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Subsurface damage of Nd-doped phosphate glasses in optical fabrication

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Abstract

We present a destructive method for detecting and measuring subsurface damage of Nd-doped phosphate glasses. An instrument based on the dimple method – a destructive method – was developed. Subsurface damage depth produced in each fabrication procedure was obtained. We extend the surface roughness–subsurface damage relation to Nd-doped phosphate glasses. The constant ratio of subsurface damage and surface roughness was obtained as well. We also analyse the relation of abrasive size and subsurface damage experimentally. From a measurement of the surface roughness or abrasive size, one can obtain an accurate estimate of the damage layer thickness that must be eliminated by polishing or subsequent grinding operations.

Keywords: Subsurface damage; Subsurface defect; Laser-induced damage threshold; Nd-doped phosphate glass

1. Introduction

Nd-doped phosphate glasses have been widely used in high average power solid-state lasers. It is the working material and core material of the amplifier. However, during the optical fabrication process of cutting, grinding, and polishing, different kinds of defects such as microcracks, fractures, scratches, and inclusions can exist under the finished surface as illustrated conceptually in Fig. 1. Subsurface damage (SSD) is the result of the brittle material removal mechanism, which may lower the laser damage threshold by reducing fracture strength, providing sites for absorbing inclusions, and modulating the electromagnetic field. According to Genin's simulation [1], micro-cracks can cause 100-fold light intensity enhancements in fused silica. In the case of high average power laser applications, SSD may cause a catastrophic failure. Hence, research interests have been concentrated on measurements and treatments of SSD.

In order to upgrade the output power density and improve the final quality of optical elements, SSD must be minimized or eliminated by optimization of process parameters.

In this paper, we focus on the SSD of Nd-doped phosphate glasses produced in an optical fabrication procedure with a developed instrument. Furthermore, the relation between SSD and roughness was brought forward, and the correlation of abrasive size with SSD was discussed as well.

2. Experimental procedure

2.1. Grinding

Three separate N31 Nd-doped phosphate glasses were investigated. All samples were originally cylindrical blanks with 60 mm diameter and 15 mm thickness.

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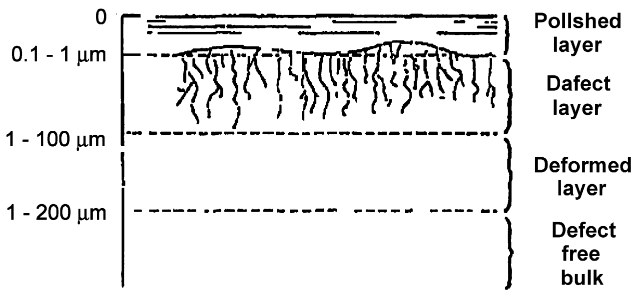

Fig. 1. Schematic illustration of subsurface damage.

Samples were ground with diamond abrasive size range (size from 100 to 10 µm). A single N31 part was first lapped by 100–80 µm abrasives, then with 50–40 µm abrasives, and finally with 28–20 µm, and 14–10 µm abrasives. SSD and surface roughness (SR) were measured at each step. Each grinding step removed between 0.3 and 1 mm of material and thus removed all the residual SSD from the previous abrasives used in the sequence. Generally, larger abrasives typically resulted in higher SSD and higher SR.

2.2. Dimpling

After lapping, parts of each sample were etched with 1% HF solution for 30 s to reveal SSD. Following etching, the dimple method [2,3] as described by Zhou et al. was used initially for determining SSD depth. A steel ball with a radius of 23.81 mm was adopted with an abrasive to polish a dimple in the etched region. Based on the dimple equipment, an automatic instrument was developed. This instrument was driven by an electromotor, which replaces manpower. Observation of SSD was carried out by conventional optical microscopy. Three samples were observed in this study. On each sample, three dimples were made after each grinding step. In all the experiments, SR was measured by an SJ-201P profilometer.

3. Principle and results

The goal of the grinding experiment was to investigate whether SR can provide enough information about surface damage. Kachalov [4] was first to report that the thicknesses of the two layers were related as follows: $F = kh$, where h is the peak-to-valley SR and F is the thickness of the SSD layer. The proportionality constant k is 3.7 for the case of plate glass ground with sand on a cast iron lap.

A recent model [5] proposed the quantitative relation between SSD and SR in brittle materials:

$$\frac{\mathrm{SSD}}{\mathrm{SR}} = 2.33\alpha_k^{2/3}\left(\frac{E}{H}\right)^{(2-5m)/3}\frac{(\cot\psi)^{1/9}}{(\sin\psi)^{1/2}}\left[\frac{P}{(K_c^4/H^3)}\right]^{1/6}, \tag{1}$$

where E, H, and K_c are the material's Young's modulus, hardness, and fracture toughness, respectively; 2ψ is the abrasive included angle, P is the indenting force on the abrasive; α_k is a numerical factor in the range 0.03–0.04, and m is another factor in the range 0.33–0.50.

This model predicts that for typical grinding forces P acting on typical optical glasses, the ratio of SSD/SR is in the range 4 ± 2.

Research has been done in detail, and the results of these measurements are summarized in Table 1.

Table 1. SR and SSD measurements of Nd-doped glass in optical fabrication

Abrasive size R (µm)	Surface roughness PV SR (µm)	Subsurface damage SSD (µm)	SSD/SR
100–80	18.30	32.72	1.77
50–40	11.03	14.61	1.32
40–28	6.42	8.70	1.36
20–14	2.74	4.61	1.68

4. Discussion

4.1. Correlation of SSD with SR

In grinding conditions the depth of the abrasive grain penetration into glass surface scales with the SR. The maximum SSD depth measured with the dimple method is 32.72 µm produced by abrasives with a size of 100–80 µm. The average ratio of SSD and SR is 1.56 ± 0.11. Fig. 2 shows the distribution of the ratio of SSD and SR. The ratios turn out to be linear. SSD depth produced by the maximum and the minimum abrasive size is in good agreement. Although there is some discrepancy between the ratios, they are in reasonable agreement. Fig. 3 shows the correlation of SR (p–v) with SSD for loose-abrasive lapping of optical glasses [6]. We focus on laser glass for comparison. Taking the abrasives difference into consideration, the slopes for N31 laser glass is in great agreement with that for LHG8. The slope for N31 laser glass is different from that for BK7, which is due to the glass hardness and Young's modulus. The relation of abrasive and SR will be discussed in the next section.

4.2. Relation of abrasive size and surface roughness

In order to determine the abrasive size and SR, Russian experts made great efforts. Fig. 4 shows the results from Russia. From the data, the ratio of abrasive size and the produced SR turns out to be a line in wide abrasive size range. Roughness for Al_2O_3 abrasives is