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Cutting mechanics and subsurface integrity in diamond machining of chalcogenide glass

J. R. Troutman[1], J. D. Owen[1], A. Zare[2], T. A. Harriman[2], D. A. Lucca[2], M. A. Davies[1]*

[1]*Center for Precision Metrology, Department of Mechanical Engineering and Engineering Science, University of North Carolina at Charlotte, Charlotte, NC, USA*
[2]*School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater OK, USA*

* Corresponding author. Tel.: +1-704-687-8326; *E-mail address:* madavies@uncc.edu

Abstract

Infrared-transparent chalcogenide glasses are important for the manufacturing of optics for thermal imaging. These brittle materials can be diamond machined, but material removal rates are often limited by the occurrence of surface/subsurface damage. In this paper, the cutting mechanics of orthogonal cutting, orthogonal flycutting and ball-milling of a common chalcogenide glass ($As_{40}Se_{60}$) are measured and analyzed. The nature of the resulting surface/subsurface was characterized with atomic force microscopy, Raman spectroscopy, and nanoindentation. Results of this study contribute to both the fundamental understanding of material behavior and the cost-effective production of novel freeform infrared optics.

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Keywords: Surface; Subsurface; Diamond cutting; Nanoindentation

1. Introduction

For centuries, optical devices have consisted of axi-symmetric elements - often spherical - due to the relative ease of manufacturing and metrology. Recent advances in optical simulation software, manufacturing equipment and control have broadened the design space by allowing nearly arbitrary optical surfaces - freeform optics - to be manufactured. Current manufacturing technologies, such as CNC diamond machining, are most suited to the tolerance and surface finishes required for longer wavelength applications (e.g., infrared (IR)) [1]. However, many challenges associated with the diamond machining of IR freeform optics remain. Here, we address the connection between the cutting mechanics of brittle IR materials and surface and subsurface integrity. While this work targets IR optics, techniques are applicable to optics functioning in the visible spectrum as well.

It is well known that some brittle materials can be successfully diamond turned to produce an optical quality surface [2-8]. Lucca et al. [6] showed that under certain conditions brittle materials can be machined in a manner that leaves a surface free of significant brittle fracture, while under other conditions, tensile stresses in the cutting zone result in significant surface fracture. IR optics have been diamond turned in brittle semiconductor materials including Si and Ge. Chalcogenide glasses, which contain S, Se, or Te, have numerous advantages for use in IR imaging systems. Owen et al. [1] showed that chalcogenide glass can be milled to produce optical quality freeform surfaces with little visible surface fracture. Owen et al. [1] and Troutman et al. [9] demonstrated that significant changes in specific cutting energy in these glasses, for both continuous and interrupted cutting, coincide with the production of fracture-dominated surfaces. In this paper, we correlate these changes in cutting mechanics with quantitative measurements of surface and subsurface integrity. This is of importance for maximizing the lifetime of optics designed to function at high power or in harsh environments

We focus on $As_{40}Se_{60}$, a brittle chalcogenide glass. This material has a low glass transition temperature and is suitable

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for molded IR optics. Despite being brittle, the material can also be ultra-precision machined with relatively high material removal rates [1]. To investigate the machining mechanics, orthogonal turning and interrupted flycutting experiments were performed and the cutting mechanics were correlated to uncut chip thickness (t_c). Using this knowledge, ball-milled patches were generated for measurement of surface and subsurface integrity. Atomic force microscopy (AFM), Raman spectroscopy, and nanoindentation were used to characterize surface and subsurface integrity.

2. Cutting Mechanics Characterization

2.1. Orthogonal turning

Machining experiments were conducted on a Moore Nanotechnology 350FG ultraprecision diamond machining center. Cutting forces (F_c) and thrust forces (F_t) were measured while machining the outer diameter of a 30 mm diameter, 5 mm thick cylindrical workpiece. A "dead sharp" single crystal diamond (SCD) tool with 60° included angle, 0° rake angle, and 10° clearance angle was mounted on a Kistler 9256C1 miniature cutting force dynamometer. The chip had a width, w_c, determined by the depth of cut, and uncut chip thickness, t_c, determined by the feed per revolution.

With the surface speed held constant at 2 m/s, and a fixed chip width of 100 µm, t_c was varied from 200 nm to 2.0 µm. For each set of parameters, 80 revolutions of cutting data were used to generate average forces. To minimize initial subsurface damage, the surface was pre-machined with a t_c of 100 nm for 250 revolutions prior to each experiment. Experiments performed in ascending and descending order agreed, indicating that the initial surface condition was the same for each experiment. Figure 1 shows average F_c and F_t as a function of t_c and representative SEM images of the chips.

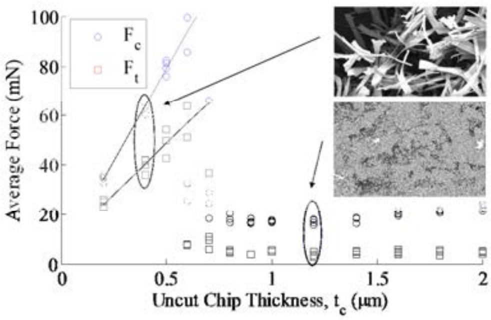

Fig. 1. Measured forces from orthogonal turning experiments. Linear fits of the low t_c regime are shown by solid lines. Insets show chips from the two regimes (400 nm, top) and (1.2 µm, bottom).

At t_c values above 600 nm, the chips were fragmented indicating a material removal mechanism dominated by brittle fracture. With decreasing t_c down to roughly 600 nm, cutting forces were found to decrease slowly. At t_c values near 600 nm, both F_c and F_t increase by approximately a factor of five. The increase in F_c is accompanied by a significant jump in the energy per unit volume of material removed, from 0.2 J/mm^3 to 1.3 J/mm^3, as reported previously by Owen et al. [1]. Further decrease in t_c results in a rapid, nearly linear decrease in the cutting forces. The mechanics of this force behavior remain unknown, but could potentially indicate a visco-plastic response, strain rate sensitivity, thermal sensitivity, or other material behavior. Chips created when t_c was less than 600 nm were not consistent with the fragmented chips observed for higher t_c, but were instead curled.

2.2 Orthogonal flycutting

To study the effect of an interrupted cut under orthogonal cutting conditions, an orthogonal flycutting arrangement was developed. In this configuration, the workpiece was pre-machined to leave only thin ribs. Each rib was machined using a flycutter that was 100 mm in diameter, with the same tool used for the orthogonal turning. A more detailed description of both the turning and flycutting experiments is given in Troutman et al. [9]. At a constant surface speed of 2 m/s, cutting experiments were performed on workpieces with rib widths of 1 mm, 2 mm, and 4 mm, corresponding to tool-workpiece contact times of 0.5 ms, 1 ms, and 2 ms.

For each rib, six total experiments were performed at each t_c and the progression from low to high t_c was repeated three times. Figure 2 shows the mean values of F_c and F_t for each of the three progressions. Force magnitudes are in agreement with Fig. 1 and relatively little variation due to rib size is evident. Further, the increase in F_c and F_t occurred at a higher t_c between 800 nm and 1.0 µm. The uncertainties in the mean values of F_c and F_t were greatest near the transition region with standard deviations of 19 mN and 15 mN at t_c equal to 1.0 µm and 1.2 µm respectively. At all other values of t_c, the standard deviation was less than 4 mN. The possibility that the transition in cutting mechanics is altered by an interrupted cut is also supported by observations in ultraprecision diamond ball-milling where brittle materials such as Ge can be successfully milled with zero rake angle tools [10], whereas the turning literature indicates a negative rake angle is required [5].

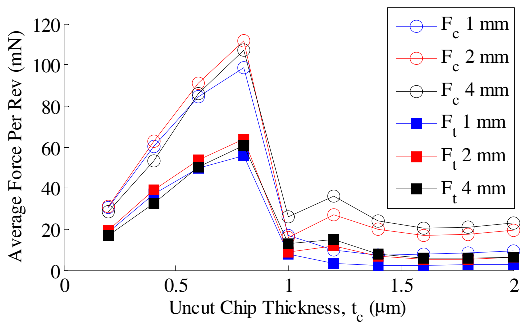

Fig. 2. Measured forces during orthogonal flycutting.

2.3 Ball-milling experiments

To investigate the changes in the governing mechanics of the milling process and their effect on the nature of the generated surface and subsurface generated, chalcogenide glass was raster ball milled. A SCD, single flute, 1 mm diameter, zero rake angle ball end-mill was used to machine 2 mm × 2 mm patches with the parameters summarized in