Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Journal of Non-Crystalline Solids 352 (2006) 5601–5617
JOURNAL OF NON-CRYSTALLINE SOLIDS
www.elsevier.com/locate/jnoncrysol

Sub-surface mechanical damage distributions during grinding of fused silica

T. Suratwala *, L. Wong, P. Miller, M.D. Feit, J. Menapace, R. Steele, P. Davis, D. Walmer

Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551, USA

Received 6 March 2006; received in revised form 29 August 2006
Available online 30 October 2006

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.
Published by Elsevier B.V.

PACS: 42.86.+b; 81.40.Np; 46.55.+d

Keywords: Crack growth; Fracture; Indentation; Microindentation; Optical microscopy; Lasers; Silica

1. Introduction

Sub-surface mechanical damage (SSD) consists of surface 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 microscopy until exposed by chemical etching [1]. In some applications, the removal or minimization of SSD is required for improving the material strength (e.g., spacecraft, underwater 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 (abrasives) sliding on the surface of an optic during various cutting, 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 function of load, material properties of the indenter and substrate are known (see Fig. 1 and discussion in Section

* Corresponding author. Tel.: +1 925 4221884; fax: +1 925 4230792.
E-mail address: suratwala1@llnl.gov (T. Suratwala).

0022-3093/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jnoncrysol.2006.09.012

Nomenclature

χ_h	Hertzian crack depth growth constant (unitless)
χ_ℓ	lateral crack depth growth constant (unitless)
χ_r	radial crack depth growth constant (unitless)
$\langle c\rangle$	mean crack depth (m)
$\langle d\rangle$	mean particle size causing surface fracture (m)
$\langle L\rangle$	mean crack length (m)
A	Auerbach's constant for initiation of Hertzian fracture (N/m)
a	contact zone radius for a Hertzian indent (m)
B	friction effect constant for trailing indent fracture (unitless)
c_h	Hertzian crack depth (m)
c_ℓ	lateral crack depth (m)
c_{max}	maximum crack depth (m)
c_r	radial crack depth (m)
c_t	trailing indent crack depth (m)
d	abrasive particle size (m)
d_c	mean abrasive particle size (m)
d_c	mean particle size of abrasive used during polishing
d_{max}	maximum particle size causing surface cracking (m)
d_{optic}	diameter of optic/workpiece (m)
E	Young's modulus of optic/workpiece (GPa)
E_p	Young's modulus of abrasive particle (GPa)
f	fill fraction of particles between lap and workpiece
$F_c(c)$	cumulative distribution of crack depths
$F_c(c)$	fractional distribution of crack depths
$F_d(d)$	cumulative distribution of particle sizes participating in causing surface cracking
$f_d(d)$	fractional distribution of particle sizes participate in causing surface cracking
$F_L(L)$	cumulative distribution of crack lengths
$F_L(L)$	fractional distribution of crack lengths
$f_{load}(c)$	fraction of particles being loaded for various crack depths (unitless)
$f_o(c)$	instantaneous fractional distribution of crack depths created
i	number of increments of material removal (unitless)
k	material constant for Poisson's ratio and modulus of indenter and substrate (unitless)
K_{Ic}	fracture toughness of optic/workpiece (MPa m$^{1/2}$)
K_{Ic}	fracture toughness of fused silica
k_{max}	proportionality constant between c_{max} and δ
L	crack length (m)
L_{max}	maximum crack length (m)
L_t	length of a trailing Indent crack (m)
n	number density of cracks at the surface (cm^{-2})
N_L	number of abrasive particles being loaded
N_T	total number of particle between workpiece/optic and lap
$O(c)$	cumulative obscuration of cracks
$o(c)$	fractional obscuration of cracks
P	normal load (N)
P_{ch}	fracture initiation load for Hertzian cone crack (N)
$P_{c\ell}$	fracture initiation load for lateral crack (N)
P_{cr}	fracture initiation load for radial crack (N)
P_{ct}	fracture initiation load for trailing indent crack (N)
P_{max}	load/particle that leads to the maximum SSD (N)
P_T	total load on sample (N)
r	radius of curvature for indent indenter (m)
s	shape factor relating the radius of curvature of contact of the particle with the vertical dimension of the particle
t	time of grinding or polishing (sec)
w	crack width (m)
z	coordinate describing amount of material removed during grinding/polishing (m)
z_w	wedge depth (m)
δ_{rms}	root-mean-square surface roughness
δ	surface roughness using ($n^* = 4$)
Δ	surface material removal increment (m)
Ω	proportionality constant between crack length and depth (unitless)
α_r	fracture initiation constant for radial cracks (unitless)
v	Poisson's ratio of optic/workpiece (unitless)
v_p	Poisson's ratio of abrasive particle (unitless)

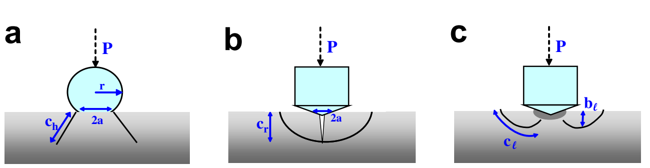

Fig. 1. Schematic illustration of the fracture geometry of the idealized fractures created by static indentation: (a) Hertzian cone crack from a blunt indenter; (b) radial or median cracks from a sharp indenter; (c) lateral crack from a sharp indenter.

4.1) [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 chatter 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