ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING 18 (2018) 320–330

Available online at www.sciencedirect.com

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journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

Robust and automatic measurement of grinding-induced subsurface damage in optical glass K9 based on digital image processing

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ARTICLE INFO

Article history:
Received 4 May 2017
Accepted 25 July 2017
Available online

Keywords:
Measurement
Optical glass
Image processing
Subsurface damage
Grinding

ABSTRACT

Optical glass K9 is a critical kind of optical materials, however experiments have indicated that the mechanical grinding of K9 easily led to subsurface damage (SSD). Although substantial SSD measurement methods have been suggested, the problems including the prior knowledge of SSD and slow measurement speed still impede the reported method applications. To this end, this paper has presented an image-process-based method that can identify and measure the grinding-induced SSD in K9 specimens. By performing grinding trials, the method has been found to be able to accurately (with biggest relative error of 3.13% in comparison with the manually measured results) and quickly (with the measurement speed of 1.68 s per image) measure SSD depths. Without any parameter presetting, the method enables automatic SSD measurements, allowing the users without SSD knowledge to be able to use the method. Moreover, the method has shown the good robustness to the input image size, illumination, tilted specimen placement, and material flaws. The method is therefore anticipated to be meaningful for the industrial manufacturing, design and application of optical glass.

1. Introduction

Optical glass K9 offers good optical transparency, high hardness, and superior wear resistance, and therefore is considered as one of the most widely employed materials in the optics industry [1]. However, many experimental observations [1,2] have indicated the mechanical grinding process of K9 easily led to subsurface damage (SSD). The grinding-induced SSD can be characterized by the cracks nucleating at the machined surface and vertically spreading tens of micrometers to the specimen bottom [3], and has been found [4,5] harmful to both mechanical properties and optical performances of K9 products. To this end, many methods have been suggested to evaluate the grinding-induced SSD in brittle materials, and most proposed methods can be generally categorized into (i) indirect and (ii) direct methods.

Indirect methods usually evaluate SSD depths based on certain physics, chemistry or mechanics principles, so that any additional operations to expose subsurface cracks can be avoided. Lundt et al. [6] have quantified the subsurface cracks by utilizing the scanning infrared depolarisation effect, where the SSD depths were quantified by analyzing the missing wavelengths of the polarized laser beam that can penetrate the

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http://dx.doi.org/10.1016/j.acme.2017.07.009
1644-9665/

K9 substrate. However, the precise control of the laser beam power is also in demand otherwise the laser would probably burn the K9 sample. Aida et al. [7] have evaluated the grinding-induced SSD depths in the GaN substrate based on the cathodoluminescence effect. However, the additional experiments [8] have proved that the electrons impacting on the optical glass would probably degrade the functional performances (e.g. optical transmissivity) of K9. A series of interesting studies by Li et al. [9], Lv et al. [4] and Yao et al. [1] established the explicit mathematical relationships between the ground surface roughness R_z and the SSD depths so that SSD values can be obtained based on measured R_z. However, substantial assumptions have been made in these above studies. Although indirect methods would not introduce any additional SSD, expensive equipment, high requirement of professional knowledge, and complex calculations during the SSD measurement are still needed for the indirect SSD evaluation. Moreover, the material flaw may also largely influence the measurement accuracy [10,11].

In comparison, direct SSD evaluation methods have been believed more reliable, because the subsurface cracks would be somehow exposed in the direct methods so that the crack depths are visible and measureable. Tonshoff et al. [12] and Esmaeilzare et al. [13] have proposed the angle polishing method (APM), where the ground K9 surface was lapped and polished under an angle of about 30° and then the exposed subsurface cracks were measured. The results have proved the method feasibility, but the polishing operation may introduce additional SSD. Pei et al. [14] have proposed the section polishing method (SPM), where before grinding the K9 sample was firstly cleaved into two parts, then the interested cross-sections were carefully polished to remove any cracks, and finally glued together, so that SSD can be measured after the grinding process by melting the glue and observing the subsurface cracks in the interested cross-sections. However, during the grinding process, the material behaviors of the glued sample may differ from the original sample as the second phase material (i.e. glue) was introduced. A more reliable direct method has been presented by Li et al. [9–11], in which a slot (1 mm width and 5 mm uncut margin) was firstly produced from the bottom of the specimen, and then a soft rubber hammer impacted the specimen so that the specimen can be cleaved along the energetically preferential crystalline plane and therefore the newly-introduced SSD can be minimized.

Although direct SSD evaluation methods have been believed more reliable than indirect methods, the SSD measurement in direct methods still requires human involvement after the SSD micrographs (see typical example given in Fig. 1) are captured. Even trickier problems may include: (i) the ground surface in most cases is tilted therefore the SSD depth in Fig. 1 should be "SSD", rather than "L_1" according to the SSD definition [15]. However, most microscopes can not precisely identify and measure this; (ii) the prior professional knowledge of SSD is required during the manual measurements, and (iii) the manual measurement of SSD depths may be feasible only when small quantities of measurements are required.

Based on above, the critical need for the automatic SSD measurements would become increasingly pronounced when considering the demanding requirements from the modern industrial manufacturing. To fill this gap, this paper presents an image-process-technique-based method that can robustly and automatically identify and measure the grinding-induced SSD in optical glass K9. The method is believed to be able to considerably stretch the limitations of most of the direct methods reported in the literature (e.g. Ref. [9–14]), and promote the realization of the automatic SSD measurements in large quantities. Therefore the method is anticipated to be meaningful and helpful for not only the industrial manufacturing, but also the design and application of optical glass.

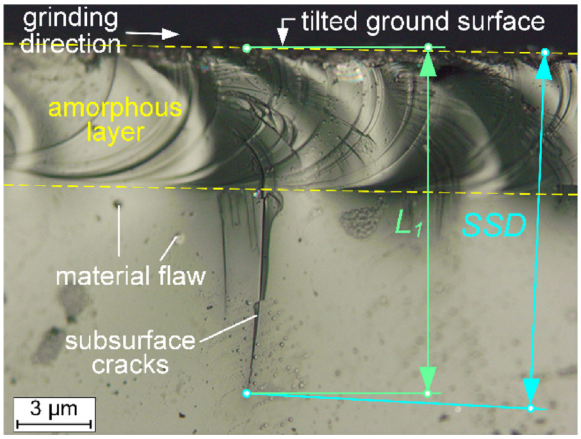

Fig. 1 – Captured cross section micrograph with subsurface damage.

2. Method description

2.1. Method flowchart

The proposed method mainly includes three modular algorithms (MAs) (see Fig. 2): MA (i) the recognition and reconstruction of the tilted ground specimen surface, MA (ii) the recognition of the subsurface cracks, MA (iii) the calculation of the SSD depths by using the unit of pixels, and MA (iv) the recognition of the scale bar and the SSD length unit conversion from pixels to length units.

2.2. Recognition and reconstruction of the ground specimen surface

The basic principle of the ground surface recognition is based on an important feature of SSD micrographs: a dark region without any visual details is located at the top of the ground specimen surface because the specimen thickness changes the optical pathway around the ground surface (see Fig. 3a). Therefore, no matter the surface is tilted or not, the bottom profile of the dark region can be approximately regarded as the ground specimen surface, which can be further employed as the landmark for the SSD measurement. The detailed recognition procedures are as follows:

(i) Considering the aim of the proposed method is to automatically measure SSD depths in large quantities, the measurement speed should be as fast as possible. Therefore the captured SSD micrographs (see Fig. 1) are firstly converted into the gray images (see Fig. 3b).