The Effect of Diamond Wheel Wear on Surface and Sub-Surface Quality in Fused Silica Optics Grinding

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Abstract. During the ultra-precision grinding process of fused silica optics, the micro-removal processes of brittle and hard fused silica material by diamond grits in different wheel wear states are inconsistent, which leads to the instability of the grinding quality of the components. First, the wear forms of diamond wheel in the process of grinding brittle and hard fused silica material were analysed. The main wear form of diamond grinding wheel was diamond abrasive wear. Then taking the cumulative removal volume of material as the evaluation parameter of wheel wear state, the evolution laws of surface roughness and sub-surface defects of components under different cumulative removal volume of material were studied. With the aggravation of grinding wheel wear, the surface roughness and depth of sub-surface defects layer decreased first, and then fluctuated and increased slowly. In the rapid wear stage, the falling diamond particles scratched deep grooves on the surface of components, and the roughness and sub-surface depth increased sharply. According to the results, it’s reliable to monitor the wheel wear state and predict the life of wheel.

1. Introduction
Fused silica has been widely used in high power laser devices as lens, window sheet for its excellent optical properties such as high chemical purity, low expansion coefficient and high optical transmittance [1]. Surface and sub-surface quality of fused silica optics have important effects on the overall output performance of optical systems and laser damage threshold of components [2]. Due to the brittleness and rigidity, diamond wheels are needed for precise forming grinding of optical components made of fused silica material [3], but there would be a large number of micro-cracks on the surface and in the sub-surface of the element for the brittle removal of material in the grinding process [4]. The cutting ability of diamond particles relative to the wear state of grinding wheel has an important influence on the surface and sub-surface quality of the work piece in the machining process [5].

A. Chandra et al. developed modeling framework for describing the wear process of electroplated CBN grinding wheel based on grit pullout mechanism and the associated state of damage percolation [6]. S. Kumar investigated the prediction of wear and surface roughness in electro-discharge diamond grinding by experiments and neural network [7]. Y. W. Zhu et al. studied on the influence of grinding...
wheel wear on work-piece surface quality by high speed cylindrical grinding test of 20CrMnTi carburizing steel using ceramic bond CBN wheel. Based on the experiment, the influence mechanism of grinding wheel wear on the work-piece surface roughness, surface residual stress, microstructure and surface micro-hardness change had been analyzed. It was found that the work-piece surface roughness was increased with an increase of grinding wheel wear [8]. Y. J. Zhang analyzed the influence of tool wear and machining parameters on the cutting temperature by the finite element simulation and experiments of ultra-precision cutting of aluminum. And the thermal elongation model of tool considering tool wear in ultra-precision cutting of aluminum was established based on the analysis of metal cutting theory and finite element simulation. Then the major and minor relationship of the influence of cutting parameters, tool geometry parameters and tool wear on thermal elongation of tool was analyzed [9].

In order to achieve surface and sub-surface quality of fused silica optics in ultra-precision grinding process steadily and improve the processing efficiency, the wear forms of diamond wheel were analyzed when grinding brittle and hard fused silica material firstly. Then taking the cumulative removal volume of material as the evaluation parameter of wheel wear state, the effect of grinding wheel wear on surface quality of components was investigated, and the relationships between grinding wheel wear and surface roughness, the depth of sub-surface defect layer were established. The results provided bases for monitoring wheel wear and predicting the life of wheel in the future.

2. Experiments setup

Fused silica is prepared by melting high purity silicon dioxide at temperatures above 1760°C in an electric furnace and then cooling rapidly. In this process, the crystalline of silicon dioxide is transformed to amorphous glass. Thus fused silica is a type of typical brittle and hard material. The thermodynamic properties are shown in Table 1.

| Item                              | Value  |
|-----------------------------------|--------|
| Melting point (°C)                | 1713   |
| Mohs hardness                     | 7      |
| Density (g/cm³)                   | 2.2    |
| Coefficient of expansion          | 5×10⁻⁷ |
| Coefficient of thermal conductivity (W/mK) | 1.951  |
| Modulus of elasticity (GPa)       | 72     |
| Poisson’s ratio                   | 0.143  |

Based on the ultra-precision grinder, experiment platform of diamond wheel wear in fused silica optics grinding was established. The D91 ceramic bonded diamond wheel with grain size between 80μm and 100μm was used in the experiments. After fixed on the spindle of grinder, the diamond wheel was dressed by SiC cup wheel to make the circular run-out error of wheel to be less than 5μm and remove the passivation layer on the surface of wheel. According to the technological parameters shown in Table 2, flat fused silica specimens with size of 200mm × 200mm were grinded. At the end of each experiment, KENGYCE VHX-2000 ultra-depth-of-field microscope was used to observe the wear morphology of abrasive particles on the surface of grinding wheel in situ. And the surface roughness of optics was measured by KENGYCE LJ-V7020 high precision profile scanner. Then cylindrical grooved polishing spots were machined on the surface of optics by CeO polishing wheel. The surface cracks were exposed by etching for 20min in HF solution with a mass concentration of 3%. At the end, the depth of defects layer could be calculated by measuring the profile of polishing spot and the width of corresponding defects, as shown in Figure 1 [10].
Table 2. Processing parameters

| Item                                      | Value                        |
|-------------------------------------------|------------------------------|
| Velocity of grinding wheel (m/s)          | 30                           |
| Feed speed (mm/min)                       | 5000                         |
| Grinding depth of each time (μm)         | 30                           |
| Cumulative removal volume of material (cm³)| 180, 360, 540, 720, 900, 1080, 1260, 1440, 1620, 1800 |

![Diagram of grinding process](image)

Figure 1 Measurement of the Depth of Crack Layer

3. Experimental results and discussions

3.1. Wear forms of diamond wheel

Cumulative material removal volume was taken as a quantitative parameter of grinding wheel wear state. The micro-morphologies of the same point on the wheel surface under different wear conditions were observed by KENGYCE VHX-2000 ultra-depth-of-field microscope, which were shown in Figure 2. In the grinding process, while the fused silica material was micro-cut by diamond abrasives,
the sharp diamond particles were all so gradually worn flat. With the increase of wear, the size of wear flat increased gradually. At the later stage of wheel wear, with the aggravation of grinding force, diamond abrasive grains broke up and fell off.

Figure 2. Micro-morphology of grinding wheel at different cumulative removal volumes of material

3.2. Effect of grinding wheel wear on surface roughness of components

The 3-D surface roughness of optics machined by the diamond wheel on different wear conditions was measured by KENGYCE LJ-V7020 high precision profile scanner on the 1-D precision motion platform. As shown in Figure 3, the direction of component motion is perpendicular to the measured profile. Each profile had 800 measuring points, and the distance between adjacent measuring points
was 10μm. During the motion of optical elements, the contour scanner simultaneously recorded all the scanned contours. The sampling frequency was 1000Hz, and the motion speed was 10mm/s, then the distance between adjacent contours was 10μm. The measured 1-D contour data were reconstructed into 2-D matrix, and the environmental noise error and the waviness error of the component surface were filtered out. Finally, the 3-D surface roughness data of the component were obtained.

Figure 3. Surface roughness measurement

The surface roughness of optics machined by diamond wheel at different wear conditions was shown in Figure 4 and Figure 5. At the initial stage of wheel wear, when the cumulative removal volume of material was less than 540cm³, the number of abrasive particles participating in grinding increased gradually. With the same processing parameters, the actual cutting thickness of single abrasive particle decreased gradually, so the surface roughness tended to decrease. After entering the stable wear stage, although the wear flats of abrasive particles were gradually increasing, the number of abrasive particles involved in grinding remained unchanged, so the surface roughness was relatively stable with the increase of wear. In the later stage of rapid wear, when the cumulative removal volume of material was larger than 1440cm³, some abrasive grains with weak grip fell off the wheel surface. The number of abrasive particles involved in grinding decreased, and the cutting thickness of single abrasive particle increased, which resulted in a sharp increasing of surface roughness.
3.3. Effect of grinding wheel wear on the depth of sub-surface damage

Using CeO polishing wheel, the polishing spots with cylindrical grooves were machined perpendicular to the grinding direction of the components, which were grinded by the diamond wheel at different wear conditions, respectively. The polished component was shown in Figure 6. After optics etched in HF solution with a mass concentration of 3% for 20min to expose cracks, the distances between the farthest defects and the edge of polishing spot were measured by microscope, and the profiles of polish spots were detected by SLIT CL2-MG140 spectral confocal displacement sensor on the 1-D precision motion platform, as shown in Figure 7. According to the distance between the farthest defect and the edge of the polished spot and the contour of the polished spot, the depth of the most serious sub-surface defect could be calculated out.
Figure 6. Cylindrical grooved polishing spots on the surface of optics

Figure 7. Defects and profile of polishing spot

The variation of the sub-surface defects depth with the wear of the grinding wheel was shown in Figure 8. At the beginning of grinding, the sub-surface defects depth fluctuated greatly, with the maximum value was more than 60μm and the minimum value was less than 40μm. A small amount of diamond particles loosen during the dressing process of wheel and the abrasive particles fell off during grinding and scratched the component surface, resulting in deeper sub-surface defects. Then the wheel entered the stability period, and the depth of sub-surface defects in a single process fluctuated between 40μm and 50μm, and the average depth of sub-surface defects increased slowly. In the stable stage, the abrasive particles involved in cutting were all fixed on the surface of the wheel. The scratching force of single abrasive particles increased slowly with the abrasive wear. And the depths of sub-surface defects also increased slowly in the fluctuation. After entering the stage of rapid wear, some abrasives fell off from the surface of wheel. And the free diamond abrasive particles were squeezed into the surface of the components, resulting in a sharp increasing in the depth of sub-surface defects and their fluctuation amplitude.

Figure 8. Depth of sub-surface defects at different cumulative removal volumes of material
4. Conclusion
In this paper, the cumulative removal volume of fused silica material was used as a quantitative evaluation parameter for grinding wheel wear. The influences of wheel wear on the surface and subsurface quality of brittle and hard fused silica optical elements during ultra-precision grinding were studied.

In the grinding process of fused silica, the main wear form of diamond grinding wheel was diamond abrasive wear. After entering the stage of rapid wear, a small amount of abrasives fell off and broke up.

In the initial wear stage, the surface roughness of components decreased slightly with the wear of grinding wheel. After entering the stable wear stage, the surface roughness increased slightly. In the rapid wear stage, the falling diamond particles scratched deep grooves on the surface of components, resulting in a sharp increasing of roughness.

At the beginning of grinding, the loose abrasive particles due to dressing process fell off from the surface of wheel, which increased the depth of sub-surface defects greatly. Then the grinding wheel entered a stable wear stage, and the depth of sub-surface defects increased slowly in the fluctuation. In the stage of rapid wear, the free diamond particles falling off the grinding wheel surface aggravated the propagation of sub-surface cracks and the sub-surface defects depth increased sharply.

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