Characterization Methods of Subsurface Cracks in Grinding of Optical Elements

Rui Gao, Hongxiang Wang*, Chu Wang, Shunzhi Feng and Benwen Zhu
School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, Heilongjing, 150001, China
*whx@hit.edu.cn

Abstract. In this paper, the subsurface cracks of fused silica introduced in grinding were detected by taper polishing method, and then characterized by the maximum depth, the cluster depth, and the density of cracks. The quantitative relationship between maximum depth and cluster depth of subsurface cracks was determined, and the distribution of subsurface crack density along the depth was studied. The results showed that the abrasive grain size had a great influence on maximum depth and cluster depth of subsurface cracks, while the grinding fluid concentration had little effect on them. The different processing parameters changed maximum depth and cluster depth, but their ratio was almost unchanged. The subsurface crack density decreased exponentially along the depth, and the decrease trend had slowed down significantly at the half of cluster depth.

1. Introduction
The grinding for the optical brittle materials mainly removes the material by brittle fracture, leaving subsurface defects on the final surfaces. The subsurface defects inevitably affect laser induced damage threshold (LIDT) which will shorten the lifetime of optical components [1-2]. In the early subsurface defect detection, due to the lack of advanced detection equipment and reliable detection methods, the subsurface crack depth was mainly estimated by the processing conditions such as the average abrasive grain size. Sabia et al. [3] found the subsurface crack depth was about 5 times to the abrasive size for fixed abrasive grinding, and it was 1~1.8 times for loose abrasive grinding (lapping). Menapace et al. [4] pointed out it was about 3 times in grinding, and Hed and Edwards [5] thought it was 1 time in lapping. Differences in estimated values were caused by differences in processing methods, equipment and parameters. These estimated values of subsurface crack depth were not very accurate, reducing processing efficiency. Tonnellier et al. [6] examined the subsurface cracks during the grinding of fused silica glass, and found that the majority of subsurface cracks clustered together near the machined surface and terminated at cluster depth. With the further increase of depth, there were separate cracks remaining, and the maximum depth of such cracks was much larger than the cluster depth. Researchers of Lawrence Livermore National Laboratory (LLNL) made breakthroughs in the study on characterization methods of subsurface cracks, and broke the limitations of only using maximum depth to characterize. Suratwala et al. [7] utilized magnetorheological finishing (MRF) method to detect subsurface cracks produced by the grinding of fused silica, and obtained the binary images of subsurface crack distribution by image processing technology. The results showed that the subsurface crack density decreased exponentially along the depth. With the continuous progress of science and technology, there have been many advanced detection equipment based on optics, mechanics, acoustics, electromagnetics, quantum mechanics and other fields, promoting the
development of subsurface defect detection technology. There are non-destructive detection methods including ultrasonic, eddy current, radiographic, magnetic particle, ultrasonic-infrared phase testing and so on. In addition, there are destructive detection methods including chemical etching method [8-9], taper polishing method, bonded interface technique, and MRF method. Compared with subsurface crack detection technology, the research on characterization of subsurface cracks is still in the initial stage. In order to realize the quantitative characterization of subsurface cracks in optical element, it is necessary to study the density distribution and depth of subsurface cracks. In this paper, the subsurface cracks of fused silica introduced in grinding were characterized by the maximum depth, the cluster depth, and the density of cracks. The distribution of subsurface crack density along the depth was studied.

2. Maximum depth and cluster depth of subsurface cracks

The grinding experiments of fused silica specimens were carried out by grinding and polishing machine (ZYP300), with grinding pressure of 22kPa, grinding time of 30min, spindle speed of 50r/min, and grinding fluid concentration of 8wt.%. The specimen dimension was $\Phi50\text{mm}$ x $6\text{mm}$ and the abrasive grains were W45, W28, and W14, respectively. In order to analyze the relationship between maximum depth and cluster depth, the subsurface cracks were detected by taper polishing method and MRF method, respectively. The detection results are shown in table 1, and the ratio of maximum depth to cluster depth remained between 1.12~1.19.

| Abrasive grains | maximum depth (µm) | cluster depth (µm) | ratio |
|----------------|---------------------|--------------------|-------|
|                | taper polishing     | MRF                | taper polishing | MRF |
| W45            | 26.7                | 25.2               | 23.8            | 21.4 | 1.12 | 1.18 |
| W28            | 15.6                | 13.7               | 13.4            | 12.0 | 1.16 | 1.14 |
| W14            | 11.3                | 10.9               | 9.5             | 9.8  | 1.19 | 1.15 |

The morphologies of subsurface cracks obtained by taper polishing method are shown in figure 1. The subsurface cracks produced by grinding overlapped each other near the machined surface and connected together into dense distribution. The crack density decreased gradually with the increase of depth, and the dense cracks disappeared at a certain depth. This depth was defined as the cluster depth of subsurface cracks, which is the distance between the horizontal line and the machined surface (see figure 1). With the further increase of depth, there were separate cracks remaining under the cluster depth. After reaching a certain depth, there was the non-damaged matrix, and cracks no longer existed. This depth was defined as the maximum depth of subsurface cracks, as shown in the circle (see figure 1). Each stage of grinding for optical elements always introduces a certain depth of subsurface cracks. In the rough grinding stage, the cluster depth is used to characterize the subsurface crack depth. In order to reduce processing time and improve processing efficiency, each operation step should eliminate the dense cracks left from the previous step. In the fine grinding stage, the maximum depth is used to characterize the subsurface crack depth, guaranteeing that the subsurface cracks produced by fine grinding can be completely removed in the subsequent polishing process.
(a) Surface machined by W45    (b) Surface machined by W28   (c) Surface machined by W14

Figure 1. Morphologies of subsurface cracks after grinding with different abrasive grains

3. Subsurface crack density

Grinding is a very complex dynamic random micro-cutting process. With inconsistency of protrusion height, uneven distribution of abrasive grain sizes, and random distribution of subsurface cracks, it is very difficult to calculate the number of cracks at different depths by traditional method. At the near-surface, subsurface cracks overlap each other, so it is more difficult to describe the crack distribution accurately. MATLAB has powerful image processing function, which can realize the evaluation and characterization of subsurface crack distribution at different depths.

Because of the difference of gray scale between cracks and non-damaged matrix in the images, the cracks can be detected from the matrix by setting a suitable threshold $T$. The gray scale of input image is $F(x, y)$ and the gray scale of output image is $g(x, y)$:

$$
g(x, y) = \begin{cases} 
1 & \text{if } F(x, y) > T \\
0 & \text{if } F(x, y) \leq T 
\end{cases}
$$

The image processing flow is shown in figure 2. Firstly, the true color image of subsurface cracks acquired by microscope was transformed into a gray scale image. Then, the median filter removed the noise and improved the clarity of crack edge. Subsequently, the appropriate threshold $T$ was selected to turn the gray scale image into a binary image, where cracks were showed black and non-damaged matrix was showed white. Finally, the pixel number of cracks at a certain depth and all the pixel number of binary image were counted. The ratio of them was defined as the subsurface crack density at this depth. The original image obtained by optical microscopy, the gray scale image, and the binary image processed by MATLAB are shown in figure 3.

Figure 2. Image processing flow

Figure 3. Original image, gray scale image, and binary image in image processing

4. Distribution of subsurface crack density along the depth

The distribution of the subsurface crack density along the depth depends on instantaneous distribution of cracks, overlapping of cracks at different grinding moments, and continuous removal of cracks. The subsurface crack distribution at a certain depth introduced at time $t$ is assumed to conform to the normal distribution, and denoted as $f_0(c)$. After time $\Delta t$, the material removal increment is $\Delta$, and it is assumed that the same crack distribution as time $t$ is produced on the new surface at this time, which is denoted as $f_0(c+\Delta)$. In the same way, when the material removal increment is $i\Delta$, the distribution is denoted as $f_0(c+i\Delta)$ [7]. The generation and removal of subsurface cracks in grinding process indicate
that the subsurface crack density decreases gradually with the increase of subsurface depth (see figure 4).

When \( i \) is large enough, the generation and removal of subsurface cracks reach a dynamic equilibrium (the specimen surface is adequately grinded), and the function of subsurface crack distribution \( f_i(c) \) [7] can be expressed as:

\[
f_i(c) = f_0(c) + f_0(c + \Delta) + \ldots + f_0(c + i\Delta) = \sum f_0(c + i\Delta)
\]

The distribution of subsurface crack density along the depth \( F_i(c) \) can be obtained by integrating \( f_i(c) \):

\[
F_i(c) = \int f_i(c)dc
\]

**Figure 4.** Generation and removal of subsurface cracks in grinding process

In the actual grinding process, abrasive grains are randomly distributed on the grinding plate, and the space between abrasive grains is also random. The interactions between abrasive grains will inevitably affect the subsurface crack depth. In order to determine the relationship between cluster depth and maximum depth, the pre-polished fused silica specimens with dimension of \( \Phi 20mm \times 5mm \) were used in the experiment. The abrasive grains were 320#, 400#, 600#, and 800#, respectively. The grinding fluid concentrations were 5wt.%, 8wt.%, 12wt.%, and 15wt.%, respectively. Other processing parameters remained constant. Maximum depth and cluster depth of subsurface cracks detected by taper polishing method were calculated by MATLAB, and their relationships with abrasive grains are shown in figure 5.

**Figure 5.** Relationships between maximum depth and cluster depth with abrasive grains under different grinding fluid concentrations
As shown in figure 5, 1) with the decrease of abrasive grain size, maximum depth and cluster depth of subsurface cracks were reduced. The smaller the abrasive grain size was, the more the effective abrasives involved in the grinding process. In the case, with the same grinding pressure, the effective load of each abrasive grain was smaller, leaving the decrease in maximum depth and cluster depth. 2) When the abrasive grain size was constant, with the increase of grinding fluid concentration, maximum depth and cluster depth changed very little. The reason for this phenomenon was that the effective abrasive grains were alternately updated in the actual grinding process, resulting in the actual grinding fluid concentration tended to be consistent. 3) Although the different processing parameters changed maximum depth and cluster depth, their ratio was almost unchanged. This is because the random distribution of space between abrasive grains existed during the grinding, and the crack propagation depth reached a dynamic equilibrium after a long period of grinding.

According to the experimental data, the variations in subsurface crack density along the depth are shown in figure 6. The subsurface crack density decreased exponentially along the depth, and the decrease trend had slowed down significantly at the half of cluster depth. With the continuous processing of grinding, the irregular pyramid-like abrasive grain tips were gradually passivated or broken. The subsurface crack distribution corresponding to each material removal increment Δ was changed, and inconsistent with the theoretical assumptions, which was the root cause of the differences between experiment and theoretical analysis.

![Figure 6. Variations in subsurface crack density along the depth under different abrasive grains](image)

5. Conclusions
The present work studied the characterization methods of subsurface cracks in grinding of optical elements. Following conclusions can be drawn from this investigation:

1) The subsurface crack distribution in grinding of fused silica was detected by taper polishing method. The quantitative relationship between maximum depth and cluster depth was determined, and their ratio remained at 1.12~1.19.

2) The subsurface crack density at a certain depth was calculated through image gray processing, median filter, and image thresholding method. The subsurface cracks were characterized by maximum depth, cluster depth, and crack density.

3) For maximum depth and cluster depth of subsurface cracks, they were reduced with the decrease of abrasive grain size, while the grinding fluid concentration had little effect on them. Although they were changed with the processing parameters, their ratio was almost constant.

4) The subsurface crack density decreased exponentially along the depth, and then the decrease trend had slowed down significantly at the half of cluster depth.
6. Acknowledgments
This research was financially supported by National Natural Science Foundation of China (Grant No.51475106) and Science Challenge Project (Grant No.JCKY2016212A506-0503).

7. References
[1] Jiang Y, et al. Effect of residual stress on laser-induced damage characterization of mitigated damage sites in fused silica 2015 Journal of Non-Crystalline Solids 410 88-95.
[2] Lv D, Wang H, Zhang W and Yin Z Subsurface damage depth and distribution in rotary ultrasonic machining and conventional grinding of glass BK7 2016 International Journal of Advanced Manufacturing Technology 86 2361-2371.
[3] Sabia R, Stevens H J and Varner J R Pitting of a glass-ceramic during polishing with cerium oxide 1999 Journal of Non-Crystalline Solids 249 123-130.
[4] Menapace J A, Suratwala T I and Miller P E MRF applications: measurement of process-dependent subsurface damage in optical materials using the MRF wedge technique 2005 Proceedings of SPIE - The International Society for Optical Engineering (2005)599103-599103-11.
[5] Hed P P and Edwards D F Optical glass fabrication technology. 2: Relationship between surface roughness and subsurface damage 1987 Applied Optics 26 4677.
[6] Tonnellier X, Morantz P, Shore P, Baldwin A, Evans R and Walker D D Subsurface damage in precision ground ULE® and Zerodur® surfaces 2007 Optics Express 15 12197-12205.
[7] Suratwala T, Wong L, Miller P, Feit M D, Menapace J, Steele R, Davis P and Walmer D Subsurface mechanical damage distributions during grinding of fused silica 2006 Journal of Non-Crystalline Solids 352 5601-5617.
[8] Neauport J, Ambard C, Cormont P, Darbois N, Destribats J, Luitot C and Rondeau O Subsurface damage measurement of ground fused silica parts by HF etching techniques 2009 Optics Express 17 20448-56.
[9] Zhou Y, Funkenbusch P D, Quesnel D J, Golini D and Lindquist A Effect of Etching and Imaging Mode on the Measurement of Subsurface Damage in Microground Optical Glasses 2010 Journal of the American Ceramic Society 77 3277-3280.