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Subsurface mechanical damage during bound abrasive grinding of fused silica glass

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ABSTRACT

The subsurface damage (SSD) introduced during bound abrasive grinding of fused silica glass was measured using a wet etch technique. Various process parameters and grinding configurations were studied. The relation between the SSD depth, the process parameters and forces applied by the grinding wheel on the sample was investigated and compared to a simulation using a discrete element method to model the grinding interface. The results reveal a relation between the SSD depth and the grinding forces normalized by the abrasive concentration. Regarding the creation of the SSD, numerical simulations indicate that only a small fraction of the largest particles in the diamond wheel are responsible for the depth of the damaged layer.

1. Introduction

Subsurface cracks appear in fused silica optical components during the grinding process where diamond grains present in tools act as indenters that embrittle the material locally [1]. Most of this SSD can be removed by subsequent loose abrasive polishing. However, on large meter size optics it has been shown that the rare residual subsurface cracks can trigger laser damage when the optics are subjected to a high fluence in the ultraviolet [2]. Since laser damage grows during successive laser shots, the optic lifetime is therefore drastically reduced. Consequently, reducing the SSD introduced during the whole polishing process is a major objective to produce high damage threshold optics in the context of high energy laser facilities such as Laser Megajoule (LMJ) [3] or National Ignition Facility (NIF) [4]. In this paper, we focus on optimizing the bound abrasive grinding of these optical components.

Understanding the formation of SSD in relation to process parameters and grinding forces is very important when we wish to optimize the grinding process in order to minimize damage created during machining. Although there is some literature on rough to micro grinding of brittle materials that can be explored, few studies have looked at fused silica in particular.

For bound abrasive grinding, three grinding modes (Fig. 1) can be distinguished. First, (Fig. 1(a)) the grinding wheel rotation plane is parallel to the rotation of the workpiece and the feed direction is perpendicular to this plane. For this mode Pei et al. studied fine grinding (grain size up to 25 μm) of Si wafers and found that feed rate and wheel rotation speed had no influence on the SSD [5]. For the second mode (Fig. 1(b)), the grinding wheel rotation plane and the feed direction are parallel to the workpiece plane. For this mode, Agarwal et al. showed that for rough grinding of SiC an increase in the depth of cut implies an increase in SSD depth [6]. Perveen et al. demonstrated the same phenomenon for micro grinding of BK7 glass [7]. Esmaeilzare et al. found that when rough grinding Zerodur glass, SSD depth increases when the grinding wheel rotation speed decreases [8]. For the third grinding mode (Fig. 1(c)) the feed direction is parallel to the workpiece plane but the grinding wheel rotation plane is perpendicular to that plane. In such a configuration, Maksoud et al. (for Si_3N_4 grinding) and Li et al. (for rough to finish grinding of fused silica) found that SSD depth increases when the depth of cut increases, but they saw no influence of the grinding wheel speed and the feed rate [9,10].

In the specific case of loose abrasive lap grinding, Wang et al. found that SSD depth in BK7 glass decreases when the abrasive concentration in the slurry increases [11], Zhang et al. found that

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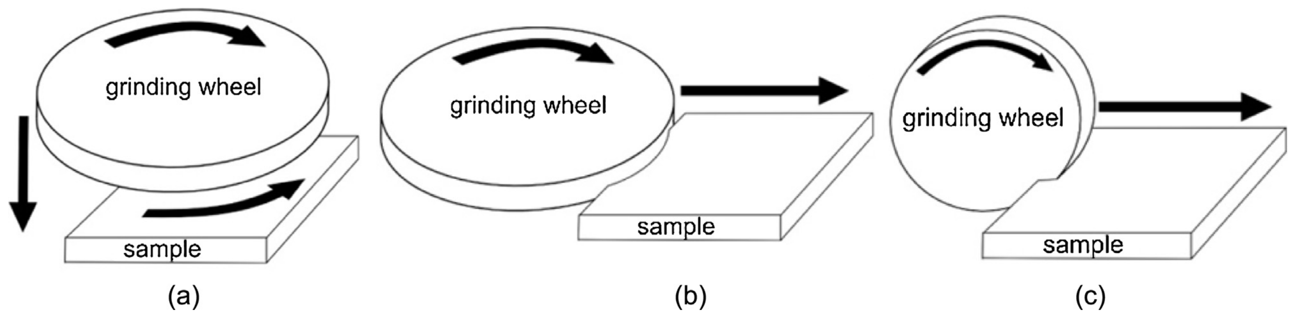

Fig. 1. Grinding modes. The grinding wheel rotation and workpiece are parallel and the feed direction is perpendicular to this direction (a). The grinding wheel rotation and the feed direction are parallel to the workpiece (b).The feed direction is parallel to the workpiece and the grinding wheel rotation is perpendicular (c)

SSD depth in neodymium-doped phosphate glass decreases when the spindle speed increases [12], and Neauport et al. found that SSD depth in fused silica decreases when the spindle speed, the load and the abrasive concentration increase [13].

Regarding the measurement of grinding forces, Zhao et al. and Huang et al. performed this on ultra-precision grinding (electrolytic in-process dressing) of fused silica and rough grinding of zircon respectively, but did not study the relation between grinding forces and SSD depth [14,15]. All these results are summarized in Table 1.

Thus various authors have shown that SSD depth increases with the depth of cut in bound abrasive grinding for a wide range of brittle materials. An increase in the spindle speed tends to reduce SSD depth in the lapping process and one study found the same conclusion on Zerodur glass for rough abrasive grinding [8]. However, no clear evidence has been found for the link between feed rate and SSD depth for the three grinding modes in bound abrasive grinding. Moreover, the link between SSD depth and grinding forces and moments has not been studied.

In the following study, we investigate the relation between SSD depth, process parameters and the mechanical forces applied by the grinding wheel on fused silica samples in the context of bound abrasive grinding. Our aim is to try to assess the prevailing factors for the creation of SSD during the grinding process. For this purpose 100 mm × 100 mm fused silica samples were ground using various parameters. Mechanical grinding actions were measured during the grinding process using a dedicated six-component device. Ground samples were then characterized in terms of both roughness and SSD. This dataset, combined with a discrete element model simulating interaction between grinding wheel and workpiece, gives an understanding of factors detrimental to the creation of SSD during the bound abrasive grinding of fused silica and glass in general.

2. Experimental

2.1. Sample preparation

An OPTOTECH SMP500-2C grinder machine was used for bound abrasive grinding. To measure the grinding forces and moments, the following grinding mode was used (Fig. 2) where the workpiece rotation is blocked and the feed direction is along the horizontal X axis. To ensure good repeatability of the process, we controlled the spindle temperature of the machine.

The samples used for this study are square-shaped (100 mm × 100 mm × 20 mm thick) fused silica glass (HOQ from Heraeus). A first roughing operation was performed on each sample with a D126 grit metallic bond diamond wheel and the following process parameters: spindle speed $N = 1500$ rpm, workpiece rotation speed $n = -16$ rpm (when not blocked), feed rate $f = 0.15$ mm/rev and depth of cut $a_p = 0.2$ mm. This roughing operation was done in order to have the same reference state for each sample, to guarantee a depth of SSD less than 100 μm prior to the grinding experiments. All further grinding experiments then used a depth of cut greater than or equal to 100 μm.

Five bound abrasive wheels, with a diameter of 25 cm, were used from rough grinding to intermediate grinding with 3 abrasive sizes (D126, D91, D64 grit) and 3 abrasive concentrations for D91. The grinding wheels were dressed using an alumina dressing stick for 20 s every five grinding tests (corresponds to every 15 min of grinding). Table 2 shows the grinding experiments for each wheel.

To study the influence of process parameters on SSD depth, two 2^3 factorial experiments were carried out with 3 factors (spindle speed, feed rate and depth of cut) and 2 levels for each factor, one for the D64 wheel and one for the D126 wheel. Several center point experiments were performed for each factorial experiment to verify the linearity of the response. Table 3 shows the level used for each factor. For the three D91 wheels, grinding tests used the center point parameters.

2.2. Surface roughness and SSD characterization methods

Surface roughness was measured using a MITUTOYO (SJ-201) contact stylus profilometer, equipped with an inductive probe with 2 μm radius and 90° angle. Each profile was filtered with a Gaussian filter with a cut-off length of 0.8 mm, according to norm ISO 13565 [16]. *Ra* and *Rt* were then computed. Typical *Ra* surface roughness ranging from 0.4 to 2 μm were obtained for D126 grit, 0.2–1.4 μm for D91 and 0.2–0.9 μm for D64. Our study is focused on the link between SSD and process parameters, hence we paid little attention to these surface roughness values. The relation between SSD depth and surface roughness has been investigated in a previous paper [17].

SSD depth was measured by means of acid etching (80% HF, 20% HNO_3); this consists in following the evolution of the peak to valley surface roughness *Rt* during successive acid etching. The *Rt* is measured 16 times at different spots on the sample after each etching step and the maximal value of *Rt* among the whole set of measurements is considered equal to the SSD depth, as described elsewhere [18]. Previous work performed on the same machine with D126 and D64 diamond wheels evidenced an error in the SSD measurement of less than 3% [17].

2.3. Measurement of grinding forces

The 3 forces (Fx, Fy, Fz) and the 3 moments (Mx, My, Mz) at point A of the sample resulting from the action of the grinding wheel on the sample during the grinding process along the X, Y, Z axes respectively are measured with a dynamometer device developed in the laboratory (Fig. 2). The dynamometer is built with three 3D piezoelectric sensors (3 forces measured by sensor) and is placed under