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Surface integrity of precision ground fused silica for high power laser applications

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Abstract

Surface integrity of optics used in high power laser systems is vital to their successful application. Reduction of subsurface damage is demanded during their processing. Rapid grinding of large and complex shape optics can be performed using the BoX® ultra precision grinding machine. Importantly, the depth of subsurface damage induced, even at high material removal rates, has been shown to be very small in comparison to previous studies.
In this paper, grinding experiments have been conducted to verify the amount of defects beneath ground fused silica surfaces produced under selected processing conditions. The subsurface damage levels were revealed using a sub-aperture polishing process in combination with an etching technique. Observed subsurface damage can be separated in two distinct depth zones characterised as 'process' and 'machine dynamics' related.

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1. Introduction

Developments of a number of major science projects have increased the demand of large size optics. The National Ignition Facility (NIF, US) and the Laser Mega Joule (LMJ, France) projects are demanding continuous replacement of large quantities of optics. These projects have driven the need for improving optical manufacturing and measurements. Others similar projects currently at different stages of development are LIFE (US) and HiPER (UK) [1-4]. For example, the NIF project required 7360 optics between 500 mm to 1000 mm diameter in materials such as BK7 and SiO_2. This corresponds to a production rate of about hundred large optics per month [5]. The LMJ project also needs a large amount

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of optics. The testing facility for this fusion technology is called "Ligne Intégration laser" (LIL). It used 135 m^2 of polished glass. The full scale project, LMJ, will required 4000 m^2 of polished glass optics. Development of improved manufacturing processes will be necessary to produce its 4200 glass laser plates with a dimension of 810 mm x 460 mm [6].

Surface integrity of optics used in high power laser systems is vital to their successful application. These optics sustain very large fluences of 15 J/cm^3 causing cumulative damage and ultimately leading to frequent optics replacement. A laser damage threshold (LDT) limit is reached and is largely influenced by the amount of surface and subsurface damage induced during the manufacturing process. The control of each manufacturing process stage is necessary in particular subsurface damage levels [7-8].

This can be achieved through an efficient grinding process [9] reducing the amount of subsurface damage and therefore the amount of subsequent polishing required. The BoX grinding machine process has demonstrated a low level of subsurface damage in glass and glass ceramics. Rapid grinding of those large and complex shape optics can be performed using the BoX® ultra precision grinding machine. Importantly, the depth of subsurface damage induced, even at high material removal rates, has been shown to be very small in comparison to previous studies [10, 11].

2. Surface integrity

Material removal of brittle materials can be achieved through brittle, semi-ductile or ductile mode grinding. The initiation and propagation of median and lateral cracks in brittle materials was described by Lawn. An indentation load is applied which leads to a small median crack creation that increases with the load. With the unloading, the median crack starts to close and a lateral crack appears which grows toward the surface [12]. Cook and Pharr (1990) illustrated that the formation of radial cracks occurred at different stage of the loading and unloading cycle for glasses and ceramics [13]. For crystalline materials and densifying glass (i.e., fused silica), the radial crack formation occurs during loading. For other glasses (i.e., borosilicate, soda lime), the unloading cycle generates cracks.

Argon (1959) observed that the distribution of number of cracks per unit area per crack depth versus crack depth on 7740 Pyrex glass follows a power law function [14]. In fused silica, the crack distribution is explained in three fractures zones. A rubble zone is followed by shallow fractures. After that point, heavy fracture network disappears. Fracture pattern and length are observed and characterise the process used. Those split finally into radial fracture of set length before no damage is seen [7].

Subsurface damage initiation and penetration depth are influenced by material characteristics of the ground substrates. An important parameter to calculate is the material brittleness (B). It corresponds to the micro hardness (H) divided by the fracture toughness (K_c) for a given material. Lawn and Evans (1977) showed that an initial load P* has to be applied to develop an initial penetration crack depth c*. The values obtained from those two parameters are approximated within an order of magnitude [15].

Table 1. Reference materials characteristics.

Material	Brittleness (B) $1/m^{1/2}$	Initial applied load (P*) N	Initial penetration depth (c*) µm
Fused silica	7020	0.06	1.05
ULE	2560	2.37	6.74
Zerodur	6890	0.06	0.93

The initial applied load to create subsurface damage is similar for fused silica and Zerodur (see Table 1]. Their threshold is forty times lower than ULE. Similar trend is shown for the initial penetration depth. Fused silica has significant shallower damage depth than ULE for a similar initial applied load. However, it may generate a slightly deeper crack depth than Zerodur. Observations made for P* and c* can be described using material brittleness parameter. A lower material brittleness value leads to a higher initial load required to generate subsurface damage. Once the subsurface damage starts, the fracture toughness is the main controlling factor [15].

3. Grinding experiments

Experiments were conducted on square specimens 100 mm x 100 mm x 20 mm. All edges were chamfered prior to grinding to avoid chipping during handling. Each surface was ground to same specification to remove subsurface damage induced by previous processes using the BoX® ultra precision grinding machine.

3.1. Material

The material selected is Corning Fused Silica 7980 HPFS® Standard grade [16]. Table 2 shows its characteristics against other materials (ULE, Zerodur) previously tested for subsurface damage after grinding using the BoX machine.

Table 2. Materials characteristics.

Material	Density (ρ) g/cm^3	Elastic modulus (*E*) GPa	Micro Hardness (*H*) GPa	Fracture toughness (K_{Ic}) $MPa.m^{1/2}$
Fused silica	2.2	72.7	5.2	0.7
ULE	2.2	70	4.6	1.8
Zerodur	2.5	91	6.2	0.9

3.2. Grinding parameters

Two resin bonded diamond grinding wheels were employed with D16 and D25 grit sizes and 50 concentrations. Depths of cut employed were 20 µm and 50 µm respectively in order to obtain similar normal grinding forces. The grinding surface speed, wheel speed and step per revolution were kept constant. The material removal rates obtained were 0.75 mm^3/s and 1.87 mm^3/s respectively. The process time for a finish cut is 3.7 hours for a half meter square area optic. The normal grinding forces were recorded using a Kistler dynamometer. The surface roughness and profile were measured using a Form Talysurf profilometer 120L.

3.3. Sample preparation

In order to measure the depth of subsurface damage, two wedges were polished across the samples after grinding. Those wedges have a typical depth of 80 µm over a distance of 80 mm (Figure 1a). The inflated bonnet sub-aperture polishing process employed is thought not to induce additional subsurface damage into the surface. Each sample was carefully acid etched using HF acid removing the redeposition layer left during polishing. This etching process removed less than a micrometer depth. An HF solution

(40% HF) was applied for 210 seconds over the assessed face in order to reveal cracks. The number of cracks were counted using an optical microscope. The depth of the wedge for a given micrograph is obtained using a Form Talysurf. By combining this data, the number of subsurface damage features per mm^2 was obtained (Figure 1b).

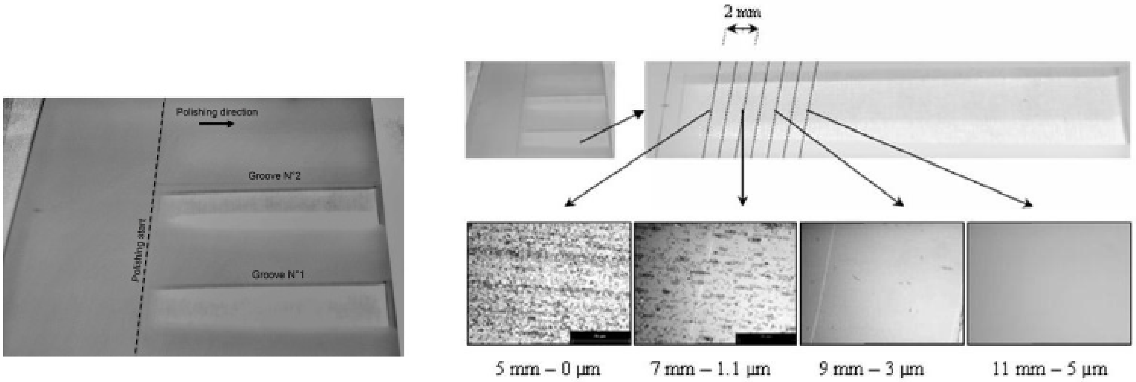

Fig. 1. Sample preparation (a) Wedges polishing; (b) Assessment technique.

4. Experimental results and discussions

Table 3 shows results obtained in terms of surface integrity and grinding forces using both D25 and D16 grinding wheels. For both experiments, the grinding wheel geometry and step per revolution used are the same, consequently the surface profile (P_t) measured is similar. Surface roughness (R_a) is reduced using smaller grit size and depth of cut. The normal grinding forces are minimised below 100 N by reducing the depth of cut when using smaller wheel grit size.

Table 3. Experimental results.

Depth of cut (ae) µm	Wheel grit size µm	Normal grinding force (Fz) N	Surface profile (P_t) µm	Surface roughness (R_a) nm
20	D16	53-70	0.8	60-100
50	D25	100	0.8	155

Figure 2a and 2b are showing two micrographs of subsurface damage cracks observed using each grinding wheel. Lateral cracks are shortened with a reduction in grit size. The crack length increases along with grit size.

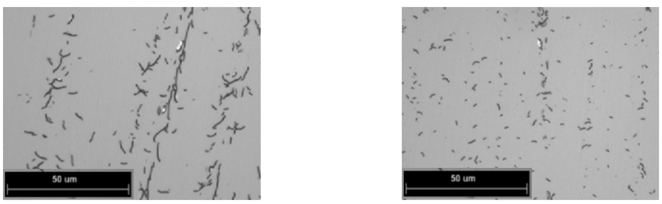

Fig. 2. Subsurface damage (a) D25 grinding wheel; (b) D16 grinding wheel.

The crack distribution for the D25 grit size is oriented along the grinding wheel rotation direction. This shows a preference in subsurface damage generated by some larger grits inside the grinding wheel. The grinding pattern left using D16 grinding wheel is less easily deciphered.

Figures 3a and 3b show the distribution of number of damage sites for a given depth below the ground surface.

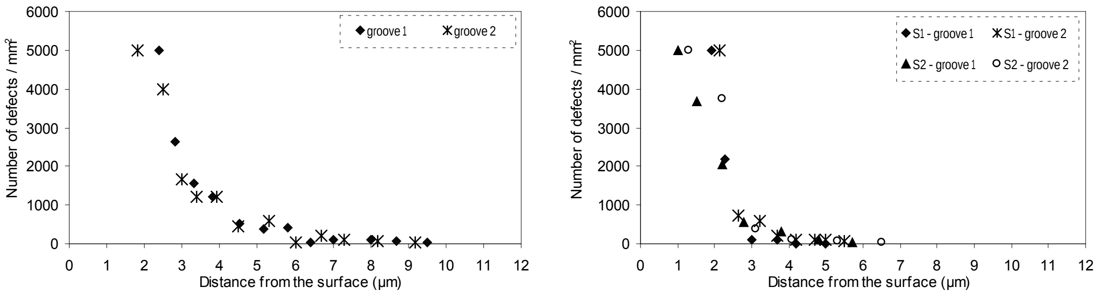

Fig. 3. Subsurface damage (a) D25 grinding wheel; (b) D16 grinding wheel.

Typically, the number of defects decreases rapidly below 100 defects per mm^2. The number of cracks reduced quicker for the smaller grit size processed surfaces. For a given specimen, the measured subsurface defect sites are comparable for both polished wedges (Figure 1b). This repeatability shows that the grinding process is consistent across the whole of the ground specimen. In addition, for the D16 grinding wheel, the grinding process in terms of subsurface damage is repeatable on a number of ground surfaces. The subsurface damage depth is 6.5 µm using the D16 grinding wheel and 9.5 µm using the D25 grinding wheel.

Figure 4a and 4b show partition of subsurface damage in terms of 'cluster' depth and 'single last fracture' depth.

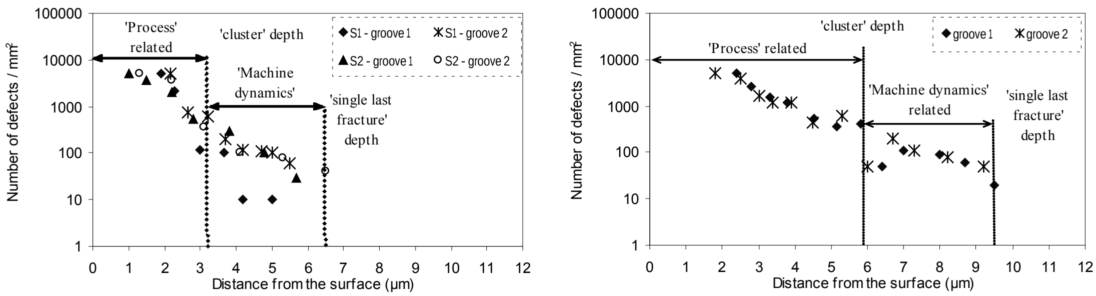

Fig. 4. Subsurface damage (a) D25 grinding wheel; (b) D16 grinding wheel.

By using a logarithm scale, this partition in terms of number of defects is highlighted. The cluster depth is reduced with a reduction in grit size. Low material brittleness gives longer cracks that combine with machine dynamics related cracks. The values obtained for P* and c* showed that fused silica requires a small initial load to generate subsurface damage. Once the subsurface damage starts, the fracture toughness is the main controlling factor which leads to deeper cracks even with controlled machine dynamics. As previously shown for Zerodur and ULE, ‘cluster depth’ is process related (highly material dependant) and ‘last fracture depth’ corresponds to machine dynamics.

5. Conclusion

BoX machine ground surfaces produced using resin bonded grinding wheels with fine grit sizes have been investigated. The grinding results show a reduction of surface roughness using smaller grit size wheels. The subsurface damage levels are below 10 microns for both D25 and D16 grit wheel finishing processes. The reduction of depth of cut and grit size leads to a better finished optic while processing time is kept constant. Fused silica 7980 HPFS material is showing higher values of subsurface damage than previously reported levels for ULE and Zerodur yet these levels remain a significant improvement and offer significantly reduced subsequent polishing times.

Acknowledgements

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