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Characterizing subsurface damage in loose abrasive grinding of fused silica glass

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We assessed the subsurface damage (SSD) of loose-abrasive-ground fused silica with a recently proposed method. The method is capable of concurrently acquiring the depth of surface damage and morphologies at varied depths. The experimental results show that the depth of SSD is predominantly determined by the size of silicon carbide abrasives while machining parameters have little effects on the SSD depth under experimented conditions. To explain the interesting phenomenon, we proposed an interpretation that the depth of SSD is presumably controlled by fracture load of abrasives (i.e. the minimum load needed to crack abrasives) rather than applied downward load. Moreover, we found that relative velocity between glass workpiece and lapping plate in typical lapping has insignificant influence on the depth of SSD. The SSD depth scales well with abrasive size down to W7 SiC grits (~7microns of median size) in our experiments, which is different from previous research in which it was reported that the SSD asymptotically increased when the 7-micron abrasives was utilized.

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1. Introduction

Subsurface damage (SSD) is introduced during the cold working of brittle materials. When an indenter harder than glass is pressed against the surface of glass, the glass will fracture if the load on the indenter is in excess of a certain value. In lapping processes, abrasive particles behave like indenters. The abrasives used in lapping/grinding process usually possess greater hardness than glasses and induce micro-cracks beneath the ground surface. These cracks determine the material removal and cause subsurface damage in the top layer of ground/lapped glass. The SSD cracks should be removed in subsequent processes (e.g. polishing or chemical etching) so as to obtain defect-free optical components resistant to laser damage. As to fused silica glass, when the load imposing upon the indenter is beyond 0.02N [1], the glass will rupture due to extreme pressure [2]. The fracture system is illustrated in Fig. 1. The lateral crack will control the material removal while the median crack will be the source of SSD.

SSD cracks can serve as reservoirs for absorbers that can strongly absorb the incident laser light or modulate the electric field or open up a possibility for electronics to transit from laser to glass, which may lead to physical breakdown of optical components in high power laser systems [3-5]. In addition, SSD cracks can also weaken mechanical strength and shorten the lifetime of optical components. Therefore, it is necessary to eliminate SSD cracks in finishing processes. If the removed material is not sufficient, some cracks will be left in the top surface of optics. On the other hand, when the excessive materials is polished out in successive processing procedures, the cost will rise due to quite low removal rate of polishing compared to grinding. As a result, it is of great importance to ascertain the depth of SSD in the optics ground with various processing parameters and different abrasives.

We here investigated the depth of SSD and the influence of machining parameters on the SSD in loose abrasive grinding. The depth of SSD was measured with a newly developed method. Then the explanations for the results are presented.

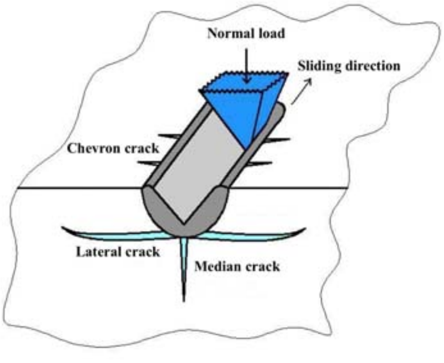


Fig. 1 Crack system induced by a sharp indenter: microcracks emanate from the boundary of plastically deformed- region immediately beneath the indenter; when the lateral cracks intersect the surface of brittle material, the material is removed in the form of chips; the radial cracks can extend much farther below the surface and thereby form subsurface damage [adapted from Ref. 2].

2. Experimental

Fused silica samples (50mm×5mm), which pre-polished with pitch lap, were lapped on a single spindle machine equipped with a reticulated lapping plate made of copper. The sample was stuck onto an aluminum backing plate. The sample together with the backing plate weighed ~420g. The slurry was freshly fed onto the copper plate with volume ratio ~1:3 of SiC:H_2O every 3 minutes. The samples were ground under different downward pressures and rotational rates (the lapping plate was driven independently, while the sample rotated due to the frictional force between the sample and the plate). Four silicon carbide abrasives were tested (W40, W20, W14, and W7). The distributions of abrasives were analyzed (Mastersizer 2000, Malvern Instruments, UK) (Fig. 2). These samples were ground consecutively with W7, W14, W20, and W40 on the same machine. The machine was cleaned carefully with tap water before coarser abrasives were used in the next step.

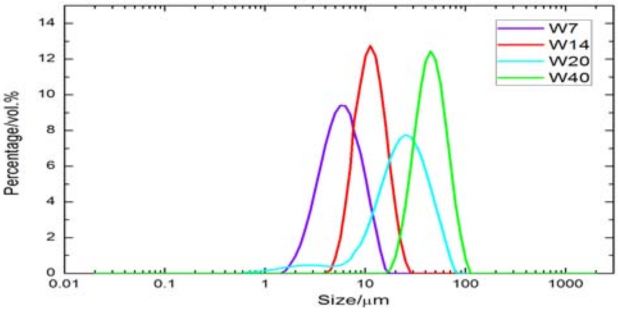


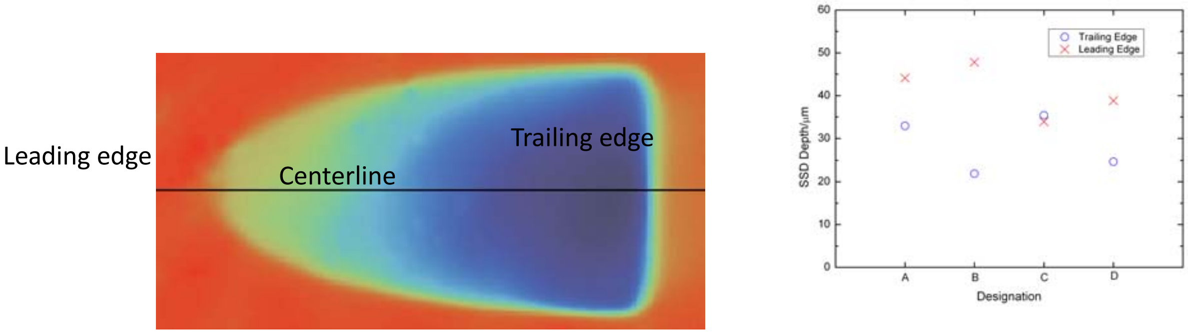
Fig. 2 The size distribution of silicon carbide abrasives employed in the experiments. The horizontal axis denotes the abrasive size in microns while vertical axis represents the percentage of a certain size of particles in the abrasives.

After lapping, four spots were made on each sample with a commercial MRF machine (QED Technologies Q22-400X, USA) and the samples were etched with HF/NH_4F solution (wt.1%HF, wt.10%NH_4F) for 15min at room temperature (20℃) to open cracks. Then the samples were ready for inspection. We employed a new method to measure and observe SSD, which has been detailed previously [6] and here we describe it in brief. An optical microscope (Leica DM4000 M, Germany, NA=0.9 and depth of field~0.2μm for 100× objective) and a laser displacement sensor (Keyence LK-G10, Japan) with resolution of 0.1μm (wavelength of laser: 650nm) were combined to measure the depth of SSD and to observe the morphology at a certain depth. An objective lens is first focused on the ground surface. Then moving the objective to the area to be examined along the centerline of an MRF spot and adjusting the translation stage, one can focus the microscope on the area. The displacement of the objective with respect to the original position in vertical direction (Z axis) is registered with the laser sensor. If cracks are present in the area, the recorded displacement can be referred to as the depth of cracks. Scanning the MRF spot, both SSD depth and the morphology at different depths will be acquired simultaneously. This method has no need for prohibitively expensive profilometer.

3. Results and discussion

3.1 Measuring position effects on measured depth of SSD

A number of methods have been proposed to measure SSD depth [7], including ball dimpling [8], slanted/wedge polishing [9], MRF spotting [10], etc. The MRF spotting technique was applied to the measurement of SSD depth in our study. The typical MRF spot appears a D-shaped pattern, which is axisymmetric regarding the centerline (Fig. 3a). We compared the results of SSD at the leading edge with the trailing edge (Fig. 3b). The results show that the SSD at the leading edge is, in general, greater than that at the trailing edge. Our results are consistent with Randi's [10]. The reasons have not been fully understood at present. The SSD depths reported here were measured at the leading edge in this paper unless otherwise specified.



(a) (b)

Fig. 3 (a) D-shaped MRF spot symmetric along the centerline. (b) The SSD measurements of four spots at the leading edge and trailing edge. The SSD is basically great at the leading edge compared to those at trailing edge. We measured the SSD at leading edge of MRF spots unless otherwise specified.

3.2 Effect of abrasive size on the depth of SSD

The SSD depths for different abrasive size are plotted in Fig. 4. An upper and lower limit of the SSD depth exists for each abrasive and the limit scales well with the abrasive size. The SSD depths fall into the range of 0.4d ~1.6d (d is the median size of SiC abrasive), ~2 times the SSD depth in diamond wheel grinding with the similar nominal size of abrasive/grit [11]. Our results indicate that the finer abrasives (i.e. D7 diamond wheel & W7 SiC) did not increase the SSD depth in fused silica samples, which are inconsistent with those reported by Suratwala *et al.* who have shown an increase in SSD depth if using 7μm alumina grinding wheel [12-13]. The mechanics of the phenomena is not clear yet, although they explained that a new grinding mechanism occurring in 7μm alumina grinding increased the SSD depth. On the other hand, our results are in accordance with J. Neauport's [14] who employed alumina as lapping abrasives and found SSD depth was proportionate to the size of abrasives used.

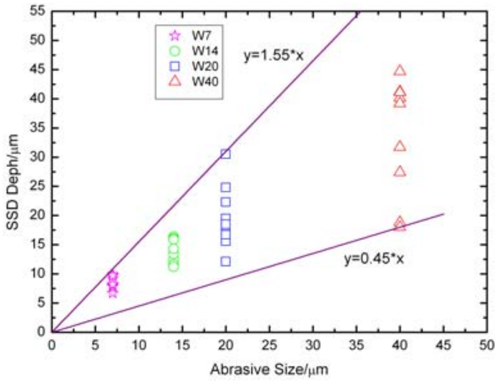


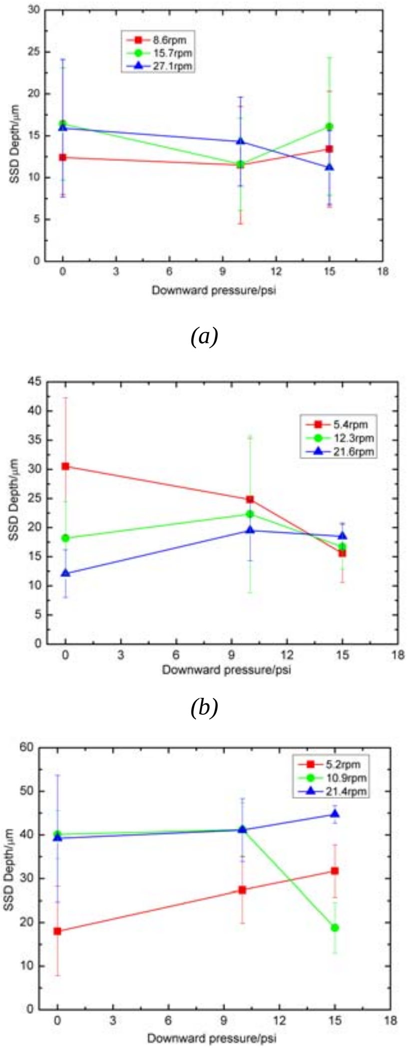
Fig. 4 Subsurface damage by four SiC abrasives. SSD depth generally decreases with abrasive size. One measurement containing 5 images of subsurface cracks beneath the ground surface needed 3~5 minutes, depending on the operator's experience.

3.3 External downward pressure effects on SSD depth

Fig. 5 presents the downward pressure effect on SSD depth, but we cannot find significant changes in SSD depth when the downward pressure is elevated, which seems unreasonable. However, if the experiment conditions are taken into account, our results are not difficult to be understood. According to brittle fracture theory, SSD derives from median cracks during indentation processes. The depth of median cracks can be written as[15]

$$c_m = \kappa^{2/3} \cdot \left(\frac{E}{H}\right)^{2(1-\alpha)/3} \cdot (\cot\psi)^{4/9} \cdot \left(\frac{P}{K_C}\right)^{2/3} \qquad (1)$$

where κ is a constant, $\kappa = 0.090 \times (\alpha - 1/3) + 0.027$, α is a constant with the value of 1/3 to 1/2[15], E is the Young's modulus and H the hardness of glass, ψ is the angle of the indenter sharpness, Kc is the fracture toughness of glass and P is the load applied to the indenter. When the formula is applied to "anomalous" glasses such as fused silica and borosilicate glass, the modified fracture toughness Kc is used, as detailed in Ref. [16]. If the load P is augmented and other parameters are kept constant, the crack depth will also increase. Consequently, the SSD depth will deepen at the initial stage (i.e. under the low pressure). However, in most lapping processes, the SiC grits will be crushed [17-18]. Increasing the downward pressure, larger grits will crack due to extreme pressure and the number of the "active" grits that participate the removal of material will rise, as a consequence of which the load imposed upon a single abrasive will decrease. The process will continue unless the pressure acting on each single abrasive/grit is not more than the fracture load of the abrasives (i.e. the minimum load to crack abrasives). Therefore, the crack depth is controlled by the fracture load of abrasives rather than downward load (applied pressure), which is experimentally verified in reported research [17,19-20] and our experiments. On the other hand, the SSD depth can be linearly related to surface roughness of ground fused silica, and Phillips' [21] results that surface roughness remains unchanged when enhancing the applied pressure (downward load) also substantiate the argument. That the surface roughness keeps constant means the SSD depth changes little when escalating downward load. The experiments performed by Phillips also evidenced that the bed thickness of abrasive was thinned when the applied pressure rose in the initial stages and tended to a steady state, indirectly reflecting that the abrasive particles do not fracture into small pieces until the loads exerted on abrasives are beyond the fracture load of abrasive particles. The load on a single abrasive is affected by the bed thickness (Eqn. B3 and B4 in Ref. [21], θ is affected by the shape of abrasives), resulting in that the load will keep constant in the typical steady grinding. Accordingly, the SSD depth will vary little with the downward load in general grinding processes. J. Neauport's [14] latest paper mentions that SSD depth diminishes with the downward load, which is not coherent with our experiments. The reasons might be that the slurry was continuously added into the gap between the glass workpiece and lapping plate every second and the abrasive particles keep being crushed before the new slurry was replenished, that is, the grinding conducted by Neauport did not step into a steady state. Hence, the abrasives were milled into smaller particles and the load imposed on a single abrasive dwindled during the lapping when the downward load was elevated; thus, the SSD depth will correspondingly deceased with the augmented downward load.



(a)

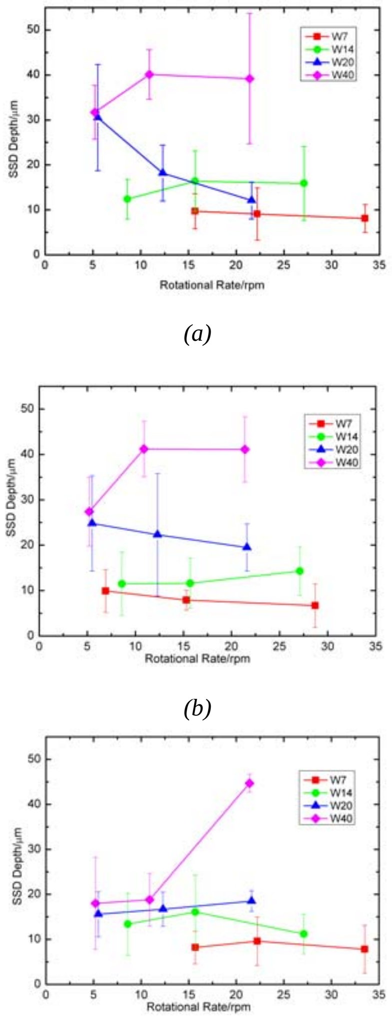
(b)

(c)

Fig. 5 The variation in SSD with the downward pressure. No obvious characteristics can be found from these plots. Note that the SSD is non-zero since the samples were glued to backing aluminum plates. The sample together with the backing plate weighed ~420g. Thereby, even if the external applied downward pressure is zero, the pressure between the glass surface and copper lapping plate is unequal to zero. (a) Ground with W14 SiC abrasives (b) Ground with W20 SiC abrasives (c) Ground with W40 SiC abrasives.

3.4 Rotational rate effects on SSD depth

The relative velocity has trivial effect on SSD depth in our loose abrasive SiC grinding as seen from Fig. 6. The three-body interaction among abrasive, lapping plate and glass will transit to two-body effect when the abrasive particles imbed in the surface of lapping plate. Theoretically speaking, there exists a criterion that the ratio of particle size to the separation between the glass workpiece and lapping plate determines whether the grinding is a two-body or three-body effect [22]. Lapping process is a hybrid of two-body (scratching-indenting) and three-body (rolling-indenting) interactions, whereas the three-body effect dominates the lapping process. Bujis and Houten [23-24] have modeled the lapping process and the crack depth. The crack depth is independent of the velocity. Increasing the velocity will raise the frequency of the collision between the abrasives and glass rather than the depth of crack. Consequently, the material removal rate will increase while the depth of SSD is little influenced. J. Neauport *et al.* [14] have obtained the results that the material removal rate increases while the SSD depth decreases with increasing the rotational rate, which is inconsistent with ours experiments. Supposing that the abrasives particles can be crushed more easily by the lapping plate and glass workpiece when two or more particles collide, the increase of rotational rate will result in smaller abrasive particles that lead to shallower subsurface damage. Then the experimental results by J. Neauport [14] can be interpreted. Whether the explanation is rational needs further investigations.



(a)

(b)

(c)

Fig. 6. The effect of rotation rate on the SSD depth: (a) download load=0 psi (b) download load=10 psi (c) download load=15 psi.

4. Conclusions

The SSD depth in loose abrasive grinding was explored with a newly proposed method. It is found that the SSD depth is insensitive to processing parameters and is governed overwhelmingly by the size of abrasives used in grinding process. Decreasing the size of the abrasives in grinding process is the most effective ways to achieve low subsurface damage in ground fused silica. However, it is difficult to obtain a well-ground surface if the abrasives are extreme fine in loose abrasive grinding. Experiences show that grinding with very small size abrasive is inclined to incur scratches on ground surface and the material removal rate descends rapidly using fine abrasives. The rotation rate and downward pressure make little difference to the depth of SSD. The velocity impacts the material removal rate through increasing the sliding/rolling-indenting distance in unit time while having limited influence on the depth of SSD. The downward pressure seems to influence the SSD at first glance. Nevertheless, it is the load exerted on a single abrasive particle not the overall downward load that determines the SSD depth when the load is not in excess of the fracture load of abrasives. In the case that abrasives are broken during grinding process, the SSD depth is governed by fracture load of abrasives in lieu of downward load in loose abrasive grinding. In general, the larger the abrasives, the greater the facture load of the abrasives [25] and therefore the deeper the SSD.

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