Machining Grooves in Silica Glass by Using Picosecond Lasers

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Abstract. A picosecond laser with 1064nm wavelength was used to machine grooves in fused silica in this paper. A surface texturing method was applied to increase the laser absorption. The relationship between the width, the depth of the groove and the laser parameters such as laser power, scanning speed, number of scanning cycles was studied. The machining quality of the groove was detected by the laser scanning confocal microscopy. It showed that there were no micro-cracks on the grooving surface, and the surface roughness Ra<1.6um. The width, the depth and the shape of the groove could be controlled accurately by changing the laser parameters. And, a “V-shape” groove with 1mm width, 1mm depth was obtained with the as the frequency, the laser power, the scanning velocity and the number scanning cycle was fixed at 400KHz, 141W, 5000mm/s and 12, respectively.

1. Introduction
Fused silica is an important material widely used in aerospace, nuclear, electrics, optics, mechanical engineering. However, it is difficult to micro-machine with traditional methods because of its hardness and brittle characters. With the development of laser technology, laser has been applied in machining brittle materials. Jiao[1,2] cut glass plates using CO₂ lasers with fracture control method, and the glass can be cut with a high quality using dual laser beam method. The temperature and the thermal stress was simulated in the cutting process by Tian[3] and Wei[4]. The result showed that the cutting quality was affected by the temperature distribution greatly. Brugan [5] used simultaneous CO₂ lasers to cut alumina ceramics and Wang [6,7] cleaved glass sheets by using a line-shape laser beam with controlled fracture and volumetric heat absorption.

As mentioned above, CO₂ laser was used to machine glass in most of these studies because of its high absorption coefficient for glass. As we all know, the fused silica was transparent to light with wavelength around 1000nm. Long pulse laser or CW laser around this wavelength has a low efficiency in processing glass material. However, the short or ultra-short pulse laser has a great talent in fused silica machining [8]. In this study, a surface texturing method was applied to increase the laser absorption coefficient. Picosecond laser with 1064nm wavelength was used to machining grooves in the fused silica. The relationship between the width, the depth of the groove and the laser parameters was researched.
2 Experimental design
In this study, a picosecond laser by EdgeWave was used. The maximum laser power is 300W at 2-20MHz, the wavelength is 1064nm, the frequency can be adjusted from 400KHz to 20MHz. The laser beam is reflected into a laser scanner, the focused laser diameter is ~75 microns. The micro-processing path was controlled by the laser scanner, and the maximum speed is 10m/s. The experimental setup is shown in Figure 1 and Figure 2(a).

To measure the cross section and the roughness of these grooves, a Keyence confocal laser scanning microscope (Figure 2(b)) was used to examine the characteristics of the microgrooves, and the width, depth, cross section, roughness and the taper of the grooves can be measured conveniently. This microscope has 110 nanometer XY-plane resolution and 10 nanometer Z-resolution, a 50 mm by 50 mm zone can be scanned automatically to get the 3D geometry of the machined features. The optical magnification is 3000X, with digital magnification, the final magnification reaches 24000X.

In the experiment, the laser beam scans N lines on the substrate surface for one scanning layer (Figure 3). The pulse overlap of two scanning is about 1/4 of laser spot size (Δd=20um), which is the best value obtained through previous experiments. For one scanning cycle, there are N scanning layers. The laser beam scans N times for the first layer, and N-1 times for the second layer, then N-2 times for the third layer, and so on, 1 time for the last layer. The schematic diagram of this scanning method was shown in Figure 3.

Figure.1 Experimental setup (1. Control system, 2. Picosecond laser, 3. Laser scanner, 4. XYZ motion system, 5. Substrate, 6. Laser beam, 7. Dust exhaustion apparatus)

Figure.2 (a) The experimental setup and (b) the confocal scanning microscope
3 Result and discussions

For lasers with 1064nm wavelength, more than 90% laser energy transmits out from fused silica [9]. In order to increase the absorption coefficient, the fused silica surface was polished with the abrasive paper to increase the surface roughness in this study. The roughness of the polished surface was measured by using a confocal laser scanning microscope. The measured result showed that there are lots of micro-pits on the surface and the roughness is about 9.2um (Figure 4). The absorption coefficient can be increased because of these micro-pits and roughness surface.

After polished with the abrasive paper, the fused silica surface absorption coefficient to laser increases greatly. The material was vaporized under the high power picosecond laser, and micro-grooves were achieved. However, the fused silica without any treatment, the absorption coefficient is very low in the surface, and some cracks were produced in the substrate, especially on the laser-in surface. One traditional method to improve the absorption coefficient is coating high absorption material on the fused silica surface. In this study, a material with high absorption coefficient to 1064nm laser was coated on the surface. With this method, more than 85% laser energy was absorbed. With this method, lots of micro cracks were produced on the surface because of thermal stress accumulation. With these micro
cracks, the surface roughness was improved and more laser energy could absorbed by fused silica. The glass material was vaporized by the high power laser pulse in this case, and a new surface with micro-pits was produced, the laser absorption coefficient increases again. With this method, the fused silica material was vaporized layer by layer, and micro groove was produced. However, lots of cracks were produced on the edge of the groove (as shown in Figure 5) because of a great of thermal energy accumulated on the surface in a short of time as the laser beam irradiating on it. On the other hand, the fused silica polished with abrasive paper could be machined by picosecond laser without any micro cracks. As shown in Figure 6, a groove with 900um width and 620um depth was produced, and the roughness on the groove bottom Ra=0.82um, which is smaller than that of polished with abrasive paper, and it satisfy most of applications in industry.

![Figure 5](image1.png) Micro-grooves in fused silica with coating high absorption material

![Figure 6](image2.png) Micro-grooves in fused silica with abrasive paper polishing

In our previous research, it was found that the material removal efficient increases firstly and then decreases with the increasing of the frequency, and the most efficient material removal frequency was fixed at 400KHz. Under this frequency, the maximum laser power is 141W. The scanning velocity is chosen as 5000mm/s, which is the best value under 141W laser power. With these laser parameters, the shape of the micro-groove under different number of scanning cycle was researched. In this study, the number scanning cycle was chosen as 7, 8, 9, 10, 12, separately. As shown in Figure 7, d indicates the 1/2 width of the groove, h is the depth of the groove, and s is the 1/2 cross section area of the groove.

As shown in Fig.7, with the increasing of the scanning cycle number, the depth of the groove increases firstly, and then nearly keeps in a constant value after 9 scanning cycles, which is about 570um. It because the vaporized material could not escape from the groove as the groove depth reached a specific value. The width of the groove increases with the increasing of scanning cycles, which is about 1020um for 12 scanning cycles. Fig.8 gives the changing of groove taper with scanning cycle number. The angle
is smaller, the taper of the groove is larger. As shown in the Figure 8, the taper of the groove becomes larger with increasing of the scanning cycle number.

Figure.7 Shape of the micro-groove

Figure.8 The groove taper changing with scanning cycle number

Figure.9 V-shape grooves produced in the fused silica

Grooves with different shape could be obtained by controlling the scanning cycle number, scanning line number for different layer and the laser parameters. As shown in Figure 9, V-shape (h=0.6mm, d=0.5mm) groove was achieved under the scanning parameters as shown in table1.
Table 1 Laser parameters for groove machining

| Laser power | Frequency | Scanning velocity | number of scanning cycle |
|-------------|-----------|-------------------|--------------------------|
| 141W        | 400KHz    | 5m/s              | 12                       |

4 Conclusion
The absorption coefficient of fused silica for 1064nm laser could be improved by texturing method. After polishing with abrasive paper, the fused silica could be machined by picosecond laser without any micro cracks. And the roughness of the groove bottom was Ra=0.82um. The shape of the groove could be controlled accurately by controlling the laser parameters and the cycle number of scanning.

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