Experimental Study on Surface Integrity and Subsurface Damage of Fused Silica in Ultra-Precision Grinding

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Experimental study on surface integrity and subsurface damage of fused silica in ultra-precision grinding

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Abstract: To realize low-damage ultra-precision grinding on fused silica, the surface quality and subsurface damage (SSD) distribution with fine-grained grinding wheel under different depth-of-cut and cutting speed are experimentally studied. The material removal mechanism under different grinding parameters is revealed by calculating undeformed chip thickness and observed with the help of transmission electron microscopy. The results show that brittle-ductile surfaces and ductile-like surfaces are generated during grinding. With the decrease of depth-of-cut and the increase of wheel cutting speed, the ultra-precision grinding changes to ductile-regime grinding with plastic flow removal. Besides, the surface roughness (SR) and SSD depth are reduced. The fracture defects such as fractured pits and grinding streaks on brittle-ductile surface gradually decrease. Instead, a ductile-like surface covered with grinding streaks is found. On brittle-ductile surfaces, the nonlinear relationship $SSD \propto SR^{4/3}$ is no longer proper under the influence of plastic flow. Using surface roughness R_a to predict SSD depth is more accurate. When depth-of-cut is 1 μm , cutting speed is 23.4 m/s and the material removal mode is dominated by plastic flow removal, the surface R_a is improved to 2.0 nm and there is no crack but only a 3.4 nm deep plastic flow layer in subsurface after grinding.

Keywords: Fused silica, ultra-precision grinding, ductile material removal, surface integrity, subsurface damage

1. Introduction

Fused silica has been widely utilized in the fabrication of large laser facilities, such as inertial confinement fusion (ICF), due to its unique optical, mechanical and thermal properties [1,2]. However, when exposed to high fluences in the ultra violet range, some defects on the fused silica will evolve into damage precursor induced laser damage, which make the lifetime of fused silica decreases rapidly [3,4]. Subsurface damage (SSD) including surface microcracks and scratches are typical precursors for laser induced damage [3-6]. In order to withstand the irradiation of high-power laser, it is necessary to avoid SSD as much as possible in the machining technologies for fused silica. Ultra-precision grinding, as an efficient and economical manufacturing technology for optical elements, is one of the important technologies for processing high-precision and high-quality fused silica [7-12]. But the surface and subsurface of fused silica after ultra-precision grinding usually contains SSD. The SSD must be removed by subsequent polishing technologies, which is mandatory for ICF laser systems. So, the investigation on the surface integrity and SSD of fused silica induced by ultra-precision grinding has great importance.

Lambropoulos et al. analysis the ratio of SSD to surface roughness (SR) based on indentation fracture mechanics [13,14]. S. Li et al. established a theoretical nonlinear model for an assessment of SSD depth. They investigated SSD depth and SR of ground and lapped BK7

glass to verify the nonlinear model [15]. T. Suratwala et al. investigated the distribution and characteristics of subsurface cracking formed during grinding on fused silica [16]. The subsurface crack depth was determined by testing the mean crack length and surface roughness. H. Li et al. established an explicit relation between SSD and surface roughness R_z in the BK7 grinding process, which can not only evaluate SSD depth but also guide optimizing grinding parameters to reduce SSD [17]. Relationships between SSD depth and SR have been widely studied which promote the rapid and accurate measurement of SSD induced by grinding [18, 19]. However, the above research results are based on the brittle-regime grinding. The research on surface/subsurface characteristics of ductile-regime grinding with fine-grained wheel is rarely published. S. Gao et al. investigated the surface/subsurface qualities of ground quartz glasses using fine-grained diamond wheels [20]. But the relationship between the SSD depth and SR affected by ductile-regime grinding is not analyzed. The influence of other grinding parameters on surface/subsurface qualities is not involved as well. The surface characteristics shaped by ductile-regime grinding on fused silica still need to be further studied.

This work aims to characterize surface/subsurface characteristics of fused silica induced by ultra-precision grinding. The paper is organized as follows: Section 1 is the introduction. The sample preprocessing and experimental design are presented in Section 2, a series of ultra-precision grinding experiment with different grinding parameters are carried out. Then, the SR and SSD are analyzed in Section 3. The material removal mechanism in ultra-precision grinding is revealed. The relationship between SSD depth and SR are discussed in Section 4. Section 5 presents the conclusion.

2. Sample Preprocessing and Experimental Design

Fused silica samples are treated by a chemical mechanical polishing prior to ultra-precision grinding. There are few cracks beneath the sample surfaces except for the Beilby layer of about 100nm depth. The surface roughness R_a of each sample is about 1 nm in white light interferometer (WLI, ZYGO® NV700S). The sizes of fused silica samples are all $\varnothing 50$ mm $\times$ 10 mm.

Fig. 1 The self-developed ultra-precision grinder.

The ultra-precision grinding of fused silica in cross grinding modes has been carried out. The ultra-precision grinder is self-developed by National University of Defense Technology, shown in Fig.1. It adopts hydrostatic guideway, whose motion accuracy is less than $0.2 \mu\text{m}/200$ mm. The spindle of grinding wheel is an air spindle, has a nominal rotary accuracy of 0.05

μm . The spindle of the workpiece is another air spindle, which has a nominal rotary accuracy of $0.025 \mu\text{m}$. Diamond grinding wheels of mesh size of 3000 are used in grinding experiment. The diameter of the grinding wheel is 75 mm. The grinding conditions used are shown in Table 1. This work aims to study the influences of depth-of-cut (a_e) and cutting speed (V_c) on surface roughness and subsurface damage. The feed speed (V_w) is 1 mm/min and the rotation speed of workpiece is 20 rpm.

Table 1. Grinding conditions for single-factor tests.

Test group no.	Work material	Grinding parameters		
		Depth of cut (a_e , μm)	Cutting speed (V_c , m/s)	Wheel mesh size
1	Fused silica; $E=72.0 \text{ GPa}$; $H=10.0 \text{ GPa}$; $K_c=1.0 \text{ MPa}\cdot\text{m}^{1/2}$	1	19.6	#3000
2		2		
3		3		
4		4		
5		1	3.9	
6			11.8	
7			19.6	
8			23.4	

The ultra-precision grinder can produce a flat and smooth fused silica surface. Therefore, in single-factor tests the ground surface roughness is investigated via white light interferometer (WLI, ZYGO® NV700S). Measurements are conducted on 10 random areas of $0.94 \text{ mm} \times 0.70 \text{ mm}$ on each ground surface. MRF (magnetorheological finishing) spot method is used to investigating subsurface damage [15, 16]. As shown in Fig. 2, each sample surface is polished by MRF to create 2 wedges that contain all SSD. And by averaging SSD depth of two MRF wedges, SSD depth of each sample is obtained. After MRF, the sample surfaces should be etched with 5% hydrofluoric acid for 10-15 min to remove the Beilby layer and enable cracks to be distinguished by high resolution optical microscopy (KEYENCE® VHX3000) at $500\times$ magnification at various depths along the surface wedge. Finally, image analysis is performed by thresholding the optical microscopy images of subsurface damage at various depths to create binary renderings such that the cracks on the surface are white pixels and the background is dark. The SSD depth and the SSD density (ratio of area that is composed of cracks to total area) at various depths along the wedge is determined. To investigate the grinding material removing mechanics and more detailed present SSD beneath the ground surface, cross-sectional high-resolution transmission electron microscopy (HRTEM, FEI® Talos F200X) experiments are taken.

Fig. 2 SSD is studied by MRF spot method. (a) ground sample #2 after etching and two MRF wedges (b) depth profile of MRF wedge 2 on Sample #2 across the centerline.

3. Results

3.1 Surface characteristics evolution

Fig. 3 shows the ground surface morphologies under WLI of fused silica at different cutting depths. Four typical roughness values (PV, RMS, R_z and R_a) are investigated and their evolutions at different cutting depths are shown in Fig. 4.

Fig. 3. Surface morphologies evolution of ground fused silica at different depth-of-cuts. (a) $a_c = 1 \mu\text{m}$ (b) $a_c = 2 \mu\text{m}$ (c) $a_c = 3 \mu\text{m}$ (d) $a_c = 4 \mu\text{m}$

Fig. 4. Surface roughness evolution of fused silica at different depth-of-cuts. (a) PV (b) R_a (c) R_z (d) RMS

When the cutting depth is 1 μm , the dominate feature of ground surface is shallow grinding streaks. The surface roughness PV, R_a , R_z and RMS at 1 μm depth-of-cut is 0.51 μm , 5.07 nm, 0.24 μm and 6.70 nm respectively. The roughness values of surface morphology are very low. As the cutting depth increases, all the roughness values are increased gradually as well. The surface roughness PV, R_a , R_z and RMS at 4 μm depth-of-cut is 1.34 μm , 15.23 nm, 0.94 μm and 22.24 nm respectively. Moreover, the pixel data of image at 4 μm depth-of-cut began to appear missing under WLI, which suggests brittle groove and fracture pit begin to appear and the surface integrity becomes worse. Fig. 3 and Fig. 4 indicate that the surface integrity of the smaller cutting depth is better than that of the large cutting depth grinding.

Fig. 5 shows that the ground surface morphologies under WLI of fused silica at different wheel speeds. The ground surface roughness PV, R_a , R_z and RMS of fused silica at different wheel speeds are shown in Fig. 6. The surface morphology at different cutting speeds present distinct differences. When the cutting speed is 3.9 m/s, the surface is covered with deep grinding streaks. The surface roughness PV, R_a , R_z and RMS at cutting speed of 3.9 m/s is 1.03 μm , 15.01 nm, 0.82 μm and 21.43 nm respectively. As the cutting speed increases, there remained a few microcracks and brittle groove as well as fracture pit on the ground surface in Fig. 5(b). As the cutting speed continues to increase, the roughness values are significantly reduced. The surface roughness PV, R_a , R_z and RMS at cutting speed of 23.4 m/s drop to 0.12 μm , 3.17 nm, 0.07 μm and 4.65 nm respectively. It can be found that the increase of cutting speed contributes to a smoother surface. When the cutting speed reached 23.4 m/s, surface microcracks are disappear and shallow grinding streaks are generated on the smooth surface, suggests that ductile cutting of abrasive grains dominates the surface morphology. One point to note is that both the surface roughness of PV and R_z at cutting speed of 11.8 m/s are slightly larger than that at wheel speed of 3.9 m/s, which may be caused by the inhomogeneity of the surface roughness.

Fig. 5. Surface morphologies evolution of ground fused silica at different cutting speeds. (a) $V_c = 3.9$ m/s (b) $V_c = 11.7$ m/s (c) $V_c = 19.5$ m/s (d) $V_c = 23.4$ m/s

Fig. 6. Surface roughness evolution of fused silica at different wheel cutting speeds. (a) PV (b) R_a (c) R_z (d) RMS

3.2 Subsurface damage density evolution

Fig. 7 and Fig. 8 illustrate that a series of typical cracks images under optical microscopic at various depths along the MRF wedges after etching. From the Fig. 7 and Fig. 8, samples (#1-#7) have similar subsurface crack characteristics, their main surface/subsurface damage morphology contains fracture pits, groove and microcracks. The observed subsurface cracks are mainly herringbone cracks induced by sharp indenter. The crack density on the ground sample surface is highest. At a depth of several microns beneath the ground surface, crack density decreases sharply. But for sample #8, there is no obvious fracture defects beneath the ground surface, which indicating material removal mechanism has changed here. The MRF spot method cannot determine its SSD depth.

Fig. 7. Subsurface crack morphologies of ground fused silica (#1-#4) in depth.

Fig. 8. Subsurface crack morphologies of ground fused silica (#5-#8) in depth.

Then, image processing technology is used to process the subsurface crack images of samples (#1-#7). The crack area in the image is set to be white, while the non-crack area around the cracks is set to be black. The crack densities at different depths are obtained by calculating the ratio of the white area to the image area, so as to quantitatively characterize the subsurface crack density evolution in depth. Fig. 9 and Fig. 10 show the distribution of subsurface crack

density of samples (#1-#7) at various depth. The crack density distribution show single exponential function features, which is expressed as follows:

$$d(x) = d_0 e^{-ax}$$

where x is the depth, d_0 is the initial crack density and a is constant related to the grinding process.

Fig. 9. Crack density of ground fused silica (#1-#4) in depth.

Fig. 10. Crack density of ground fused silica (#5-#7) in depth.

Overall, higher cutting speed and smaller depth-of-cut contribute to a smoother subsurface. In Fig. 9, after grinding with different depth-of-cuts, the subsurface crack density all decreases exponentially in depth. As the increase of depth-of-cut, the initial crack density of ground surface and the maximum crack depth are both increases. However, as the increase of cutting speed in Fig. 10, the maximum crack depth are decreases significantly and the initial crack density of ground surface increases on the contrary. The initial crack density increase can be attributed to a decrease in the grinding wheel dynamic balance performance, resulting in the appearance of unexpected vibration and causing more brittle fracture on ground surface.

3.3 Subsurface damage in TEM analysis

TEM analysis is taken in sample #6 and #8 to investigate the subsurface damage dominated by different removal mechanisms. In Fig. 11(a), a few subsurface cracks of sample #6 can be

observed in the overview image. In the area without subsurface cracks, TEM image at the resolution of 50 nm in Fig. 11(b) shows the local material particles are densified and subsurface is about to induce cracks, which indicate that the workpiece material has been extruded and plastic deformation has occurred in local area. In the area over subsurface cracks, a typical craterlike morphology is found in Fig. 11(c) at the resolution of 200 nm. Lateral cracks and median cracks are generated in ground subsurface, demonstrating that the material removal mechanism is brittle fracture. The subsurface morphology in sample #6 is the result of both ductile and brittle cutting removal. For sample #8, a smooth and non-crack subsurface is observed in Fig. 12(a). In addition, TEM image at the resolution of 10 nm in Fig. 12(b) shows there is a 3.4 nm thick plastic flow beneath ground surface. Below 3.4 nm depth, the arrangement of the material particles approaches to the uniformity. In sample #8, the dominant removal mode is ductile cutting removal.

Fig. 11. Cross-sectional HRTEM image showing subsurface damage of sample #6: (a) Overview of subsurface: cracks; (b) Detail view: local material particles are densified and plastic deformation has occurred; (c) Detail view: lateral cracks and median cracks are formed during ultra-precision grinding.

Fig. 12. Cross-sectional HRTEM image showing subsurface damage of sample #8: (a) Overview of subsurface: no fracture defects; (b) Detail view: plastic flow of fused silica is formed during ultra-precision grinding.

4. Discussion

In this section, the material removal mechanism in ultra-precision grinding experiments is revealed and the relationship between SSD depth and SR is discussed. A modified SSD prediction principle on surface characteristics for fused silica is proposed.

4.1 Material removal mechanism

For machining brittle materials, according to the critical depth-of-cut model in ductile-regime grinding established by Bifano et al. [21], the critical chip thickness h_c for brittle-plastic transition of fused silica can be obtained. The critical chip thickness model is:

$$h_c = 0.15 \left(\frac{E}{H} \right) \left(\frac{K_c}{H} \right)^2 \quad (1)$$

where E is the Young's modulus, H is the hardness and K_c is the fracture toughness. For fused silica, $E=72$ GPa, $H=10$ GPa, $K_c=1$ MPa·m^{1/2}. The value of critical chip thickness h_c can be calculated and is approximately equal to 10.8 nm.

To reveal the material removal mechanism in machining fused silica, it is necessary to calculate the maximum undeformed chip thickness (UCT) h_{max} in the grinding experiments with different parameters and compare it with the critical chip thickness of fused silica in ductile-regime grinding. The maximum UCT h_{max} can be calculated by the expression [22, 23]:

$$h_{max} = \left[\frac{4}{C \cdot r} \cdot \left(\frac{R \cdot \omega_w}{V_c} \right) \cdot \sqrt{\frac{a_e}{d_c}} \right]^{1/2} \quad (2)$$

where C is the active grit concentration, r is the ratio of mean chip width to chip thickness, whose value is in the range of 10-20. r is assumed to be 15 in calculation. R is the radius of workpiece, ω_w is the angular velocity of workpiece, V_c is the linear velocity of the grinding wheel, a_e is the depth of cut, d_c is the equivalent diameter of grinding wheel.

The active grit concentration C can be estimated by G_0 , the number of grains intersected per unit area on the hypothetical finely polished wheel surface [22]. G_0 can be calculated by the expression:

$$C \approx G_0 = \frac{6 \cdot V_g}{\pi \cdot d_g^2} \quad (3)$$

where V_g is the volume fraction of diamond abrasives in the grinding wheel, d_g is the average dimension of the abrasives. For our wheel, $V_g = 0.25$, $d_g = 5$ μm. The active grit concentration C is approximately equal to 1.91×10^{10} μm⁻².

According to the Eq. (2), The relationship between maximum UCT and the distance from workpiece center are illustrated in Fig. 13 and Fig. 14. It can be seen that ductile-regime grinding occurs in part near the center on the workpiece with different grinding conditions. With the increase of the distance from the workpiece center, the maximum UCT gradually increases. When the maximum UCT exceeds the critical chip thickness, brittle fracture begins

to dominate the formation of surface morphology. Taking sample #6 and #8 as examples, when the cutting speed is 11.7 m/s, the maximum UCT is close to the critical chip thickness. However, the depth of cut a_e of the abrasives shown in Eq. (2) is the average depth of cut of all the abrasives on the grinding wheel. The actual a_e of some abrasives is less than the critical depth of cut for brittle-plastic transition of fused silica, so ductile-regime grinding is predicted to occur on the sample #6 surface. The surface/subsurface morphology of sample #6 is the result of ductile-regime removal and brittle fracture which is consistent with the surface roughness results shown in Fig. 5(b) and the subsurface damage characteristics shown in Fig. 11.

For sample #8, when the cutting depth is small enough and the wheel speed is high enough, the maximum UCTs of each area on ground surface are less than the critical chip thickness. The material removal is mainly plastic flow removal, which can machine smooth ground surface/subsurface without microcracks. This result is consistent with surface roughness results (Fig. 5(d)) and TEM results (Fig. 12) as well.

Fig. 13. The relationship between maximum UCT and the distance from workpiece center with different depth-of-cuts.

Fig. 14. The relationship between maximum UCT and the distance from workpiece center with different cutting speeds.

4.2 Relationship between SSD depth and SR

According to the analysis in Section 4.1, The surface/subsurface morphology is the result of ductile- and brittle-regime material removal in sample #1-#7. The maximum depth of subsurface damage is usually caused by brittle fracture. In this section, the relationship between

crack depth and surface roughness are analyzed via indenting fracture theory firstly. Optical grinding process can be regarded as a collection of numerous indentation processes of sharp indenter on the surface of hard and brittle materials. When the sharp indenter presses the fused silica surface with a load exceeds a critical value, median and lateral cracks generate in subsurface. The median crack extends vertically to the material matrix, resulting in subsurface damage. The median crack depth often represents the subsurface damage depth. Lateral cracks extend along the direction nearly parallel to the surface, which take responsibility for removing material from the surface by brittle fracture. The depth of the lateral crack corresponds to the roughness value (usually is PV or R_z) of surface micromorphology [15, 17, 24].

Based on Lambropoulos' theory of indentation fracture mechanics and Hill model of the expanding cavity in a perfectly plastic material, the nonlinear theoretical model of the relationship between SSD depth to SR is given by Li et al. [15, 20]:

$$SSD = 3.08(\kappa\alpha_K)^{2/3} \left[\frac{1}{(\sin \psi)^{2/3}} \right] \left(\frac{H^{2m}}{E^{2m-2/3} K_c^{2/3}} \right) SR^{4/3} \quad (4)$$

where κ is the correction factor of median crack depth considering the contribution of elastic stress field and $\kappa = 2.23$, m is a dimensionless constant whose value is in the range of 1/3-1/2, ψ is the sharpness angle of indenter whose value is in the range of 45°-90°, K_c is the fracture toughness, α_K is a dimensionless number, which can be calculated by

$$\alpha_K = 0.027 + 0.09(m - 1/3) \quad (5)$$

For our case, $m=1/3$, $\psi = 45^\circ$. According to the above coefficients and the material properties of fused silica, the nonlinear model for fused silica can be obtained:

$$SSD = 2.77SR^{4/3} \quad (6)$$

Table. 2 lists the results of surface roughness in section 3.2 and subsurface crack depth in section 3.3, which are used to verify whether the above nonlinear model is correct. Fig. 15 shows the relationship between subsurface crack depth and surface roughness (PV and R_z) in ultra-precision grinding. It is found that there is a nonlinear monotonic increasing relationship between subsurface crack depth and surface roughness. For surface roughness PV, the power functions obtained by fitting are $SSD = 4.29PV^{4/3}$ (root mean square error is 1.192). For surface roughness R_z , the power functions obtained by fitting are $SSD = 6.21R_z^{4/3}$ (root mean square error is 1.229). The fitting curves both verified that the nonlinear model between subsurface crack depth and surface roughness has a low evaluation precision. Fitting curves suggest that the predicted value of subsurface crack depth based on Eq. (6) is less than experimental results. We surmise that the reason lies in a bad correspondence between SR value and lateral crack depth. The SR value is usually an average value in the measurement, which represents an overall level of surface quality of workpiece, while SSD depth is a local maximum value and represents the worst level of subsurface quality of workpiece. Under brittle material removal condition, the surface micromorphology is mainly affected by lateral cracks. The mean SR can correspond to the lateral crack depth b , that is $SR \approx b$, and the subsurface crack depth can also correspond to the median crack depth c , that is $SSD \approx c$, so the SSD depth can be accurately predicted by SR. However, under the ultra-precision grinding condition in our case, the material removal mechanism has changed. Brittle fracture removal frequently coexists with plastic flow. The surface morphology is shaped not only by the lateral crack but also plastic flow under the influence of ductile-regime grinding, which leads to a significant reduction of SR. Thus, the mean SR is less than the lateral crack depth ($SR < b$), which cannot truly correspond to the lateral crack depth. But SSD depth is determined by the maximum depth of the median crack in MRF spot method. Plastic flow is a nanoscale flow of material atoms in the shallow layer, which has little effect on the micron-scale crack depth. The subsurface crack depth is still corresponding to the median crack depth c , that is $SSD \approx c$. By using a smaller SR to predict the SSD depth, the predicted value of SSD is smaller than the actual one. In order to improve the accuracy of the model for ground SSD prediction, it is necessary to modify the coefficient of Eq. (6) according to the experimental results to ensure that the subsurface cracks generated in ultra-precision grinding are completely removed in the subsequent polishing process.

Table 2. Experimental results of ground surface roughness and SSD depth

Test group no.	Surface roughness				SSD depth (μm)
	PV (μm)	R_a (nm)	R_z (μm)	RMS (nm)	
1	0.43	4.87	0.20	6.36	1.2
2	0.62	9.06	0.33	10.96	3
3	0.79	12.19	0.71	16.64	4.6
4	1.34	15.23	0.94	22.25	6.1
5	1.03	15.01	0.83	21.43	5.6
6	1.14	12.38	0.92	19.22	3.4
7	0.59	5.11	0.27	7.04	1.8

Fig.15 Fitting curve and theoretical prediction curve of subsurface damage depth and surface roughness (PV and R_z).

Subsequently, curve fitting of SSD depth is performed using surface roughness R_a and RMS, respectively. Fig. 16 illustrates the relationship between SSD depth and surface roughness (R_a and RMS). It is found that both R_a and RMS have strong linear correlation with SSD depth. For surface roughness R_a , the polynomial functions obtained by fitting are $\text{SSD} = 0.41R_a - 0.68$ (root mean square error is 0.553). For surface roughness RMS, the polynomial functions obtained by fitting are $\text{SSD} = 0.24\text{RMS} - 0.16$ (root mean square error is 0.736). To estimate SSD depth influenced by the coexistence of brittle fracture and plastic flow, R_a is the most appropriate choice for prediction based on the principle of minimum root mean square error.

Fig.16 Fitting curve of subsurface damage depth and surface roughness (Ra and RMS).

Above all, a new SSD depth prediction principle can be proposed. When the material removal mechanism is mainly brittle fracture, meanwhile the surface morphology is full of crack, fracture pit and brittle groove, the nonlinear model $SSD \propto SR^{4/3}$ is prefer. When the material removal mechanism includes brittle fracture and plastic flow, and the surface morphology is mainly microcracks and grinding streaks, SSD depth can be estimate by the linear model: $SSD = 0.41R_a - 0.68$. When the material removal mechanism is mainly plastic flow and the surface morphology is covered with shallow grinding streaks, it suggests that there is no microcrack but a plastic flow layer in the subsurface.

5. Conclusion

The paper has investigated the materials removal mechanism in ultra-precision grinding, the relationship between SR and SSD depth by experimental and theoretical analysis. The detailed conclusions are as follows:

- (1) With the decrease of depth-of-cut and the increase of cutting speed, the surface/subsurface quality of ground fused silica is improved. When the depth-of-cut decreases from 4 μm to 1 μm , the surface roughness R_a of fused silica is improved from 15.23 nm to 5.07 nm and the maximum SSD depth is decreases from 6.1 μm to 1.2 μm . Besides, when the cutting speed increases from 3.9 m/s to 23.4 m/s, the surface roughness R_a of fused silica is improved from 15.01 nm to 3.17 nm and there is no crack but a 3.4 nm plastic flow layer in the subsurface.
- (2) The surface characteristics of fused silica in brittle-regime grinding contains pits, microcracks and deep grinding streaks caused by brittle fracture, and the SSD are microcracks; while the surface characteristics of ductile-regime grinding are mainly grinding streaks, and the SSD is plastic deformation of materials beneath the ground surface.
- (3) The material removal mechanism in ultra-precision grinding fine-grained grinding wheel includes brittle fracture and plastic flow. The nonlinear model $SSD \propto SR^{4/3}$ is not prefer to estimate SSD depth. Linear model $SSD = 0.41R_a - 0.68$ is more accurate than nonlinear model.

Declarations

Ethical Approval: Not applicable.

Consent to Participate: Not applicable.

Consent to Publish: Not applicable.

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Figures

Figure 1

The self-developed ultra-precision grinder.

Figure 2

SSD is studied by MRF spot method. (a) ground sample #2 after etching and two MRF wedges (b) depth profile of MRF wedge 2 on Sample #2 across the centerline.

Figure 3

Surface morphologies evolution of ground fused silica at different depth-of-cuts. (a) ae = 1 μm (b) ae = 2 μm (c) ae = 3 μm (d) ae = 4 μm

Figure 4

Surface roughness evolution of fused silica at different depth-of-cuts. (a) PV (b) Ra (c) Rz (d) RMS

Figure 5

Surface morphologies evolution of ground fused silica at different cutting speeds. (a) $V_c = 3.9$ m/s (b) $V_c = 11.7$ m/s (c) $V_c = 19.5$ m/s (d) $V_c = 23.4$ m/s

Figure 6

Surface roughness evolution of fused silica at different wheel cutting speeds. (a) PV (b) Ra (c) Rz (d) RMS

Figure 7

Subsurface crack morphologies of ground fused silica (#1-#4) in depth.

Figure 8

Subsurface crack morphologies of ground fused silica (#5-#8) in depth.

Figure 9

Crack density of ground fused silica (#1-#4) in depth.

Figure 10

Crack density of ground fused silica (#5-#7) in depth.

Figure 11

Cross-sectional HRTEM image showing subsurface damage of sample #6: (a) Overview of subsurface: cracks; (b) Detail view: local material particles are densified and plastic deformation has occurred; (c) Detail view: lateral cracks and median cracks are formed during ultra-precision grinding.

Figure 12

Cross-sectional HRTEM image showing subsurface damage of sample #8: (a) Overview of subsurface: no fracture defects; (b) Detail view: plastic flow of fused silica is formed during ultra-precision grinding.

Figure 13

The relationship between maximum UCT and the distance from workpiece center with different depth-of-cuts.

Figure 14

The relationship between maximum UCT and the distance from workpiece center with different cutting speeds.

Figure 15

Fitting curve and theoretical prediction curve of subsurface damage depth and surface roughness (PV and Rz).

Figure 16

Fitting curve of subsurface damage depth and surface roughness (Ra and RMS).