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Theoretical model of brittle material removal fraction related to surface roughness and subsurface damage depth of optical glass during precision grinding

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ABSTRACT

Brittle material removal fraction (BRF) is defined as the area fraction of brittle material removed on machined surface. In the present study, a novel theoretical model of BRF was proposed based on indentation profile caused by intersecting of lateral cracks. The proposed model is related to surface roughness and the subsurface damage (SSD) depth of optical glass during precision grinding. To investigate the indentation profile, indentation tests of K9 optical glass were conducted using single random-shape diamond grains. The experimental results indicate that the indentation profile is an exponent function. To verify the proposed BRF model, BRF, surface roughness and SSD depth of K9 optical glasses were investigated by a series of grinding experiments with different cutting depths. The experimental results show that BRF is dependent on surface roughness and SSD depth. The relationship between BRF, surface roughness and SSD depth is in good accordance with the proposed theoretical model. The proposed BRF model is a reasonable approach for estimating surface roughness and SSD depth during precision grinding of optical glass.

1. Introduction

Modern optics and photonics require optical components with extremely high surface quality [1]. Optical glass is widely used for high-quality optical components because it is almost bubble free and has few inclusions. However, optical glass is brittle and susceptible to damage, especially during machining [2]. Surface roughness and subsurface damage (SSD) generated during machining limit the applications of optical glasses, and reduce the quality and lifetime of optical components. Precision grinding is an efficient and cost-effective technique for machining optical glass and other hard materials [2,3]. Form accuracy of optical components is usually controlled by precision grinding, and surface roughness and SSD caused by grinding will be removed in subsequent polishing to obtain good surface finish. Thus, surface roughness and SSD of optical glass during grinding have an impact on the amount of material removal in polishing. Therefore, the influence of machining parameters on the surface and subsurface integrities of ground specimens has been intensively researched. Zhou et al. [4] applied Chemo-mechanical grinding process into machining of large size quartz glass. The surface qualities including surface roughness and optical characteristics were analyzed and evaluated. Zhao et al. [5] investigated the machined qualities of grinding of BK7 glass by using coarse-grained diamond wheels. It was found that the surface roughness R_a is around 1 nm and the SSD depth is less than 3 μm. Wang at el. [6] developed a predictive model for the relationship between the measured cutting force and SSD depth for K9 optical glass in rotary ultrasonic face machining by applying indentation fracture mechanics of brittle materials. They found that SSD depth was directly proportional to the exponent of the measured cutting force. Li et al. [7] established a theoretical model for the relationship between SSD and surface roughness by investigating median and lateral crack systems induced by sharp indenters on brittle surfaces. They measured SSD depth and surface roughness R_z of ground and lapped BK7 optical glass using a spot magnetorheological finishing (MRF) technique and a contacting profilometer. Gu et al. [8] developed a model of scratch hardness for brittle materials by taking both scratch and residual depths into consideration. Based on this model, they established the correlation between SSD depth and scratch depth. In further work, the same authors investigated four grinding modes—brittle, semi-brittle, semi-ductile and ductile—and found that surface roughness and SSD depth are strongly dependent on the grinding mode [9]. Li at el. [10] established an explicit relationship between SSD depth and R_z in the BK7 grinding process, based

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on analytical calculation of the classic brittle material crack system and grinding kinematics. Blaineau et al. [11] investigated the relation between SSD depth, the process parameters and the forces applied by the grinding wheel to the sample. They compared experimental results with discrete element method simulation results, revealing a relationship between SSD depth and the grinding forces normalized by the abrasive concentration. Esmaeilzare et al. [12] used a diamond wheel to grind Zerodur® glass-ceramic to investigate the influence of the grinding parameters on surface roughness and SSD, and developed a statistical model to predict surface roughness and SSD depth.

All brittle materials undergo a transition from brittle to ductile machining at a critical undeformed chip thickness. Below this threshold, plastic deformation becomes energetically favorable as compared with fracture and the material deforms instead of fracturing [13]. However, to attain high machining efficiency, it is difficult to grind optical glass using ductile regime machining only. Basically, brittle and ductile material removals occur simultaneously during fine grinding of optical glass. Based on this situation, brittle material removal fraction (BRF)—defined as the area fraction of brittle material removed on a machined surface—has been proposed to estimate the surface and subsurface integrities [14,15]. Based on an indentation crack model, in the present study, we developed a theoretical model of BRF, related to surface roughness and SSD depth of optical glass during precision grinding. To develop this model, indentation tests of K9 glass were conducted using single random-shape abrasive grain and the relationship between indentation depth and radius was investigated. To verify the proposed BRF model, BRF, surface roughness and SSD depth of K9 glasses were investigated by a series of experiments with different cutting depths. SSD depth was measured using the spot MRF technique [7]. The proposed model of BRF is expected to assess the surface and subsurface qualities of the optical glass during precision grinding.

2. Theoretical model of BRF

2.1. Brittle and ductile materials removals on glass surface

A representative microtopographic image of 1000× magnification of machined K9 optical glass, taken with an optical microscope (Keyence VHX-5000), is shown in Fig. 1a. The cracks and damage on the specimen surface, caused by the brittle material removal, appear dark and clustered; some patches resulting from brittle material removal are marked by red squares. Surface patches generated by ductile material removal are uniform

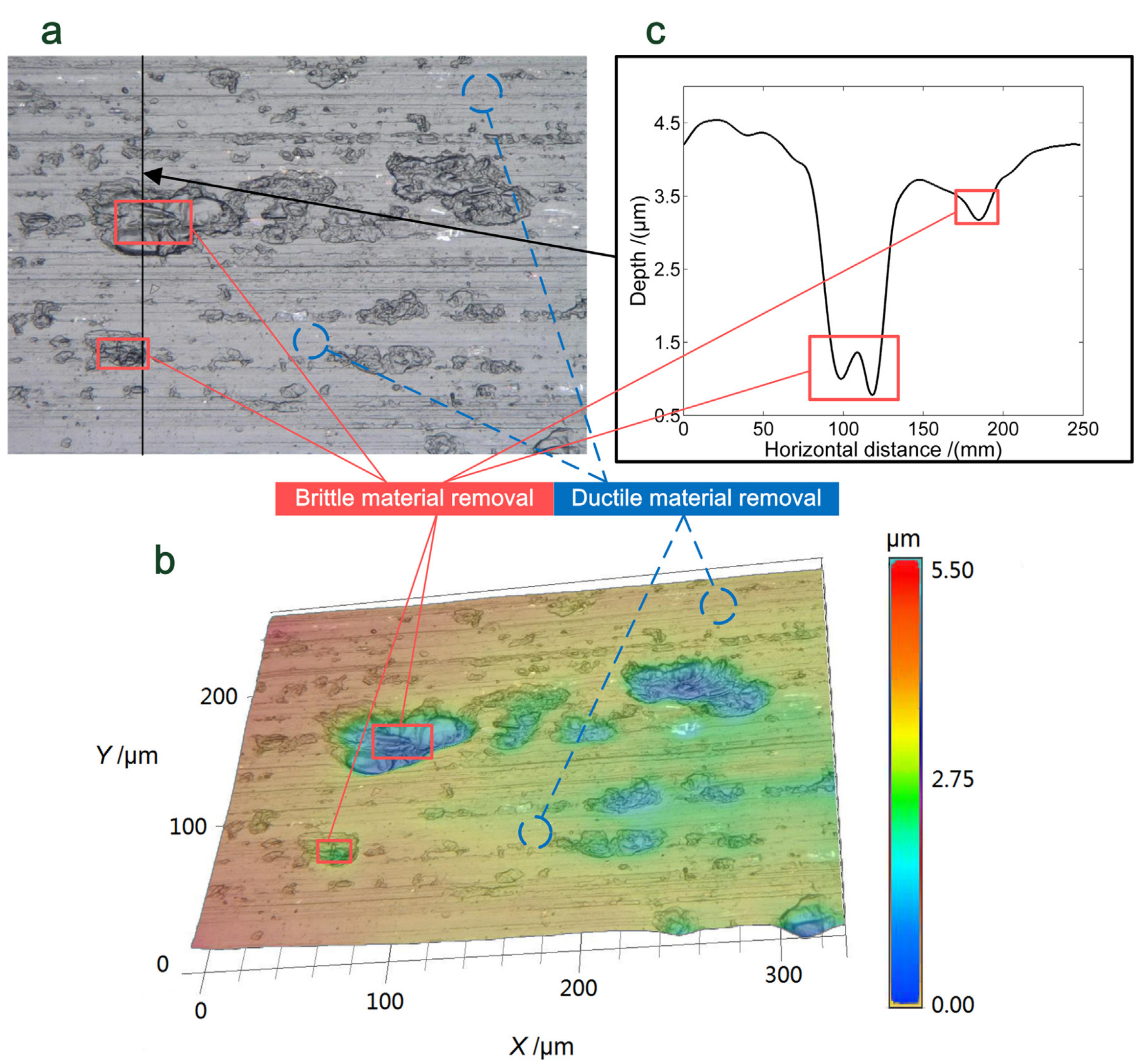

Fig. 1. Brittle and ductile material removal on the machined surface of K9 glass. Grinding conditions: W40 resin-bonded-diamond grinding wheel; cutting depths 5 µm; wheel speed 25 m s^{-1}, feed rate 60 mm min^{-1}. a 1000× magnification image; b Three-dimensional measurement of a; c Two-dimensional profile.

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