Subsurface Damage in Microgrinding Optical Glasses

In cold processing of optical glasses by microgrinding,[1,2] the resulting brittle-material-removal rate induces a cracked layer near the glass surface, referred to as subsurface damage (SSD). [Editor's note: The acronym for subsurface damage (SSD) used in this article should not be confused with its more common use as an acronym for smoothing by spectral dispersion.] In addition, there is a corresponding surface microroughness (SR), often found to increase in proportion to SSD, as originally observed by Preston.[3] SSD is a statistical measure and not necessarily equal to the flaw depth that may control mechanical strength of the brittle surface.

Direct measurement of SSD is tedious: The dimple method is often used[4,5] as well as wafering methods. Aleinikov[6] showed that SSD induced by lapping of glasses and other brittle ceramics (with hardness changing 30-fold, fracture toughness 6-fold, and Young's modulus 20-fold) was 3.9±0.2 times SR for SiC abrasives (100 to 150 μm), thus indicating that SSD may be estimated from SR. Aleinikov also found that SSD increased with increasing size of microindentation cracks (see Fig. 73.47). Thus, microindentation may be used to evaluate propensity to damage in lapping.

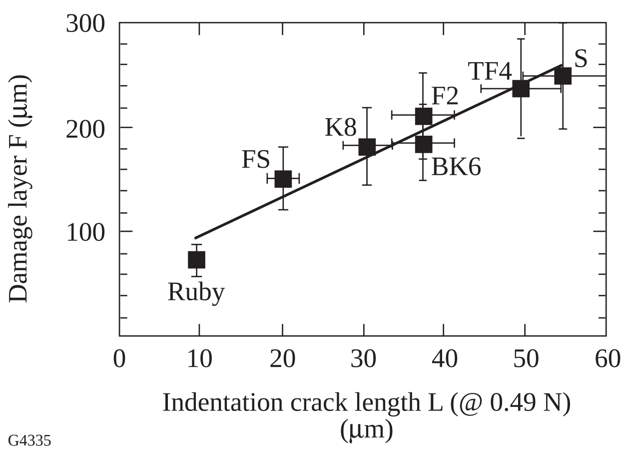

Figure 73.47
SSD in lapping versus indentation crack size (0.49 N) for brittle materials, based on Aleinikov.[6] Russian glass K8 is equivalent to Schott BK7 (Hoya BSC7, Ohara S-BSL7).[7]

More recently, Edwards and Hed[8] studied the relation of SSD to SR under bound-diamond-abrasive conditions (53 to 65 μm and 180 to 250 μm in size) and found that for the three glasses studied (borosilicate crown BK7, zerodur, and fused silica) the average SSD was 6.4±1.3 times the peak-to-valley surface roughness (measured by a profilometer). The factor of 6.4 was arrived at by dividing SSD by SR for each glass. This proportionality factor becomes identical to that of Aleinikov[6] when all three materials tested by Edwards and Hed[8] are treated together (see Fig. 73.48). Similar observations have been reported for deterministic microgrinding of optical glasses with bound-abrasive-diamond tools of smaller size (2 to 4 μm) (see Lambropoulos *et al*.[9]).

In addition to correlating SSD with SR, it is possible also to correlate SSD for brittle materials with the materials' mechanical properties. Zhang[10] used metal bond wheels with bound diamond abrasives (40 to 230 μm in size) to grind structural ceramics under fixed infeed conditions and reported a subsurface damage depth (consisting of voids induced by the grinding) that correlated with the ductility index $(K_c/H_V)^2$ of these materials (see Fig. 73.49). The ductility index[9] is

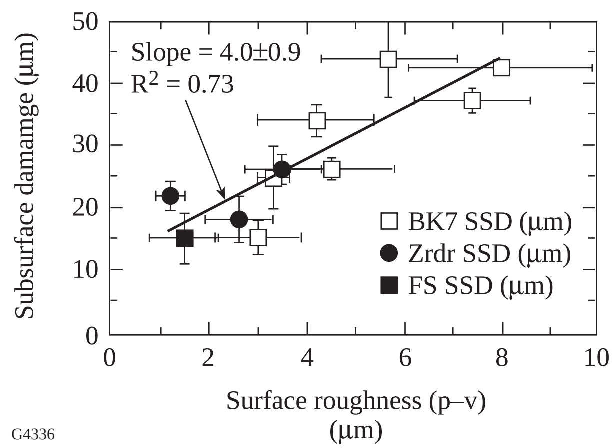

Figure 73.48
Relation of SSD to SR, as measured in bound-diamond-abrasive grinding by Edwards and Hed.[8]

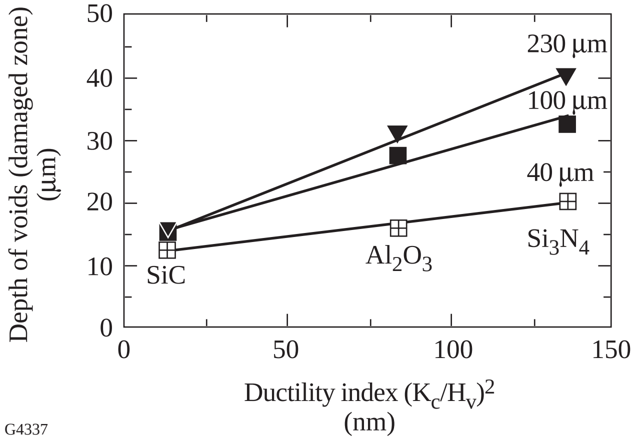

Figure 73.49
Subsurface damage versus mechanical properties of structural ceramics (SSD data from Zhang[10].)

inversely related to the brittleness H/K_c originally introduced by Lawn *et al.*[11,12]

In our notation, H denotes hardness, or resistance to plastic, irreversible deformation, measured by estimating the area of an indentation impressed under load P. Hardness is defined in terms of either projected area or actual area of contact. Specifically, H_K denotes Knoop hardness, extracted from measuring the long diagonal of a rhomboidal pyramid impression under load P by P/(projected contact area) = (constant) P/(long diagonal)^2, with the (constant) dependent on the rhomboidal pyramid geometry. H_V denotes Vickers indentation, extracted from measuring the average diagonal of a square pyramid impression under load P by P/(actual contact area) = (constant) P/(average diagonal)^2, with the (constant) dependent on the square pyramid geometry. For the same measured diagonal, Knoop indentations penetrate about half as much into the surface as Vickers indentations; thus, H_K more closely measures near-surface hardness. Generally, Knoop hardness H_K increases with Vickers hardness H_V. This correlation has been described in detail by Lambropoulos *et al.*[9]

Microgrinding Experiments

1. Lapping: Surface Roughness (SR) versus Subsurface Damage (SSD)

In all the following experiments, surface roughness was measured by a white-light interferometer (NewView 100, 0.35 × 0.26 mm^2, 20× Mirau, five measurements per surface) and subsurface damage by the dimple method (typically three to five dimples per surface[4,5]).

The goal of the lapping experiment was to investigate whether surface roughness can provide information about subsurface damage. Loose-abrasive lapping experiments were conducted on two glasses: the soft phosphate laser glass LHG8 (63% P_2O_5, 14% BaO, 12% K_2O, 7% Al_2O_3, 4% Nd_2O_3/Nb_2O_5) and the harder borosilicate crown optical glass BK7 (68.9% SiO_2, 10.1% B_2O_3, 8.8% Na_2O, 8.4% K_2O, 2.8% BaO, 1% As_2O_3, % by weight) (see Table 73.VI).

Five separate LHG8 blocks were lapped on both sides with Al_2O_3 abrasives (median size 30, 9, 5, 3, 1 μm). Measured SSD and SR, after grinding with each abrasive, are shown in Fig. 73.50.

Table 73.VI: Thermomechanical properties of optical glasses. Data for density ρ, glass transition temperature T_g, coefficient thermal expansion α, Young's modulus E, and Poisson ratio ν are from manufacturers' glass catalogs. Hardness H and fracture toughness K_c are from Schulman *et al.*[16] Knoop hardness is at 1.96 N. The fracture toughness of LaK9 was estimated from that of LaK10.

Glass	ρ (g/cm^3)	T_g (°C)	α (10^{-6} °C^{-1})	E (GPa)	ν	H_K (GPa)	K_c (MPa m$^{1/2}$)
LHG8	2.83	485	12.7	50	0.26	2.3	0.43
FS-C7940	2.20	1,090	0.52	73	0.17	5.6	0.75
SF58	5.51	422	9.0	52	0.26	2.7	0.46
SF7	3.80	448	7.9	56	0.23	3.4	0.67
BK7	2.51	559	7.1	81	0.21	5.1	0.82
K7	2.53	513	8.4	69	0.21	4.6	0.95
KzF6	2.54	444	5.5	52	0.21	3.7	1.03
LaK9	3.51	650	6.3	110	0.29	5.7	(0.90)
TaFD5	4.92	670	7.9	126	0.30	7.3	1.54

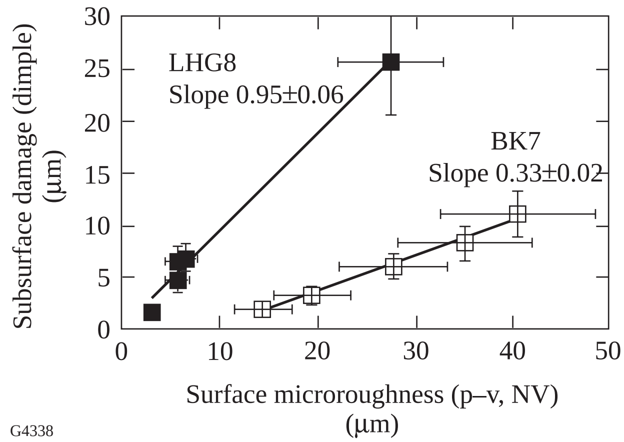

Figure 73.50
Correlation of SR (p–v) with SSD for loose-abrasive lapping of optical glasses (Al_2O_3 abrasives).

A similar experiment used BK7 with a wider abrasive size range (median size 40, 30, 20, 9, 5, 3, 1 μm). A single BK7 part was first lapped by 40-μm abrasives, then with 30-μm abrasives, and finally with 20-, 9-, 5-, 3-, and 1-μm abrasives. SSD and SR were measured at each step. Each lapping step removed between 0.3 to 1 mm of material and thus removed all the residual SSD from the previous abrasives used in the sequence. Larger abrasives typically led to higher SSD and higher SR.

The correlations of the subsurface damage to the peak-to-valley surface roughness for lapped LHG8 and BK7 are shown in Fig. 73.50. For LHG8 the p–v SR is equal to the measured SSD, whereas for BK7 the p–v SR is about 3 to 5 times the measured SSD. We conclude from these experiments that the p–v SR measured with the white-light interferometer provides an upper bound for the SSD measured by the dimple method.

2. Deterministic Microgrinding: Surface Roughness (SR) versus Subsurface Damage (SSD)

A series of multicomponent optical glasses, as well as fused silica,[13] were also ground under fixed infeed deterministic microgrinding conditions on the Opticam SM CNC machining platform,[14,15] which can manufacture planar and spherical surfaces, as well as aspheres.[9,14,15] Table 73.VI summarizes some of the glass properties.

Three metal-bonded diamond-abrasive ring tools were sequentially used on each surface (aqueous coolant Loh K-40, relative speed of work and tool of about 30 m/s): 70 to 80 μm, 10 to 20 μm, and 2 to 4 μm at infeed rates of 1 mm/min, 50 μm/min, and 5 μm/min, respectively. Three cuts were done with each tool. After each cut, SR of the optical surface was measured for microgrinding with all three tools, and SSD (three dimples for each cut) for the 2- to 4-μm and 10- to 20-μm tools.

Figure 73.51 shows the correlation between the measured p–v and rms SR for the three tools used, with each point representing one of the glasses ground and measured. Figure 73.52 shows the correlation of SSD (dimple method) and the p–v SR. It is seen that, as in lapping, the p–v SR may be used as an upper bound for the SSD for the 10- to 20-μm and 2- to 4-μm tools, within the uncertainty in the measurement of SSD and SR.

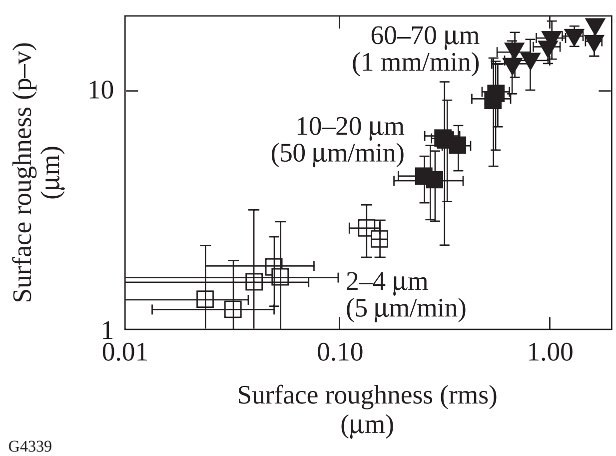

Figure 73.51
Correlation of p–v and rms SR under fixed infeed deterministic microgrinding of various optical glasses.

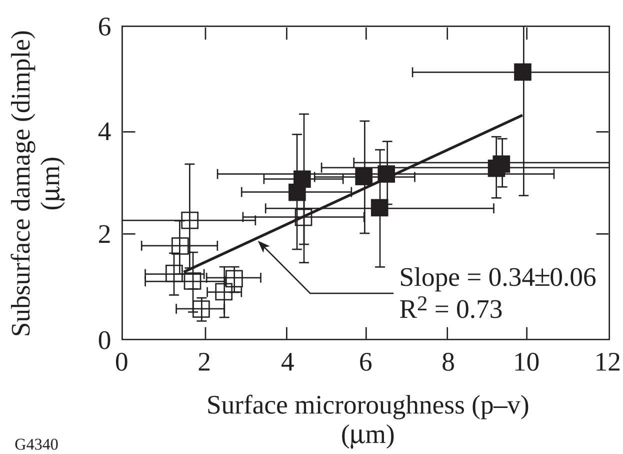

Figure 73.52
SSD (dimple method) versus p–v SR (via NewView 100 white-light interferometer) for fixed infeed deterministic microgrinding.

The effect of glass mechanical properties on SSD is shown in Fig. 73.53, where we have used the ductility index as the correlating parameter.[9] It is seen that, under fixed infeed grinding conditions, increasing ductility produces higher SSD, as observed in structural ceramics (Fig. 73.49). Correlations of measured SSD with the critical depth of cut discussed by Bifano *et al*.[17] or the critical load for fracture initiation discussed by Chiang *et al*.[18,19] gave similar trends.

The dependence of SSD on the ductility index is interpreted by a simple model of residual tensile stresses $\sigma \approx \beta\sigma_y$ (parallel to the surface), where $\beta \approx 0.08$[20] and σ_y is glass uniaxial yield stress ($\sigma_y \approx H_V/2$, see Ref. 9). Thus, crack depth a in the presence of such tensile stresses is estimated as

$$K_c = \Omega\left(\beta\ \sigma_y\right)\sqrt{\pi\, a} \Rightarrow a = \frac{1}{\pi}\left(\frac{K_c}{\Omega\,\beta\,\sigma_y}\right).$$

$\Omega \approx 1.1$ is a geometric factor accounting for the proximity of the free surface. Typical data for, say, BK7 give a crack depth of 2.1 to 4.3 μm, i.e., quite comparable to the measured SSD (see Fig. 73.52).

3. Comparison of Surface Quality Induced by Lapping and Deterministic Microgrinding

Figure 73.54 compares the surface quality of the optical glass BK7 (commonly used in many optical designs) resulting from loose-abrasive lapping with Al_2O_3 abrasives (seven sizes spanning 1 to 40 μm) and from deterministic microgrinding (three sizes spanning 3 to 75 μm) with bound diamond abrasives, over a wide range of abrasive sizes. The infeed rates for deterministic microgrinding were 5 μm/min (2- to 4-μm tool), 50 μm/min (10- to 20-μm tool), and 1 mm/min (70- to 80-μm tool). For both lapping and deterministic microgrinding, larger abrasives lead to deeper SSD and higher SR. The lapping results apparently become insensitive to abrasive size for abrasives in the 1- to 3-μm range.

For a given abrasive size, deterministic microgrinding results in surfaces with lower subsurface damage and lower surface microroughness (p–v or rms). Such surface features are in addition to any "figure" features extending over the whole aperture of the ground optical surface.

Conclusions

The quality of a manufactured optical surface can be characterized in a variety of ways, including surface microroughness[9] subsurface damage, surface figure error, residual stresses induced by the grinding process,[20,21] the rate of material removal,[22] and the rate of tool wear. In our work we have concentrated on subsurface damage and surface microroughness and addressed the following questions:

How can subsurface damage in a given brittle material be estimated from the measured surface microroughness? How can subsurface damage among brittle materials be correlated to their near-surface mechanical properties? How is the resulting

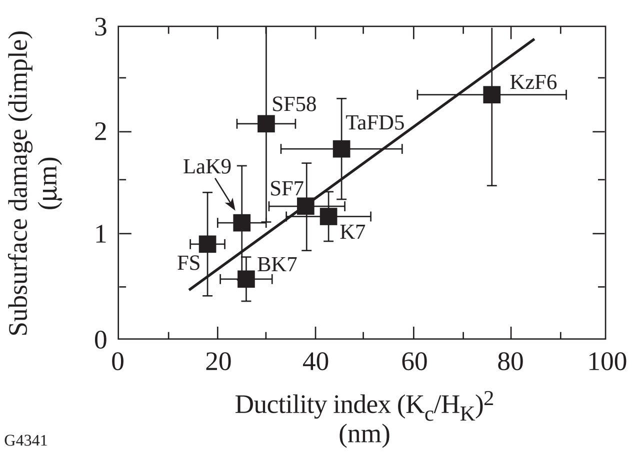

Figure 73.53
Dependence of subsurface damage SSD on glass mechanical properties via the ductility index $(K_c/H_K)^2$.

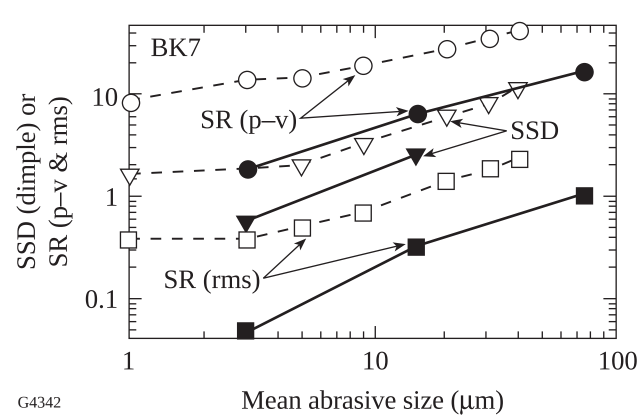

Figure 73.54
BK7 surfaces: lapping at fixed pressure (open symbols) versus deterministic microgrinding at fixed infeed with metal bonded-diamond-abrasive ring tools (solid symbols).

surface quality affected by material removal under loose-abrasive microgrinding at fixed nominal pressure (lapping) or by deterministic microgrinding under fixed infeed rate?

We have performed a series of loose-abrasive microgrinding (lapping at fixed nominal pressure) and deterministic microgrinding (at fixed infeed) experiments on various optical glasses. We summarize our results as follows:

- Peak-to-valley surface microroughness for the optical glasses tested (measured by the white-light interferometer, a relatively easy measurement to perform) provides an upper bound to the subsurface damage measured by the more-time-consuming dimple method;
- Subsurface damage in optical glasses under deterministic microgrinding conditions with 2- to 4-μm bound-diamond-abrasive tools scales with the glass ductility index $(K_c/H)^2$ in a manner similar to that reported for fixed infeed grinding of structural ceramics;[10] and
- For a given abrasive size, deterministic microgrinding produces lower subsurface damage and lower surface microroughness as compared to lapping.

The issue of residual stresses induced by grinding is also important and often referred to as the Twyman effect.[21] Although we have not measured residual stresses in this work, our previous work on optical glasses[20] and glass ceramics[23] shows that, for comparable abrasive sizes, deterministic microgrinding induces lower residual stresses than loose-abrasive lapping, while maintaining a higher material-removal rate and producing a lower surface roughness.

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