Ceramics International xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ceramics International

journal homepage: www.elsevier.com/locate/ceramint

The mechanical response characteristics of sapphire under dynamic and quasi-static indentation loading

Xiaosheng Luan[a], Feng Jiang[a,b,*], Ningchang Wang[a], Xipeng Xu[a,b], Xizhao Lu[c], Qiuling Wen[a]

[a] Institute of Manufacturing Engineering Huaqiao University, Xiamen 361021, Fujian Province, PR China
[b] MOE Engineering Research Center for Brittle Materials Machining, Huaqiao University, Xiamen 361021, Fujian Province, PR China
[c] College of Mechanical Engineering and Automation of Huaqiao University, Xiamen 361021, Fujian Province, PR China

ARTICLE INFO

Keywords:
Sapphire
Dynamic indentation
Quasi-static indentation
Crystal orientations
Failure analysis
Crack propagation

ABSTRACT

Sapphire is widely used as optical materials and substrate materials due to its excellent physical and chemical properties. The mechanism of crack propagation and fracture damage evolution has important significance for improving the manufacturing quality and application performance of sapphire parts. In this study, dynamic and quasi-static indentation tests have been performed on the *c*-plane and *a*-plane of sapphires by Hopkinson pressure bar tester and continuous indentation tester, respectively. The crack propagation path in sapphire has been captured by High-speed camera and the crack velocity has been calculated. The crack propagation and fracture damage evolution has been analyzed based on the fracture morphology of specimen. It was found that the bearing capacity of sapphire is related to the loading velocity, while the crack propagation is affected by the crystal orientation. Under the indentation loading, the cracks in sapphire first propagate steadily, and then the cracks begin to propagate uncontrollably after reaching the critical conditions, where the crack propagation velocity obviously increases, typically from 204 m/s to 1006 m/s (dynamic indentation) or from 0.0032 m/s to 820 m/s (quasi-static indentation). And the crack propagation velocity depends on the loading speed at stable stage. The *r*-planes of sapphire are weaker than other crystal planes and are prone to crack propagation.

1. Introduction

Sapphire is widely used in advanced industries such as optoelectronics, aerospace and laser weapons, due to its excellent physical, chemical and mechanical properties [1]. Sapphire parts could suffer micro-impact during their manufacturing processes or application environment. Abrasive machining processes are popular in the sapphire machining processes, where hard abrasive grits impact sapphire materials to remove them, as shown in Fig. 1.1. The mechanical response characteristics of sapphire dominate the generation of machined surface and influence the machined surface quality, especially the surface damage. In addition, some engineering fracture accidents indicate that they are caused by crack propagation from micro-impact point, as shown in Fig. 1.2. In summary, it is very meaningful to study the response characteristics of sapphire under different loading and to understand the damage mechanism of sapphire.

Sapphire is an anisotropic single crystal material with high hardness. The mechanical properties and crack propagation of sapphire depend on the crystal orientation, which has been presented in many studies [2–4]. Montagne [5] used micro-pillar compression experiments to study the mechanical behavior of four surface orientations of sapphire $m(10\bar{1}0)$, $a(1\bar{2}10)$, $c(0001)$, and $r(\bar{1}012)$. They found that fracture and plastic deformation was significantly affected by the crystal orientation, and the plastic deformation is more likely to occur along the *a*-axis than along the *m*-axis. Haney [6] conducted indentation test on the $a(11\bar{2}0)$ and $c(0001)$ of sapphire, and found that the crack propagation was related to the crystal orientation. The result is similar to that of Bhattacharya [7]. The cross scratching experiments were carried out on *c*-plane and *m*-plane sapphire to investigate the crystal-orientation dependence of crack initiation and damage mechanism [8,9]. The experimental results of Graça [10] show that the elastic modulus of different crystal direction is different. In these studies, there are many studies on the initial stage of sapphire crack propagation, and there are few studies on the further evolution of sapphire crack propagation. The process of sapphire crack propagation has yet to be further explored.

Indentation tests have been used effectively to study material failure and crack propagation [11–14]. Nowak [15] first applied continuous indentation to study the deformation characteristics of sapphire. Cook [16] has previously conducted a detailed analysis of the cracking system of glass and ceramic materials under indentation. Mao [17]

* Corresponding author at: Institute of Manufacturing Engineering Huaqiao University, Xiamen 361021, Fujian Province, PR China.
E-mail address: jiangfeng@hqu.edu.cn (F. Jiang).

https://doi.org/10.1016/j.ceramint.2018.05.162
Received 26 April 2018; Received in revised form 11 May 2018; Accepted 19 May 2018
0272-8842/

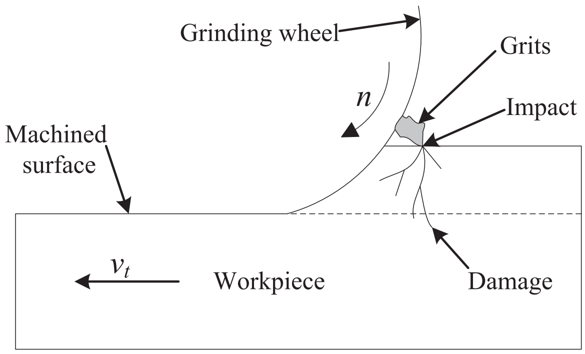

Fig. 1.1. Abrasive machining processes.

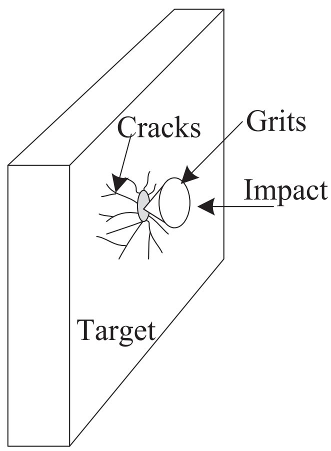

Fig. 1.2. Crack propagation under impact loading.

made nano-indentation tests on the sapphire *c*-plane and studied the elastic-plastic deformation at the nanoscale. Haney [18] studied the interaction of the crack system under two static indentations on the sapphire. This has been accepted by the majority, the static indentation fracture mechanics could not be applied to the analysis of material failure under dynamic loading. Versus quasi-static loading, the dynamic loading has a higher loading rate and faster crack propagation rate. The fracture strength and fracture toughness of the material are considered to increase when the strain rate is high [19,20]. The hardness of brittle materials increases under dynamic indentation loading compared to quasi-static indentation loading, which was observed in Anton's experiments [21]. Haney [22] presented similar results. However, more researchers focus on the two-dimensional crack propagation. The three-dimensional crack propagation mechanism is still not clear. The mechanism of crack propagation and fracture damage evolution in sapphire has still not reached a consensus.

The crack propagation mechanism is closely related to the fracture process of materials. Various methods have been used to study the crack propagation characteristics. The propagation of cracks forms the fracture morphology, and the analysis of fracture morphology is a traditional and effective means. Jonathan [23] analyzed the sapphire crack propagation and failure process by the fracture morphology. The crack velocity can be determined from the pattern of "Wallner lines" on the fracture surface [24]. In recent years, with the development of technical equipment, more scholars have used high-speed cameras or current measurement techniques to study crack propagation [25–27]. Oberg [28] used electrical methodology to monitor the crack propagation on the ceramic plate under impact load and successfully obtained the crack propagation path and velocity. Lee [29] used a high-speed camera to observe the failure process of the ceramic material under quasi-static compressive loading and found that the material had almost no plastic deformation before failure. High-speed photography can directly observe moving cracks compared to current measurement. And the translucent nature of sapphire makes its crack propagation more visible than non-transparent materials. However, the cracks moving follow the different orientations of sapphire are rarely reported.

In this study, the mechanical response characteristics of *c*-plane and *a*-plane sapphire have been studied on Hopkinson pressure bar tester and continuous indentation tester. The three-dimensional crack propagation path and velocity during loading have been detected online via high-speed photography. The fracture damage evolution mechanism of sapphire has been analyzed based on fracture morphology. It was found that the bearing capacity of sapphire is related to the loading velocity, while the crack propagation is affected by the crystal orientation. Under the indentation loading, the cracks in sapphire first propagate steadily, and then the cracks begin to propagate uncontrollably after reaching the critical conditions. Correspondingly, the crack propagation velocity rapidly increases from the arc pattern on the fracture surface. In addition, the *r*-planes of sapphire are weaker than other crystal planes and are prone to crack propagation.

2. Experimental procedure

The materials used in this study are industrial sapphire—single crystal alumina (α-Al_2O_3), which is colorless and translucent. The crystallographic diagram of sapphire is shown in Fig. 2.1. Table 2.1 shows the difference in mechanical properties of sapphire when it is parallel to the *c*-axis and perpendicular to the *c*-axis [1]. The *c*-plane and *a*-plane are the most commonly used crystal planes of sapphire, *c*-plane sapphire is used as the substrate materials in electronic devices, and *a*-plane sapphire is used as the screen panels and keyboards of smart phones. So, the dynamic indentation and quasi-static loading tests have been performed on the *a*-plane and *c*-plane sapphire respectively. The sapphire specimen design is shown in Fig. 2.2. The size of the specimen block is 3.5 mm × 3.5 mm × 5.8 mm. And the sapphire specimens are finished by ultra-precision grinding process, the side surface (3.5 mm × 5.8 mm) of the specimens is polished to observe the crack propagation in the specimen.

Split Hopkinson Pressure Bar (SHPB) has been widely used in the testing of dynamic mechanical properties of materials. Its basic principle is that the striker bar impacts the incident bar to generate the stress wave, and the stress wave loads the specimen, and finally the stress wave is absorbed by the absorption bar after passing through the transmission bar. In this process, the signal acquisition system can obtain the mechanical information of the material.

Dynamic indentation tests have been performed on the Split Hopkinson Pressure Bar system in this experiment. The modified experimental device is shown in Fig. 2.3. The Vickers diamond indenter is mounted on the end face of the incident bar. The indenter impacts sapphire at different velocities, with velocities of 6.74 m/s, 7.55 m/s, 8.35 m/s, 9.13 m/s, which is controlled by air pressure and measured by photoelectric switch. The entire indentation loading process has

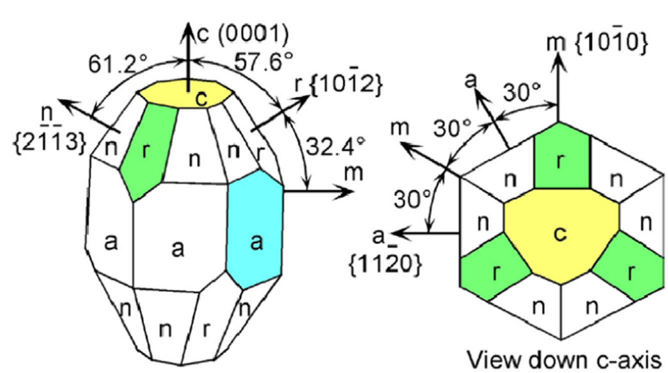

Fig. 2.1. Crystallographic diagram of sapphire [1].