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Investigation on three-dimensional surface roughness evaluation of engineering ceramic for rotary ultrasonic grinding machining

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ABSTRACT

Surface roughness has considerable influence on its quality and function of products in precision and ultra-precision machining, and the same situation applies to engineering ceramic for rotary ultrasonic grinding machining (RUGM). This paper presents a new parameter, called fractal root mean square deviation, for evaluating engineering ceramic three-dimensional (3D) surface roughness of RUGM. Based on engineering ceramics surface of RUGM is typical isotropic, the mathematical model of fractal root mean square deviation was established, and it possesses double characteristics of absolute measurement and multi-scale. Then validation has been implemented, and fractal root mean square deviation is superior to evaluate engineering ceramic 3D surface roughness with better resolution and sensitivity. Furthermore, the relationship between main factor parameters and fractal root mean square deviation was proposed. The evaluation parameter and the results could be implemented in practice to get higher quality surface.

1. Introduction

Engineering ceramic material is applied in aerospace, precision machinery, inertial guidance fields and so on at present, with small density, high strength, wear resistance and corrosion resistance and other excellent features. Rotary ultrasonic grinding, with lower cutting force, higher efficiency and machining surface integrity, is considered as the most powerful method for engineering ceramic machining [1–3]. Therefore, many scholars have been paid attention to rotary ultrasonic grinding machining technology of engineering ceramics, and carried out investigation on the material removal rate, cutting force and machined surface integrity and so on. Pei and Ferreira [4] devoted to study the rotary ultrasonic grinding mechanism of engineering ceramic materials, and established the mathematics model of material removal rate. Lv et al. [5] studied the surface formation mechanism of rotary ultrasonic grinding machining, and thought the machining method can reduce the cutting force due to the presence of ultrasonic vibration, without damage to the processing surface at the same time. Drilling process was also studied, and considered that the rotary ultrasonic grinding machining can improve the surface roughness, and reduce the burring significantly [6]. Schorderet et al. and Kai et al. analyzed the brittle material small hole of ultrasonic machining, and discussed the process parameters affecting the hole quality [7,8].

Roughness evaluation, as the important evaluation parameter of surface integrity, is also an important technical index for engineering ceramics parts function evaluation. With the development of precision and ultra-precision processing technology, two-dimensional roughness is difficult to meet the requirements of parts surface function evaluation, and 3D surface roughness evaluation is the trend of measuring technology [9]. At present, many countries have carried out lots of research work on 3D surface roughness characteristic evaluation parameters, and formed the standard system. Taking geometrical product specifications (GPS) – surface texture: regional ISO 25178-2-2012 system as an example, the main 3D surface roughness evaluation includes amplitude parameters, space parameters, mixing parameters, function parameters and characteristic parameters, total of five categories and thirty parameters [10]. Amplitude parameters are very important in all of 3D surface roughness evaluation parameters. On the one hand, the measurement is simple, on the other hand, the parameters can satisfy the demand for parts surface in most working conditions, with mainly describing the statistical characteristics and extremum characteristics of the surface height distribution. Square average deviation and root mean square deviation are mostly used to evaluate surface for amplitude parameter. However,

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there are insufficient to evaluate rotary ultrasonic grinding machining surface of engineering ceramics with square average and root mean square deviation. Details will be discussed in the later section.

In order to solve the above problems, many scholars have carried out the investigation on 3D surface roughness evaluation technology based on fractal theory [11–13]. Ge and co-workers [14] pointed out that the fractal dimension could be same or similar for different surface structure, it could not determine the only surface with the fractal dimension parameter D, and they put forward the concept of "characteristics roughness". However, the parameter was established based on two-dimensional cross section, not the fractal characterization of three-dimensional surface roughness. Li et al. [15] have analyzed the contour spectrum moment and surface spectrum moment characteristics of random surface based on fractal geometry theory, and proposed the root mean square slope assessment method of three dimensional rough surface. Root mean square slope is a function parameter, cannot reflect the amplitude characteristics of 3D surface. It is proved that it is superior to evaluate roughness with fractal dimension, but not appropriate to reflect 3D surface roughness characterization only using the parameter [14]. How to integrate the fractal dimension and the traditional evaluation parameters, solve the insufficient of single parameter evaluation and propose the new 3D surface roughness evaluation parameters are problems.

Square average deviation and root mean square deviation are mostly used to evaluate 3D surface roughness. In the paper, the insufficient of square average and root mean square deviation for three-dimensional surface roughness evaluation will be analyzed, and new parameter of three-dimensional surface roughness evaluation will be proposed, based on isotropic and fractal characteristics of engineering ceramics machining surface for rotary ultrasonic grinding.

2. Evaluation insufficient of amplitude parameters

Surface square average deviation and root mean square deviation are mostly used to evaluate surface for amplitude parameter. The computational formulae are as followed [10]:

$$S_a = \frac{1}{S}\int\int_S \left|R(x,y)\right| dxdy \tag{1}$$

$$S_q = \sqrt{\frac{1}{S}\int\int_S R^2(x,y)dxdy} \tag{2}$$

where S is definition area, μm^2. S_a is surface square average deviation, μm. S_q is surface root mean square deviation, μm. $R(x, y)$ is the measuring surface morphology height at coordinate point (x, y), μm.

It can be drawn conclusion that S_a and S_q are associated with absolute values of measuring surface morphology height from calculation formulae. Surface square average deviation will be the same, if the absolute amplitude values of test surfaces are the same. The same goes for surface root mean square deviation. Although the absolute amplitude values of test surfaces are the same, the amplitude values of surface morphology are different. So it is not reasonable to evaluate surface characteristic with S_a and S_q. For example, set the measured interval of three processing surface is one, surface roughness matrixes are as follows:

$$\begin{bmatrix} a-1 & a & a+1 \\ a+1 & a & a-1 \\ a-1 & a+1 & a \end{bmatrix} \begin{bmatrix} a-1 & a & a+1 \\ -a-a & -a & -a+1 \\ -a+1 & -a-1 & -a \end{bmatrix} \begin{bmatrix} a & a & a \\ -a & -a & -a \\ a & a & a \end{bmatrix}$$

Assumed that $a=2$, surface square average deviation values of the three surfaces are the same, while the amplitude values

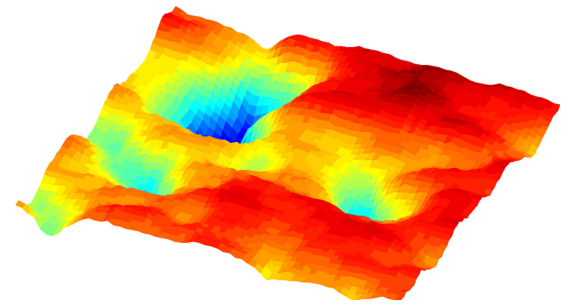

Fig. 1. The surface roughness of Al_2O_3 ceramic for rotary ultrasonic grinding.

of these surfaces are different. Surface root mean square deviation is $\sqrt{23/3}$, $\sqrt{23/3}$ and $\sqrt{4}$ respectively based on formula. For surface amplitude statistical properties, it is superior to evaluate surface roughness with surface root mean square deviation, compared with surface square average deviation. However, there is the same problem that the evaluation values are the same for different surface roughness matrixes. In the surface roughness matrixes above, the surface root mean square deviation values of the first and the second are the same, but the first surface roughness amplitude change is smaller and better.

What is more, surface square average deviation and root mean square deviation are absolute measurement parameters, without multi-scale analysis. The values vary considerably for different measurement scale or measure position, causing surface roughness statistical properties evaluation distortion. It is necessary to seek for parameters to evaluate 3D surface roughness comprehensively.

3. Mathematical model of fractal root mean square deviation

It is known that there are medical cracks and lateral cracks in the surface of engineering ceramics by rotary ultrasonic grinding. The expansion direction of lateral cracks is parallel to machined surface, while the expansion direction of medical cracks is vertical to machined surface. The material removal mechanism is a series of medical cracks and lateral cracks generation, then coupling and combining of the adjacent lateral cracks to cause the material fall off. The cracks growth presents the characteristics of randomicity, complexity, irregularity and self-similar, so there is fractal characteristics of engineering ceramics surface for rotary ultrasonic grinding. Fractal dimension is one of most important evaluation parameter for fractal surface, and the most important feature is multi-scale effect. However, fractal dimension is relativity, because it is calculated with relative value of surface amplitude. So it is also not appropriate to evaluate surface roughness with fractal dimension only.

Surface texture direction is one of the important contents for investigation on three-dimensional surface roughness evaluation of engineering ceramic by rotary ultrasonic grinding machining, and the parameter of Str called surface aspect ratio is adopted to analyze surface texture direction. Fig. 1 shows Al_2O_3 ceramic three-dimensional surface roughness for rotary ultrasonic grinding measured with Taylor PGI 1250A surface contour and nonspherical measuring instrument. Surface aspect ratio of the figure has been calculated, and the solving process is shown in Fig. 2. Surface aspect ratio of Al_2O_3 ceramic three-dimensional surface roughness for rotary ultrasonic grinding is 0.8271 from the results. It draws conclusion that engineering ceramics surface of rotary ultrasonic grinding is typical isotropic.