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Fractal analysis of surface topography in ground monocrystal sapphire

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ABSTRACT

The surface characterization of ground monocrystal sapphire is investigated by fractal analysis method. A serial of ground sapphire surfaces in ductile removal and brittle removal mode are obtained by grinding experiments, and their three dimensional (3D) and two dimensional (2D) fractal dimensions are calculated and analyzed by box-counting methods. The 3D surface fractal dimension D_s shows a negative correlation with the surface roughness parameter Ra and is sensitive to the ground surface defects. For the ground surface with larger fractal dimension D_s, its micro-topography is more exquisite with minor defects. Once the fractal dimension D_s become smaller, deep cracks and pronounced defects are exhibited in ground surface. Moreover, the material removal mode can be implied from the distribution of 2D cross-sectional profile fractal dimension D_L. The workpiece surface generated in ductile removal mode has high surface quality with high 2D and 3D fractal dimensions. This study indicates that the box-counting fractal analysis is an effective method to evaluate ground sapphire surface comprehensively.

1. Introduction

Monocrystal sapphire is widely used in precision optics, high-power laser diode devices, blue-green LEDs, visible/infrared windows and substrates for semiconductor due to its excellent mechanical and optical properties [1,2]. However, all these opto-electronic devices require sapphire with high machining quality and defect-free surfaces. For example, as a substrate material for laser diodes, the machining defects present at the sapphire surface can cause laser damage and drastically limit the optics lifetime [3,4]. So the optical performance is highly dependent on the surface quality and the degree of surface/subsurface damage. Manufacturing steps of optical component, from grinding to polishing, are known to be major contributors to the generation of such mechanical defects [5]. During grinding step, although diamond wheel grinding has used widely, some surface/subsurface damages generated during grinding are difficult to remove in a subsequent polishing operation. These surface/subsurface damages can shorten the service life and reduce the performance of the sapphire [6]. Early works mainly focus on the effect of different machining process on the surface damage layer in sapphire [7]. But the surface topography is also important to the function of many kinds of opto-electronic devices, and the number of applications keeps increasing [8], making an urgent need for comprehensive evaluation of the surface topography of sapphire.

In conventional evaluation methods of ground surface topography, a number of statistical parameters are used to depict various aspects of the surface lay, roughness, waviness and form. Unfortunately, many statistical parameters, such as Ra, Ry, and Rq, strongly depend on actually measured conditions, including the sampling and the scan lengths, and the instrumental resolution and so on [9,10]. Moreover, these parameters are not enough to characterize 3D surface topography, and actually some spatial structure information can be lost. Thus, these conventional parameters do not provide a unique evaluation. Therefore it becomes essential to use intrinsic parameters to characterize ground surfaces. Fractal theory was initiated by Mandelbrot to describe the degree of irregularity of objects of anomalous dimensions [11]. Over a period of time it has been used as a very effective tool in the topographical characterization of complex surfaces. Topography parameters derived from a fractal model are believed to be intrinsic characteristic of surfaces and considered to be independent of scale, sampling and filtering [12].

There were several attempts by some researches to characterize the surface topography of machined surfaces using different

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fractal methods. In an earlier work, Lopez et al. [13] studied the fractal characterization of the sandblasted surface and ground surface, and demonstrated that the fractal approach based upon the numerical determination of LH exponents is adapted. Zhang and Gopalakrishnan [14] developed a prototype system to perform surface roughness measurement using an area-based fractal method, and a functional calibration curve which relates the fractal dimension to the machined surface roughness is constructed. Blackmore and Zhou [15] reported a new fractal-based functional model for the fractal characterization of the anisotropic rough surfaces. Thomas et al. [16] investigated further the fractal characterization in the anisotropy of the grit-blasted, ground and plateau-honed surface by using the structure function method. Rosén et al. [17] analyzed the cylinder bore surface wear with the structure function based on the wear region data obtained by using the stylus and atomic force microscopy. Based on two-dimensional Fourier transform, Jiang et al. [18] proposed a concise method to compute the surface fractal dimension, and to analyze the anisotropy ground surfaces by using the atomic force microscope data. Zhang et al. [19] described a relation between the fractal dimension and roughness parameters (Ra, Rq and Rsm) of different ground surfaces, which was computed by means of the reticular cell counting method (RCC). Chen et al. [20] used the wavelet and fractal method to analyze and evaluate the 3D surface topography of KDP crystal material. It was found that the high-frequency information of machined surfaces is uncorrelated with the machining process, which can reflect the anisotropic features of material structure. Liang et al. [21] improved the variation method by modifying the error and succeeded in evaluating the engineering ceramics ground surface. Further, the relationship between fractal dimension and traditional roughness parameters, surface texture, surface function and material property were analyzed using the adapted method. Vilchis-Granados et al. [22] examined the surface fractal dimensions and textural properties of calcium, strontium and barium hydroxyapatite compounds, respectively. The results showed a linear correlation between the surface hydroxyl ground content at the external surface of materials and their surface fractal dimensions. Asgharifar et al. [23] have interpreted and evaluated the arc-treated surfaces by power spectral density based fractal method. An existence of a mixed fractal behavior in arc-treated surfaces is pointed out that may be linked to the process of forming the surface due to cathode spots generation. Lawrence and Ramamoorthy [24] investigated the possible characterization of automotive cylinder bore surface topography by different methods, such as differential box counting method, power spectral method and structure function method. Kong et al. [25] introduced the generalized gauchy process (GCP) to provide dual description of fractal and long-range correlation properties simultaneously.

Literature review indicates some problems. For instance, different scholars reached the opposite conclusion when they study the relationship between surface roughness and fractal dimension on different surfaces. For different materials, the surface fractal properties are significantly different from the 2D or 3D profile data. Moreover, machined sapphire crystal surfaces have the complicated anisotropic properties. It is easy to see by eye but very difficult to define mathematically. These anisotropic properties are likely to affect the functional behavior of the sapphire surface. So, it becomes important to find some possible quantitative ways of characterizing anisotropy. But by now, the machined sapphire crystal surfaces are barely evaluated by fractal method, so it is reasonable to pay a great attention to investigate their fractal properties. The present work explores the use of box counting method for the 3D surface topography characterization of sapphire crystal using different type of ground sapphire surfaces obtained in different material deformation/removal modes, i.e., ductile, ductile–brittle transition, and brittle modes. The 2D and 3D fractal properties of different sapphire crystal surfaces are calculated and analyzed by fractal method in order to comprehensively evaluate and optimize the topographic structures.

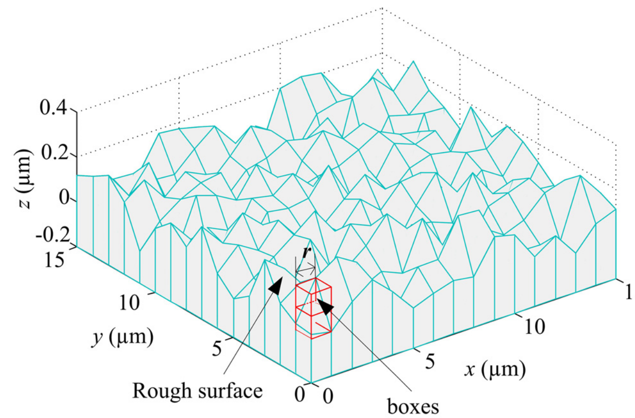

Fig. 1. Schematic view of the 3D box-counting method.

2. Fractal analysis using the box-counting method

Fractal geometry, introduced and developed by Mandelbrot, provides a mathematical description for a wide range of natural forms and phenomena. As an important parameter of fractal, the fractal dimension D is non-integer, compared with the topological dimension of conventional geometry. It is a quantitative indicator on the object irregularity over multiple scales. In this paper, it is explored as a possible tool to evaluate the ground sapphire surface.

To calculate the fractal dimension of a rough surface, several methods such as power spectral method [12], box counting method [26] and structure function method [27] can be used. For the power spectral method, after each image line is processed by Fourier transform, its power spectrum is calculated and then average values of these power spectra are obtained. Unfortunately, this calculation needs great time and requires gridded data [28]. For the structure function method, it is often used to estimate the fractal dimensions of an isotropic surface, where its value is one plus the fractal dimension of profile through the surface in any direction [29]. But in anisotropic surface, the profile fractal dimensions vary widely from direction to direction, which can bring considerable errors. In this paper, the box-counting method is selected because of its high computational efficiency and calculation accuracy. Just as two-dimensional squares can be used to cover an irregular curve, e.g., the cross-section profiles of surface, the three-dimensional boxes can be used to cover an irregular surface. In this study, a 2D and 3D box-counting method are used to analyze ground sapphire surface. The 3D box-counting method is extended based on 2D method. Fig. 1 shows an illustration of fractal analysis using 3D box-counting method. Let $N(r)$ denotes the minimal number of boxes with size r covering the fractal object. The power law relationship defines the fractal dimension D as [30]

$$N(r) \propto r^{-D} \tag{1}$$

Further, Eq. (1) can be rewritten in the form of a line

$$\ln\ N(r) = D \ln\left(\frac{1}{r}\right) + B \tag{2}$$

It means that the value of fractal dimension D can be estimated from the slope of the linear fit of $\ln N(r)$ versus $\ln(1/r)$. B is the intercept of the plot. For a 3D fractal object, the estimation procedure of its fractal dimension D can be divided into the three following steps. In the first step, reasonable cubic boxes with size r is chosen and stacked side by side to encompass the whole 3D fractal