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On the use of fractal methods for the tool flank wear characterization

Bin Li *

Department of Mechanical Engineering, Luoyang Institute of Science and Technology, Luoyang 471023, Henan Province, PR China

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ABSTRACT

Fractal theory is widely used to analyze the topography of machined surfaces, but the relationship between fractal dimensions and tool flank wear has hardly been reported. In this paper, the fractal dimensions of tool flank wear are described based on the surface roughness R_a rather than the conventional worn width *VB* to evaluate tool wear, thus providing better fractal identification in evaluating tool performance.

1. Introduction

Surface topography has recently played an important role in a multitude of physical and tribological phenomena, such as contact mechanics, friction, adhesion, wear and lubrication. It is needed to conduct on-machine surface characterization and in-process measurements of machining processes [1,2]. In general, the main parameters for describing surface topography are classified into the following four categories: I. Vertical parameters of surface topography, such as the arithmetic mean deviation of profile R_a, the root mean square (RMS) deviation of profile R_q, the ten-point height of microscopic plainness R_z, the maximum height of profile R_y and the maximum peak value of profile R_p. II. Parameters of transverse surface roughness, such as the mean space of microscopic plainness of profile S_m, the mean space of unimodal of profile S, the arithmetic mean wavelength of profile λ_a and the root mean square (RMS) wavelength of profile λ. III. Evaluation parameters of surface roughness figures, such as the distribution function of amplitude, the holding length of profile and the root mean square (RMS) slope of profile. V. Integrated evaluation parameters of surface roughness, such as the autocorrelation function $R(\tau)$, the correlation length a and the power spectral density function $p(\omega)$. The parameters in categories (I)–(III) only describe surface topography statistically. They cannot describe the complexity of a real surface, so they cannot be used as parameters for surface topography simulation [3]. The parameters in category V, with which a general model for describing a real surface cannot be constructed, are very complex. However, these methods depend on the resolution and the scan length of the roughness-measuring instrument. They are not properties of a surface alone [4–6].

It is known that fractal theory has recently been used as a useful tool in the characterization of surface texture and the understanding of tribological phenomena, such as friction and lubrication [7]. The degree of complexity of surface shapes can be represented by a value called the fractal dimension: a higher degree of complexity indicates a larger fractal dimension. In addition, natural properties can be explained without the effects of resolution owing to the characteristic properties of fractals, which do not concern magnification values. Tool wear is a factor that has dominant effects on properties that define machining precision, such as surface roughness.

The characteristics of surface roughness due to the tool wear of a rake surface have been reported in previous studies [8,9]. Moreover, many fractal models have been developed and applied to characterize elastic–plastic contact, tribology, surface texture, etc. [2]. However, no discussion has been made regarding the characteristics of fractal dimension relevant to the ceramic tool wear of a flank surface.

This paper reports a new type of fractal dimension analysis of tool flank wear. Usually, the ceramic tool failure criterion is the average amount of flank wear VB = 0.3 mm or maximum flank wear VBmax = 0.6 mm. However, the conventional standard does not consider changes in the surface roughness of ceramic tool flanks after machining, which affects the surface quality and continuity of machined workpieces. In actual operation, traditional standards are used to evaluate cutting tool wear, which may reduce the cutting efficiency. In other words, the standard parameters used to assess tool life are partial quantities, making it difficult to determine the current life of a tool and the degree of machining adaptability for one or many different cutting tools.

Fractal theory, which has been developed in recent years, can describe the complexity of curves with simple parameters. Herein, the characteristics of fractal dimensions relevant to the ceramic tool wear of flank surfaces are discussed. In other words, fractal theory is only used to interpret the complexity of flank wear for certain types of

* Department of Mechanical Engineering, Luoyang Institute of Science and Technology, Wangcheng Avenue 90, Luoyang 471023, Henan Province, PR China. Tel.: +86 15937911896.

E-mail address: libinman@gmail.com.

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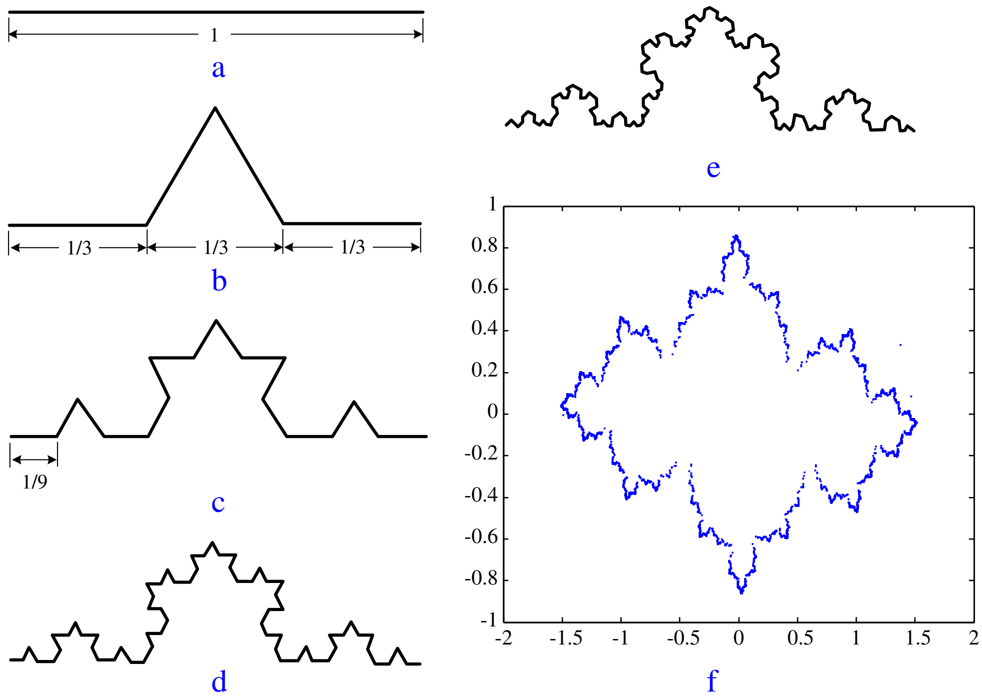

Fig. 1. Example of fractal curve generation and dimension using Koch theory; (*a*) $D = 1.00$; (*b*) D = 1.262; (*c*) D = 1.262; (*d*) D = 1.262; (*e*) D = 1.262; (f) Independence roots of G^k with Julia set for fractal characterization.

machining ceramic tools and to provide a theoretical explanation for this wear behavior.

Therefore, this study presents the relationship between surface roughness and fractal dimension, depending on cutting conditions, in ceramic tool flank wear. It also identifies the properties of tool wear by fractal analysis, which represents a new technique for the in-process monitoring of tool flank wear.

2. Fractal geometry description and calculation

The founder of fractal geometry, Mandelbrot, indicates that many disordered systems in nature have fractal features. A fractal is a type of pattern that is small in extent but very fine in structure. If magnified, it shows repetitive features, demonstrating a similar structure at all scales. The invariability of the degree of scale represents the symmetry of fractal conformation. Just as a round object shows rotational symmetry in Euclidean geometry, a fractal shows flux symmetry [10]. Most of the surface structure of a fractal features shapes that are so complex that they cannot be explained by Euclidean geometry. These shapes repeat themselves when they are observed at different magnifications, a phenomenon referred to as self-affinity or self-similarity.

A fractal refers to a structure exhibiting self-affinity or self-similarity. Thus, as a new form of geometry, fractal geometry is widely used to describe the structural irregularities and complexities of natural systems. For example, when calculating the length of a coastal line, the length becomes larger as the compass length becomes smaller. The following numerical formula can be derived from the fact that the compass length and the coastal length are related in terms of an exponential function [11]:

$$(1/\varepsilon)^D \propto L \tag{1}$$

where ε is compass length and L is the total measured length.

When the above expression is converted to log coordinates, D becomes the slope of a straight line. Such an expression is called a power law; that is, if the compass length becomes infinitely small, the total length increases to an infinite value [12].

Based on this concept, D, which can indicate the degree of complexity exhibited by a length, surface or volume, is called the fractal dimension. In general, a shape with a high measure of space-filling, that is, a shape with a high density, demonstrates a larger fractal dimension. The following example illustrates the idea of the fractal dimension. Consider the curve illustrated in Fig. 1(a) to (e), which is produced by recursion as follows. At the nth level, each straight-line segment of length L is replaced by the original template of size $L/3$. The fractal dimension is defined as

$$D = \lim_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log(1/\varepsilon)} \tag{2}$$

where the fractal dimension D can be obtained as $D = \log 4^2/\log 3^2 \approx 1.262$.

Table 1
Compositions and mechanical properties of the cutting tool materials.

Specimen	Compositions (vol.%)	Relative density (%)	Flexural strength (MPa)	Hardness (GPa)	Fracture toughness (MPa $m^{1/2}$)
AZ0	100%Al_2O_3	92.6	353.1	16.2	3.28
AZ10	90%Al_2O_3 + 10% ZrB_2/ZrO_2	96.4	621.7	24.0	5.11
AZ20	80%Al_2O_3 + 20% ZrB_2/ZrO_2	98.7	760.9	23.1	6.19
AZ30	70%Al_2O_3 + 30% ZrB_2/ZrO_2	93.6	615.4	19.5	5.14
AZ40	60%Al_2O_3 + 40% ZrB_2/ZrO_2	89.9	557.8	18.7	4.79