Fractal Characterization of Relative Machinability of Ferrous Materials

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Abstract. The surface morphology after machining has fractal characteristics. This paper attempts to establish the relationship between fractal parameters and the relative machinability of ferrous metal materials. Four kinds of common ferrous metals were selected for turning under the same machining parameters and the corresponding surface topography was obtained by OLYMPUS DX110 ultra-depth microscope. Afterwards the fractal parameters were calculated based on the fractal theory and MATLAB. Finally, the relationship between fractal dimension $D$ and relative machinability $K_r$ was analysed. The results indicated that with the increase of fractal dimension $D$, the relative machinability $K_r$ shows an increasing trend and the mathematical relationship between them was established, which could provide a theoretical basis for improving the machinability of work-piece materials.

1. Introduction
The machinability of metal materials refers to the degree of difficulty during the material removal process, which is generally related to the chemical composition of materials, heat treatment state, metallographic structure, physical and mechanical properties and cutting conditions. The machinability of work-piece materials is usually measured by one or more of the following indicators, including tool durability, allowable cutting speed for a given tool durability, cutting force, cutting temperature, surface roughness or surface quality. The machinability was studied based on surface topography analysis of metal materials after turning and milling [1-4]. Studies have shown that the machined surface has fractal characteristics [5-7]. The introduction of fractal theory provides a solution for the analysis and characterization of complex surfaces [8]. Some scholars applied fractal theory to study the surface morphology of aluminum alloy after CNC milling [9]. The author also investigated the influence of machining parameters on the fractal characterization of typical metal materials [10]. In this paper, from the point of view of turning process, the commonly industry used ferrous metal materials were machined and the corresponding surface topography was obtained under a unified machining parameter. Then the fractal parameters were calculated and analysed based on fractal theory and MATLAB program for the characterization of the relative machinability of different ferrous metal materials.

2. Materials and Methods
A total of four kinds of common ferrous metal materials were used in the experiment, including 20# steel, 45# steel, T10 tool steel and HT150 grey cast iron, and the corresponding resultant surface was
machined using turning process, which was performed on CA6140 NC lathe under uniform processing parameters with cutting speed of 600 rpm and feed rate of 0.16 mm. As illustrated in Figure 1, the surface morphology of the specimen was obtained based on OLYMPUS DSX110 ultra-depth microscope. The eyepiece used was 5 times with the final image magnification of 27 times and the resultant size obtained was $3927 \, \mu m \times 3927 \, \mu m$.

![Surface morphology of common ferrous metal materials.](image)

(a) 20# steel  
(b) 45# steel  
(c) T10 tool steel  
(d) HT150 grey cast iron  

Figure 1. Surface morphology of common ferrous metal materials.

3. Fractal Characterization

In this study, the fractal dimension $D$ of the surface topography of metal materials was calculated using the pixel covering method [11]. A two gray-scale image can be obtained using image binarization processing once the gray threshold is selected. Thus each pixel in the image will only appear two colors, white or black. Then the boundary is extracted from the feature part, and then the two-valued image is transformed into data file, each of which corresponds to the corresponding pixel location. The value 1 and 0 represent white and black respectively.

Afterwards, the digital data was divided into several parts and the number each rows and columns was $k$, all the blocks containing value 1 marked as $N(k)$. Assume $\delta^*$ as a pixel size, the length of the
block would be \( \delta = k \delta^* \). Least square method was used to carry out linear fitting in double logarithmic coordinates of data points \((\log(N(k)), \log(1/\delta))\) to calculate the fractal dimension \(D\). Based on the principle above, image binarization processing and fractal dimension \(D\) calculation was carried out by programming in MATLAB (Version 8.3, Mathworks Inc, USA).

By taking logarithms on both sides of the formula, a function can be obtained as shown in Eq.1:

\[
\log(N(k)) = \log(C) + D \log(1/\delta)
\]

The fractal dimension \(D\) is gained by taking the limit value \(\delta \to 0\) as shown in Eq.2:

\[
D = \lim_{\delta \to 0} \frac{\log(N(k))}{\log(1/\delta)}
\]

Figure 2 demonstrates the process of image binarization, boundary extraction and calculation of fractal dimension \(D\) of the surface morphology of HT150 grey cast iron.

![Image of calculation process](image)

Figure 2. Calculation of fractal dimension \(D\) of surface topography using pixel-covering method.

4. Results and Discussion

Relative machinability \(Kr\) refers to the ratio of the cutting speed of the machined material to the cutting speed of 45# steel under certain durability conditions. If \(Kr > 1\), it indicates that the material is easier to cut than 45# steel with better cutting performance; while \(Kr < 1\) means that the material is more difficult to cut than 45# steel, and the cutting performance is worse. In general, the higher the hardness of the work-piece material, the greater the cutting force, the higher the cutting temperature, the faster the tool wear, the worse the machinability; similarly, higher strength of work-piece material would result in worse machinability. In the case of that the strength of the work-piece material is the same, higher plasticity and toughness could influence the machinability a lot. During the cutting process, the work-piece material with higher thermal conductivity has better machinability under the condition of equal heat generation. Normally, ferrous metal materials have better machinability than of non-ferrous metals and the machinability of cast iron is not as good as steel, which is influenced by the chemical composition. The higher the alloy composition of steel, the harder to process. When the carbon content increases, the metal cutting performance decreases. The structure of steel is also a key factor to the metal cutting performance.

The fractal dimension \(D\) of the surface topography of 20# steel, 45# steel, T10 tool steel and HT150 grey cast iron were calculated using MATLAB program and were demonstrated in Table 1. It is obvious that the fractal dimension of 20# steel and T10 tool steel are the largest and smallest, which are 1.7257 and 1.6445 respectively, and the corresponding relative machinability are 1.7 and 0.73. As illustrated in Figure 3, the relationship between relative machinability \(Kr\) and fractal dimension \(D\) of the four kinds
of ferrous metals obtained in the experiment is approximately linear, and the mathematical relationship is \( Kr = -19.81 + 12.45 \times D \).

| Ferrous Material       | Relative machinability \( Kr \) | Fractal Dimension \( D \) |
|------------------------|----------------------------------|--------------------------|
| 20# steel              | 1.7                              | 1.7257                   |
| 45# steel              | 1                                | 1.6704                   |
| T10 tool steel         | 0.73                             | 1.6445                   |
| HT150 grey cast iron   | 0.83                             | 1.6641                   |

Figure 3. The relationship between relative machinability \( Kr \) and fractal dimension \( D \).

5. Conclusions
In this paper, four kinds of common ferrous metals were selected and machined with uniform turning parameters and the corresponding surface topography was analyzed and the fractal dimension \( D \) was calculated based on fractal theory. It can be seen from the experiment that the relative machinability \( Kr \) of ferrous metals increases with the increase of fractal dimension \( D \), and the mathematical relationship between them was established, which could provide a certain theoretical basis for machinability improvement of work-piece material. However, the application of fractal parameters to fully characterize the machinability of metal materials requires more refined experiments, and non-ferrous metals need to be taken into account, combined with the analysis of physical and mechanical properties of materials, chemical composition and cutting conditions.

6. Conflict of interest statement
The authors declare that there is no conflict of interest regarding the publication of this paper.

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