

## Fractal dimension characterization for surface microtopography of copper cut by single point diamond tool

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**Abstract.** Single point diamond turning is one of the key technologies among modern ultra-precision machining. The finished surface roughness is nanoscale. It shows that the copper surface cut by single point diamond tool exhibits tool marks as well as grain concavity and convexity under different cutting parameters. Usually roughness reflects the machining quality of the machined surface, but when the roughness of different surfaces is the same or similar, it is not sufficient to accurately distinguish the tool marks and grain concavity and convexity relying only on roughness. Therefore, the yard stick method is a better way to calculate the fractal dimension of the surface. In addition, in order to accurately reflect the grain concavity and convexity, the method of filtering can be used to weaken the influence of tool marks. The results show that the fractal dimension after filtering can reflect the features of grain concavity and convexity quantitatively.

### Introduction

The computer numerically controlled Single Point Diamond Turning (SPDT) technology was first researched and developed by the United States Department of Defense Scientific Research Institution in the 1960s. It is normally used in super-precision turning machines, whose cutting tool is made of a single crystal natural diamond. The machining process of the workpieces is single point turning under a precision-controlled and strict processing environment. In the 21st century, ultra-precision machining technologies have been developing fast in many countries, especially the United States, Japan and Germany. So far, the LODTM lathe developed by the LLNL laboratory of the United States holds the best records in machining accuracy. The LODTM lathe has processed the Hubble telescope mirror, whose machining accuracy is better than 0.025  $\mu\text{m}$  [1].

In contrast to traditional cutting methods, the cutting depth of single point diamond cutting can be micro level, the surface quality after processing is very high, while the surface roughness is nanoscale. At the same time, the changes of microstructure on the surface and subsurface cannot be ignored due to the smallness cutting depth[2].

Under normal circumstances, roughness can reflect the quality of the processed surface. It was found that the copper surface after single point diamond turning exhibited a good mirror effect [3]. But in situations of the same or similar roughness, different processed surfaces may contain different microstructure characteristics. In this case, roughness alone can't accurately describe the characteristics of the microstructure.

Scholars at home and abroad have done a lot of research on surface microstructure characterization. Among them, the fractal dimension is a good method, being an effective tool to describe non-smooth and irregular geometric solids in nature as well as nonlinear systems. Mandelbrot B B. first proposed the concept of fractal and the basic definition for the first time in 1975 [4]. At present, the fractal dimension method has been new applications in some processes, such as the characterization of surface profile curves in grinding [5] and milling [6]. For the surface microstructure of materials, such as steel, there is a closely mathematical relationship between fractal dimension and roughness [7], as well as

grain size[8]. At present, the calculation methods for fractal dimension of surface profile include the yard stick method, the power spectrum method, the covariance method, and the structure function method [9]. Different calculation methods are suitable for different characteristics of the surface [10], The yard stick method is proposed by Richardson for the measurement of the coastline, and this method is suitable for the description of the zigzag degree of the profile curves [11].

Single point diamond cutting copper experiments show that there are tool marks and grain concavity and convexity on the processed surfaces. The calculated results indicate that the roughness of the surfaces with marks and the surfaces with grain concavity and convexity are very close, so using roughness alone can not accurately distinguish the microstructure characteristics. In this paper, addressing this problem, the yard stick method within the concept of the fractal dimension is adopted for the calculation and description of surface microstructure characterization. It can reduce the interference of tool marks by means of filtering, so that the feature information of the grain concavity and convexity is effectively extruded.

### Microtopography characteristics of copper surfaces cut by a single point diamond tool

Figs.1(a) and 1(b) are copper surfaces cut by single point diamond tool. Combined with 3D views, both marks and grain concavity and convexity can be directly observed in Fig. 1(a). The rectangular boxes and circles are convex and concave respectively, whose cross section contour is shown in Fig. 2. However, there are mainly cutting marks in Fig. 1 (b). The roughnesses of the two surfaces are very close, they are 22 nm and 22.2 nm respectively. But only Fig. 1 (a) has obvious grain concavity and convexity, so roughness method alone cannot effectively represent the characteristics of surface microtopography.

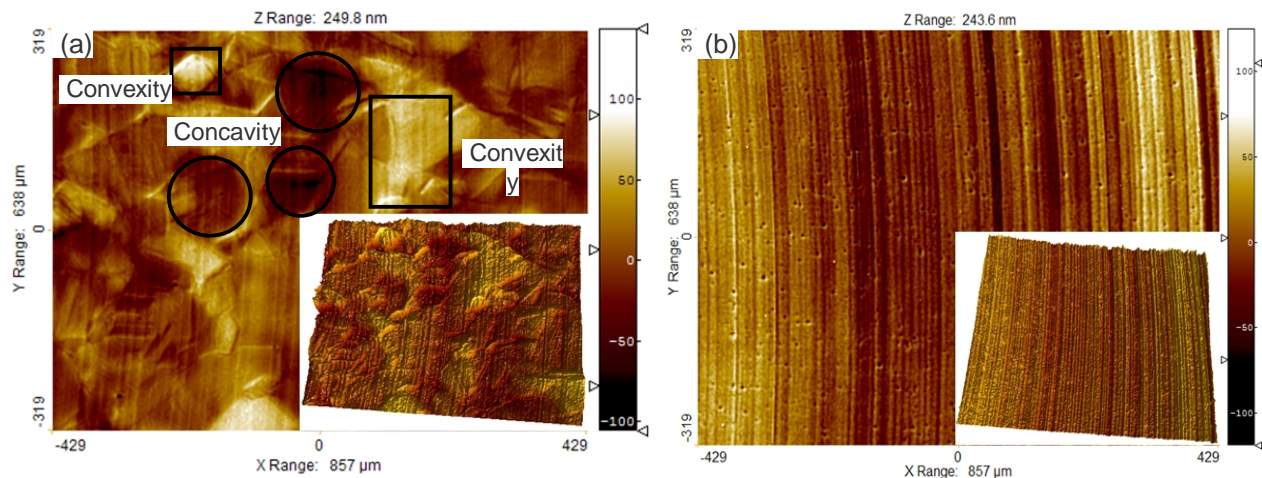


Fig. 1.(a) contains grain concavity and convexity and tool marks, (b) mainly contains tool marks.

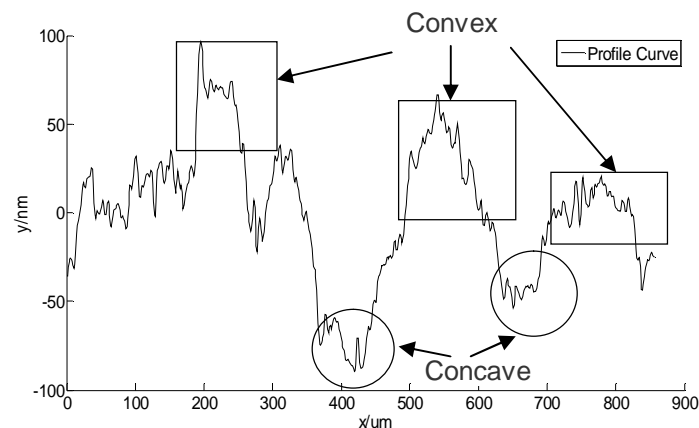


Fig. 2. Cross section contour of grain concavity and convexity.

## A fractal dimension method for characterization of surface microtopography

Since the roughness method is not suitable for the characterization of the grain concavity and convexity, a new method is needed. In this paper, a fractal dimension method combined with filtering for the characterization of the microstructure characteristics will be detailed. The common methods used to calculate the fractal dimension include the yard stick method, the box dimension method, the structure function method, and the covariance weighted method, of which the yard stick method is more suitable for the characterization of zigzag degree of the two-dimensional contour.

### The calculation principle of the yard stick method

Chose one step size, and measure along the profile curve with the step, maintaining both ends of the step on the profile curve, as shown in Fig. 3. After all curves are measured, the whole curve length is the product of the step size and the number of steps. For example, selecting  $n$  sizes  $r_i$  ( $i=1, 2, \dots, n$ ) to measure the surface profile curve, the measured curve length of each size is  $L_i$ . So a set of data includes  $[r_1 L_1], [r_2 L_2], \dots, [r_n L_n]$ . In log-log coordinates, a linear regression is performed with the least square method for the two parameters of size and curve length. The values of the fractal dimension is related to the slope of the profile curve, as shown in Fig. 4. The fractal dimension of the profile curve is expressed as  $D=1-K$ ,  $1 < D < 2$ , where,  $K$  is the regression line slope.

### The influence of tool marks on the fractal dimension method

On the surface containing only marks, we obtain a cross section contour and ensure that the roughness is equal to the roughness of the whole surface, as shown in Fig. 3(a). According to the definition of the yard stick method, the linear regression slope is -0.218, as shown in Fig. 3(b). So the fractal dimension is 1.218, which reflects mainly the influence of the tool marks on the fractal dimension.

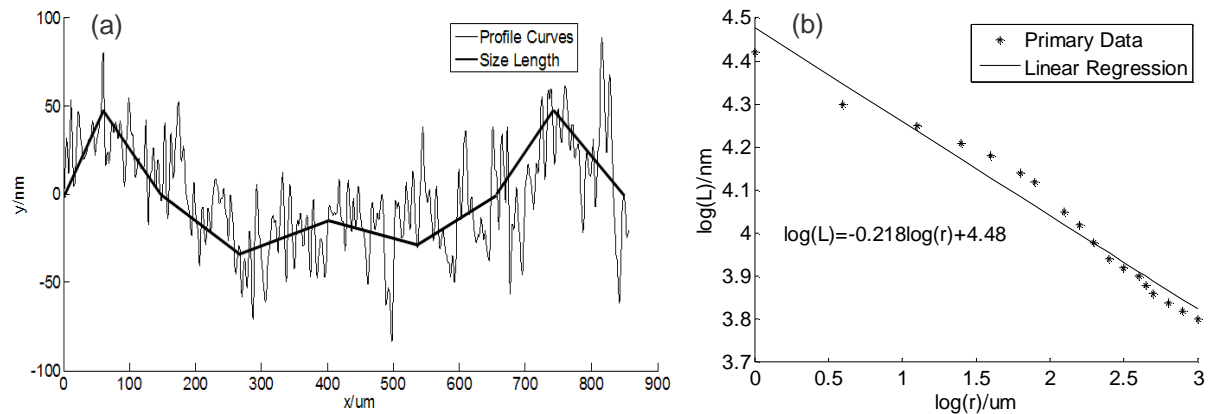


Fig. 3. (a) is principle of yard stick method, (b) stands for linear regression.

### Fractal dimension on surface profile of grain concavity and convexity

In the same way, we obtain a cross section contour on the surface containing grain concave and ensure that the roughness is equal to the roughness of the whole surface, as shown in Fig. 4(a). According to the definition of yard stick method, the slope of Linear regression is -0.4233, as shown in Fig. 4(b), so its fractal dimension is 1.4233. Because some tool marks are still contained on the surface of grain concavity and convexity, the fractal dimension here reflects the influence of grain concavity and convexity as well as tool marks.

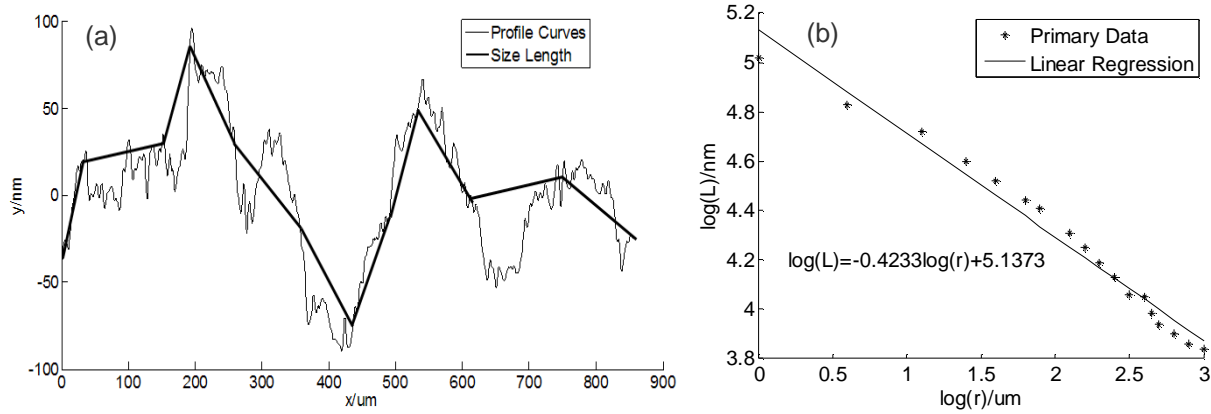


Fig. 4. Calculate fractal dimension of surface profile of concave and convex grain (a) and linear regression (b).

### Filtering on surface profile

The above results show that the fractal dimension of the surface profile with the grain concavity and convexity includes the influence of tool marks. Therefore it is necessary to eliminate the influence of tool marks. Studies show that the cutting marks information is related to the cutting parameters. In fact, the inherent frequency range of the tool marks is relatively narrow, and that of the grain concavity and convexity is wide, with complicated information. So a proper filtering is helpful for reducing the influence of the marks. Thus the information of the grain concavity and convexity is prominent as much as possible. After filtering, the calculation of fractal dimension describes the grain concavity and convexity more accurately. The cutting parameters for copper in single point diamond cutting are shown in Table 1.

Table 1. The cutting parameters

Spindle speed [r/min]	1200
Cutting depth [ $\mu\text{m}$ ]	1~5
Feeding speed[mm/min]	2
Type of cooling	Kerosene Spray

The theoretical spacing between marks, the theoretical cycle of the mark and the inherent frequency, are shown as equation (1-3) .

$$I = \frac{V_f}{V_s} . \quad (1)$$

$$T = \frac{I}{V_f} . \quad (2)$$

$$f = \frac{1}{T} . \quad (3)$$

Where,  $I$  is the adjacent mark spacing,  $V_s$  is the spindle speed ,  $V_f$  is the feeding speed.

Combined the datas of Table 1 and equation(1-3), we obtain

$$I = \frac{1}{600} \text{ mm} , T = \frac{1}{20} \text{ s} , f = 20\text{Hz} .$$

Considering the interference information such as the vibration inside and outside of machine, the actual filtering range will increase appropriately. As shown in Fig. 5(a), Fig. 5(b) and Table 2, the information of tool marks is abated, and the grain concavity and convexity is relatively obvious.

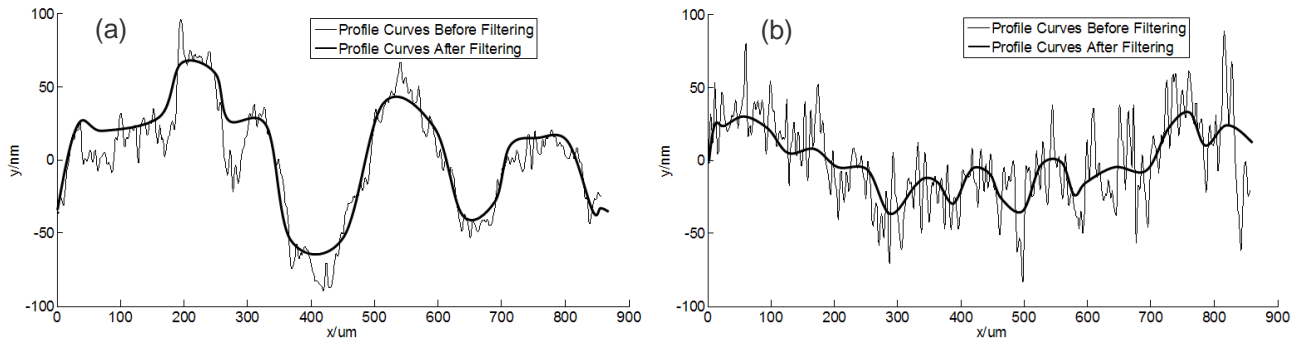


Fig. 5. Filtering on surface profile of grain concavity and convexity (a) and tool marks (b).

Table 2. Filtering result

Height change	Before filtering	After filtering	Change
Grain concavity and convexity [nm]	186	130	30.1%
Tool marks[nm]	171	55	70.8%

### Result of calculation

We choose 10 contour lines on the transverse of each cutting surface, and ensure that the average roughness is equal to the roughness of the whole surface respectively. After calculation of the average fractal dimension of the cross section contour before and after filtering, the results are shown in Fig. 6(a) and Fig. 6(b). The average fractal dimension of surface profile with grain concavity and convexity before and after filtering is 1.46 and 1.36 respectively, and the average fractal dimension of the surface containing only marks before and after filtering is 1.25 and 1.12 respectively.

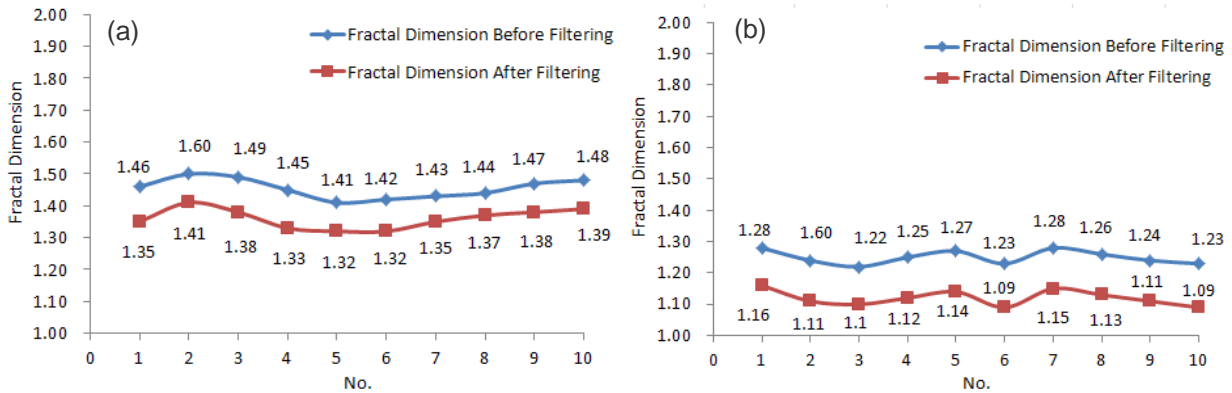


Fig. 6. Filtering on surface profile of grain concavity and convexity (a) and tool marks (b).

### Data analysis and discussion

The analysis on the fractal dimension is shown in Table 3.

1) The fractal dimension is reduced after filtering, and the weakening effect of the filtering is obvious.

2) The roughness of the two surfaces containing grain concavity and convexity and tool marks respectively is similar, differing only by 1%. The average profile fractal dimension differs significantly, when using the yard stick method, with the difference being up to 16.8%. Furthermore, the difference after filtering increases to 21.4%.

3) The marks information is obviously reduced by using filtering. The fractal dimension decreases after filtering for both surfaces, by 0.21 and 0.24 respectively, and the damping is 14.4%, 17.6% respectively.

4) The results after filtering show that the information of grain concavity and convexity has a 17.6% proportion in the forming of the fractal dimension.

Table 3. Calculation results of Profile fractal dimension

Surface	Grain concavity and convexity	Tool marks
Roughness [nm]	22.2	22
Fractal dimension before filtering	1.46	1.36
Fractal dimension after filtering	1.25	1.12

## Conclusions

For the characterization of copper surface cut by the single point diamond tool, the roughness can't effectively describe the surfaces with the grain concavity and convexity. Therefore the yard stick method, one of the fractal dimension methods, is proposed. With filtering, signal of the machining marks is weakened and information of grain concavity and convexity is highlighted.

With filtering, the largest fluctuation of marks signal in the two surfaces, Figs. 5(a) and 5(b), is reduced by 30.1% and 70.8% respectively, and the fractal dimension is reduced by 14.4% and 17.6%, thus the tool marks information is effectively restrained, the information of the grain concavity and convexity is highlighted, and the proportion of the grain concavity and convexity in the fractal dimension rises up to 17.6%.

The difference in value of the roughness of the two surfaces is 1%. However, the difference in value of the average profile fractal dimension is 16.8% (before filtering) and 21.4% (after filtering). With the comparison of the two surfaces, it's obvious that the fractal dimension characterization of the grain concavity and convexity is more effective than the roughness method.

In summary, it is more effective to identify the grain concavity and convexity combined with filtering and the yard stick method, and it is useful to reflect quantitatively the morphology characteristics of the single point diamond cutting surfaces in micro scale.

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