Sub-surface mechanical damage distributions during grinding of fused silica

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Abstract

The distribution and characteristics of surface cracking (i.e., sub-surface damage or SSD) formed during standard grinding processes have been measured on fused silica glass using a surface taper polishing technique. The measured SSD depth distributions are described by a single exponential followed by an asymptotic cutoff in depth. The observed surface cracks are characterized as near-surface lateral and deeper trailing indent type fractures (i.e., chatter marks). The length of the trailing indent is strongly correlated with a given grinding process. It is shown that only a small fraction of the abrasive particles are being mechanically loaded and causing fracture, and most likely it is the larger particles in the abrasive particle size distribution that bear the higher loads. The SSD depth increased with load and with a small amount of larger contaminant particles. Using a simple brittle fracture model for grinding, the SSD depth distribution has been related to the SSD length distribution to gain insight into 'effective' size distribution of particles participating in the fracture. Both the average crack length and the surface roughness were found to scale linearly with the maximum SSD depth. These relationships can serve as useful rules-of-thumb for non-destructively estimating SSD depth and for identifying the process that caused the SSD.
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1. Introduction

Sub-surface mechanical damage (SSD) consists of sur-face micro-cracks created during grinding and/or polishing of brittle materials surfaces, such as glass. These surface cracks, typically identified macroscopically as scratches and digs, are often hidden below an index-matched Bielby layer or have closed (i.e., healed); hence they are all not detectable by visual inspection or standard optical micros-copy until exposed by chemical etching [1]. In some appli-cations, the removal or minimization of SSD is required for improving the material strength (e.g., spacecraft, underwa-ter windows/barriers, and other military applications) where the surface flaws determine the ultimate strength or for reducing/eliminating laser-induced damage (e.g., high-peak-power laser applications [2]). For laser optic applications, SSD is believed to serve as a reservoir for absorbing precursors that will heat up and explode upon irradiation with high fluence laser light [3]. As a result, the fabrication of SSD-free optics/windows has been a goal for the optical fabrication industry for many years [4–6].

The creation of SSD can be thought of as the repeated indentation of mechanically loaded hard indenters (abra-sives) sliding on the surface of an optic during various cut-ting, grinding and polishing processes. The initiation and growth of the three basic types of cracks (lateral, radial, Hertzian) resulting from a single, static indenter as a func-tion of load, material properties of the indenter and sub-strate are known [7,8].

These relationships have served as the basis for estimating material removal during grinding of brittle materials [9,7,10]. Others have utilized these basic fracture relationships, combined with experimental data, to relate the SSD depth to basic processing parameters such as load, abrasive size and the resulting surface roughness [11–13]. Preston was among the first to recognize the presence of SSD on finished surfaces and that etching exposes the chat-ter mark cracks (which we will refer to as trailing indent fractures) [14]. Since then, a wide variety of destructive and non-destructive techniques for measuring the amount and depth of the SSD have been explored [13,15–19]. Some of the more direct SSD measurement techniques include the ball-dimple method [20], taper polishing method [21], and more recently a MRF spot method [22], where the ground or finished surface is partially removed to evaluate the depth of the SSD.

In the following study, we use a taper polishing method, where various ground, fused silica surfaces are subse-quently treated by an advanced finishing technique (mag-neto-rheological finishing or MRF), known not to induce SSD, to create a shallow surface taper over relatively large areas to determine the statistical distribution of SSD [23– 25]. We then apply known indentation fracture and wear relationships [7,8,4] to establish insights into the nature of the cracking, the load per particle present, the shape of the distributions, and the maximum SSD depth. Such a data set combined with fracture mechanic insight serves as a means to understand and to predict a SSD distribution for a given grinding/polishing process and to serve as use-ful tool for performing and designing optical fabrication processes.

Results

Fig. 1 show a selected series of microscope images for each sample at various distances along the produced surface wedge (i.e., depths below the original ground sur-face) after etching.

The crack features observed were typi-cally visible by optical microscopy only after BOE etching. The crack number density at the ground sample surface was very high, such that the individual cracks inter-sect many other cracks. This rubble-like appearance (not shown in figure) makes it difficult to categorize the crack type. However, a few microns below the surface (i.e., after polishing through the surface layer), one can now identify distinct individual cracks all of a common morphology which decrease in number density with depth. For the most part, these cracks have a ‘trailing indent’ character (com-monly referred to as chatter marks [1,7] or stick-dig frac-tures).

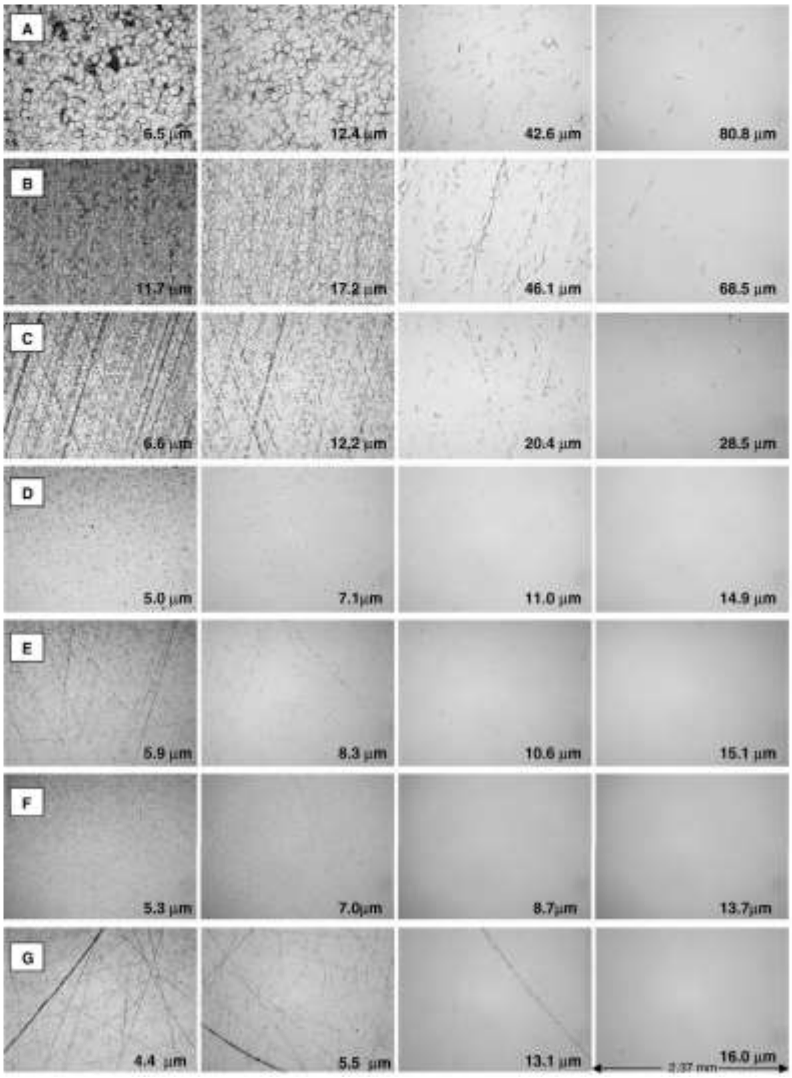

Fig. 1. Optical microscopy images for fused silica surfaces that have been treated by a wide variety of grinding processes (Samples A–G). The images for each sample are at various depths of removal using the wedge technique. The value in the bottom right is the depth below the original surface at which the image was taken.

Conclusions

The SSD depth and length distributions for various grinding processes have been directly measured and statis-tically evaluated. The observed surface cracks are charac-terized as near-surface lateral and deeper trailing indent type (i.e., chatter marks) fractures. The length of the trail-ing indent is strongly correlated with a given process. The SSD distributions are typically described by a single expo-nential distribution followed by an asymptotic cutoff in depth (c_{max}). Using fracture indentation relationships, it is shown that only a small fraction of the abrasive particles are being loaded and participating in the fracture, and it is the larger particles in the abrasive particle size distribution that bear the higher loads. Using a mechanical model to describe the grinding process, the measured crack length distribution has been related to the crack depth distribu-tion. This correlation, has also allowed for estimating the ‘effective’ particle size distribution participating in fracture, whose particle sizes are 10 times the mean abrasive particle size. The maximum SSD depth was found to correlate with both the mean crack length and the measured surface roughness. The ratio of c_{max}/d was found to be 49. Also, the observed relationship between the mean crack length and the maximum SSD depth, can be utilized as a rule-of-thumb to non-destructively estimate the depth of SSD by measuring the crack length of an individual SSD defect. For grinding performed in sequence, the SSD depth distri-bution did not noticeably influence the SSD caused from the previous grinding step provided that material removal exceeded the SSD depth of the previous step. A small amount of contaminant of larger abrasive particles can greatly increase the SSD depth.

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