indicative of a ductile-dominated machining regime. Above this threshold, cutting forces drop sharply, suggesting a machining mode dominated by brittle fracture. Scatter among the experimental results is highest near this transition region. Results were found to be unchanged if orthogonal cutting was performed on the face rather than the periphery of the workpiece. Microscopy of tool edges before and after cutting showed little evidence of tool wear.

Measured force signals for 80 revolutions of cutting are shown in Figure 2. In the ductile cutting regime, forces are constant throughout the cut. At higher chip thicknesses, the forces are larger at the beginning of the cut, and drop off quickly after several revolutions of cutting. This sharp force reduction after several revolutions is suggestive of forward-propagated damage, while the higher force levels at the beginning of the cut suggest successful removal of such damage between experiments.

Mean cutting and thrust forces, extracted from steady-state cutting behavior at each value of *h* are shown in Figure 3. Linear regressions over the ductile cutting regime indicate cutting coefficients of K_t = 1490 N/mm^2, K_c = 820 N/mm^2.

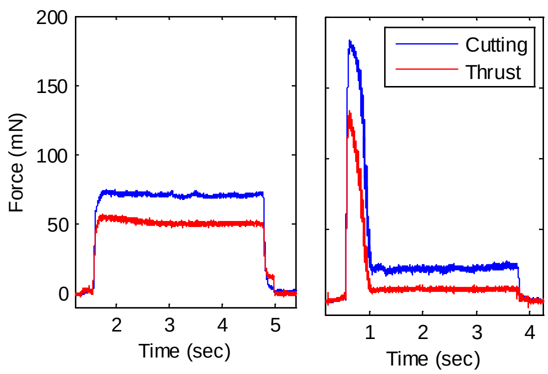

FIGURE 2. Orthogonal turning force signals at (left) h = 400 nm, (right) h = 1.4 μm.

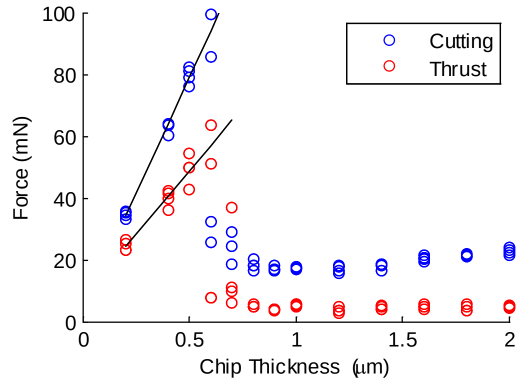

FIGURE 3. Cutting and thrust force variation with chip thickness, orthogonal turning.

SEM micrographs of resulting chips are presented in Figure 4. At a chip thickness of 400 nm, resulting chips are long and curly, similar to those seen when machining ductile metals. At higher chip thicknesses, chips are small and powder-like, suggesting cracking due to a fracture dominated process.

FIGURE 4. Chip morphology at 800X for (top) h = 400 nm and (bottom) h = 1.4 μm.

ORTHOGONAL FLYCUTTING EXPERIMENTS

While axisymmetric surfaces can be generated by diamond turning and freeform surfaces with sufficiently small departures can be produced using coordinated axis (slow- or fast-tool servo) turning, diamond milling can generate nearly arbitrary freeform surfaces useful for many optical applications. As described in [6], turning operations can be described as quasi-steady processes while interrupted milling operations often do not reach a steady state; there is evidence that this can lead to changes in the material removal mechanics. Several obstacles prohibit the direct comparison of cutting force data from simplified turning and milling operations: (1) milling cutters used in diamond machining typically have large corner radii similar to a bullnose endmill, resulting in a more complex cutting geometry which is no longer orthogonal, and (2) at cutting speeds common in ultraprecision milling, frequency content of force signals exceeds the bandwidth of available transducers.

To enable an investigation of the mechanics of quasi-steady-state orthogonal turning and interrupted cutting operations, an orthogonal flycutting setup has been designed and constructed. The flycutter mounts to the turning spindle of the Moore Nanotechnology 350FG machine and holds the same cutting tool and insert used for the orthogonal turning experiments. The tool is mounted in a manner that preserves a 0° rake angle, 0° approach angle, and 10° clearance angle. With a flycutter radius of 50 mm, cutting speeds of 0.5 m/s to 8 m/s can be attained at spindle speeds between 190 rpm and 3050 rpm. The experimental arrangement and force directions are shown in Figures 5-6. This experiment preserves the orthogonal cutting geometry and allows an independent investigation of the effect of time of cut on the cutting mechanics.

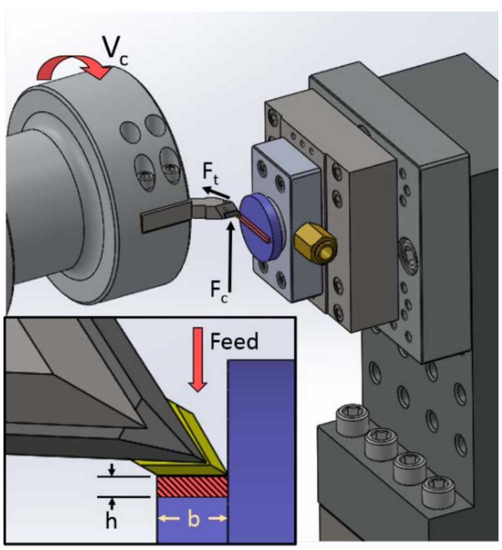

FIGURE 5. Experimental arrangement and force orientation for orthogonal flycutting.

For consistency, the same IRG26 sample was used as for the orthogonal cutting experiments. The sample was prepared using a round-nosed tool to produce a thin rib of material for flycutting tests. The rib-sample was mounted to a vacuum chuck which was attached to the cutting force dynamometer. With the centerlines of the cutter and rib coincident, orthogonal cutting conditions comparable to turning were preserved. Though coupled, cutting speed and time in the cut could be varied by adjusting spindle speed and rib width.

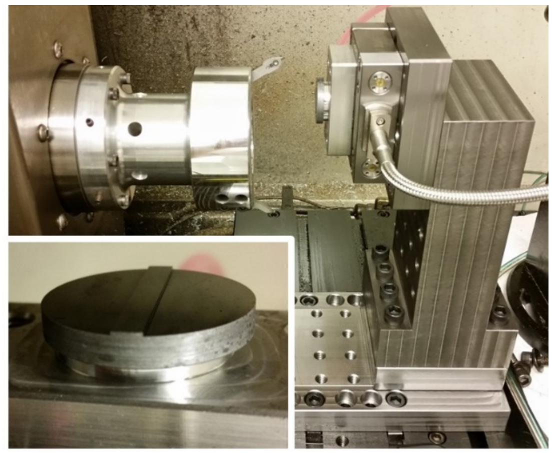

FIGURE 6. Experimental setup and specimen (inset) for orthogonal flycutting.

In this cutting configuration where the rib width is much smaller than the cutter radius, the force signals are impact-like in nature, exciting all the dynamic modes of the piezoelectric cutting force dynamometer. To remove these effects from the resultant force signal and extend the dynamic range of the measurement, inverse filtering [7] can be applied (see [8]).

Rib widths of 1, 2, and 4 mm, corresponding to tool-workpiece contact times of 500 μs, 1.0 ms, and 2.0 ms were used. For each rib width, six experiments were performed at each chip thickness. As in orthogonal turning, surface speed was held to 2 m/s (350 RPM), while chip width was 100 μm. Cleanup machining was performed at a feedrate of 100 nm/rev for 250 revolutions between each cutting experiment. No air blast or lubrication was necessary as chips were naturally ejected from the cutting zone. No differences were found between tests done in order of ascending or descending chip thickness.

Measured force signals from two experiments are shown in Figure 7. As in orthogonal turning, force levels are constant throughout the cut in the ductile regime, while cuts in the brittle regime begin with large forces and drop off rapidly.

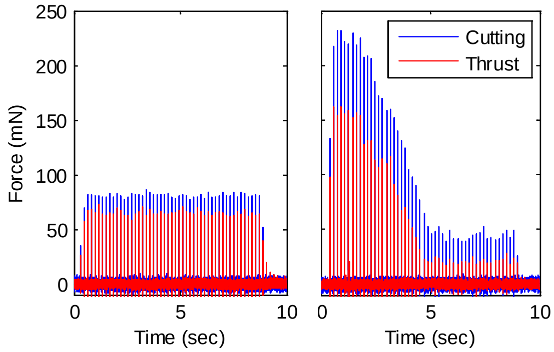

FIGURE 7. Orthogonal flycutting force signals at (left) h = 400 nm, (right) h = 1.6 μm.

After applying the inverse filter to remove the effects of dynamometer dynamics, the data was trimmed to include only the cutting data that has reached steady-state. Mean cutting and thrust forces are shown in Figure 8. A sharp decrease in cutting and thrust forces occurs at a chip thickness between 800 nm and 1 μm indicating a change in cutting mechanics similar to orthogonal cutting. While the transition in cutting mechanics appears to occur at higher chip thickness in interrupted machining than in turning, no clear change in cutting force with time of contact is evident. Linear regressions performed in the ductile regime for the three fin widths indicate cutting coefficients of K_c = 1200 -1350 N/mm^2 and K_t = 660-750 N/mm^2.

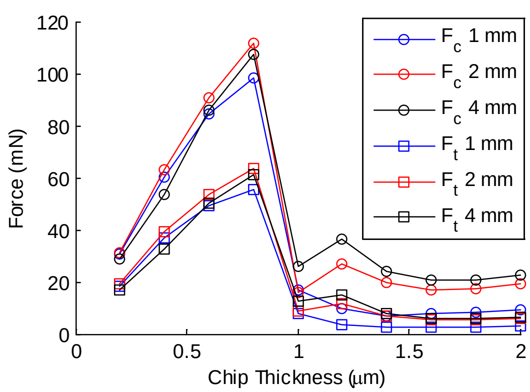

FIGURE 8. Cutting and thrust force variation with chip thickness, orthogonal flycutting.

REMARKS AND FUTURE WORK

Orthogonal turning and flycutting experiments were performed in $As_{40}Se_{60}$ (trade name IRG26) chalcogenide glass, which enable an initial comparison of quasi-steady and interrupted cutting processes. In both configurations, a transition from a high-force, ductile cutting behavior to a lower-force, brittle mechanism is present, as with other glasses [2-4]. In orthogonal turning, cutting coefficients similar to [5] were calculated, but a lower critical chip thickness of approximately 600 nm was observed. This variation may be due in part to variations in tool edge condition and material homogeneity. Lower cutting coefficients and a slightly higher critical chip thickness between 800 nm and 1 μm were observed in flycutting experiments. In the brittle regime, a more gradual decrease in force was observed for flycutting compared to turning, possibly suggesting a change in crack propagation depth at shorter times of contact.

Future work will investigate lower times of contact (several μs), and higher cutting speeds (4-8 m/s), closer to those found in milling processes. Measurements will also be made to better understand the subsurface damage generated during machining operations.

ACKNOWLEDGEMENTS

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