Fractal Characterization of Typical Metal Materials Based on Surface Topography Analysis

Wei Jiang 1 *, Cuicui Ji 2, Dandan Zhang 1, Jing Chen 1, Yuntian Dai 1

1School of Mechanical and Automobile Engineering, Changzhou Institute of Technology, Changzhou, Jiangsu 213032, PR China
2School of Mechanical and Electrical Engineering, Hohai University, Changzhou, Jiangsu 213022, PR China
* jwei@czust.edu.cn

Abstract. The surface topography of typical metal materials was analysed based on fractal theory. Six kind of metal materials were machined under the same turning parameters and the corresponding fractal dimension D of surface topography was calculated. The results indicate that the fractal dimension D can reflect the complexity of the surface morphology of metal materials; the fractal dimension D of ferrous metal materials is higher than nonferrous metal materials; no obvious linear relationship found between surface roughness Ra and fractal dimension D; fractal dimension D could reveal the intrinsic properties and the machinability of metal material with further analysis.

1. Introduction
The surface of metallic materials is rough after machining, friction, wear and corrosion. The surfaces are usually characterized by statistical parameters such as height standard deviation, curvature standard deviation and so on. However, it is found that rough surfaces are unstable processes and the traditional statistical parameters can not fully represent the random behavior and detail characteristics of rough surfaces due to the limitation caused by the resolution of the instrument [1]. Therefore, it is essential to use a parameter to characterize these complex rough surfaces with independent scale. The introduction of fractal theory provides an effective way to characterize rough surfaces [2]. Studies show that rough surface of metal materials has fractal characteristics, and the fractal dimension D can be used to characterize rough surface topography [3-5]. In recent years, many scholars have applied fractal theory to analyze the microstructure and contact mechanism of machined surface topography [6,7]. In this study, six common used metal materials including ferrous and non-ferrous were machined using the same turning parameters to obtain the corresponding surface topography. The fractal theory was applied for the analysis of surface morphology and the fractal dimension D was calculated to characterize the surface topography of metal materials as well as the classification of ferrous and non-ferrous metals.

2. Materials and Methods
The typical metallic materials used in this study are Q235-A steel, 45# steel, HT200 gray cast iron, T2 copper, HPb63-3 brass and 2A12 aluminum alloy. The corresponding surface topography was obtained using the same turning machining parameters, as shown in Table 1. The specimen diameter is 30 mm with height of 10 mm, the tool used for turning process is YT15 carbide cutter and the speed of
lathe is 820 rpm with feed rate of 0.08 mm/r and the cutting depth of 0.1 mm. The ultra-depth field microscope OLYMPUS DSX110 was used for the image acquisition of surface topography of the metal materials, as shown in Figure 1.

![Surface topography of typical metal materials.](image)

**Figure 1.** Surface topography of typical metal materials.

**Table 1.** Turning machining parameters

| Tool Material | Specimen (Φ30 mm, height 10 mm) |
|---------------|----------------------------------|
| YT15          | Q235-A, 45#, HT200, T2, HPb63-3, 2A12 |

| Turning Speed (rpm) | Feed Rate (mm/r) | Depth (mm) |
|---------------------|------------------|------------|
| 820                 | 0.08             | 0.1        |

3. Fractal Characterization

In this study, the fractal dimension $D$ of the surface topography of metal materials was calculated using the pixel covering method [8,9]. The principle is as follows: transforming the original image into gray level image, the fractal feature extraction is mainly based on its gray-scale distribution. By setting the gray threshold, a two gray-scale image can be obtained using image binarization processing, 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 is 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 log on both sides, a function is obtained as in Equation 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 Equation 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 45# steel.

![Figure 2](image)

(a) original surface topography  (b) image binarization

(c) boundary extraction  (d) fractal dimension \( D \) calculation

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

4. Results and Discussion

As shown in Figure 3, the fractal dimension \( D \) of Q235-A, 45#, HT200, T2, HPb63-3 and 2A12 was calculated from the double logarithmic coordinate and the slope of straight line is the fractal dimension \( D \) of the surface morphology. In this study, the surface roughness Ra of each sample was measured with the T1000 profilometer (Hommel, Germany), and the data was the average after...
multiple measurements. Figure 4 (a) illustrates the relationship between fractal dimension $D$ and the surface roughness $R_a$ of typical metal materials. It is not difficult to find that for ferrous metals such as Q235-A, 45# and HT200, there is no obvious corresponding relationship between fractal dimension $D$ and surface roughness $R_a$ and the surface roughness of Q235-A and HT200 is even close to each other but with different fractal dimension $D$. This may be due to the brittle characteristics of HT200, which would result in more micro concave and convex and these details were not be able to capture in the measurement of surface profile due to the scale limitation. For non-ferrous metals, with the decrease of surface roughness $R_a$, fractal dimension $D$ shows a rising trend and this reflects the characteristics of fractal characterization from a certain extent, that is fractal dimension $D$ can reflect the complexity of surface topography.

![Figure 3. Double logarithmic coordinate for the calculation of fractal dimension $D$ of typical metal materials.](image)

In this study, it is worth noting that the fractal dimension $D$ of non-ferrous metal materials (T2, HPb63-3, 2A12) is lower than that of ferrous metal materials (Q235-A, 45#, HT200), even the fractal dimension $D$ of 2A12 ($D=1.508$) aluminum alloy, which is the largest in non-ferrous metals, is still lower than that of Q235-A ($D=1.518$), which is the lowest in ferrous metals. This indicates that the fractal dimension $D$ may be able to classify the metal materials. On the other hand, the fractal dimension $D$ may be related to the inherent physical properties of the material, such as hardness and strength. From the point of view of machinability of work piece materials, fractal dimension $D$ may reflect the relative machinability of processed materials, which needs further study.
Figure 4. (a) the relationship between fractal dimension and surface roughness; (b) the relationship between fractal dimension and ferrous and non-ferrous metal materials.

5. Conclusions
Based on the presented analysis and discussion, the following main conclusions can be drawn from this study.

1. The fractal dimension $D$ is scale independent, which can reflect the complexity of the surface morphology of the metal materials.

2. The fractal dimension $D$ of the surface morphology of the ferrous metal materials (Q235-A, 45#, HT200) is higher than that of non-ferrous metal materials (T2, HPb63-3, 2A12).

3. There is no obvious linear relationship between fractal dimension $D$ and the surface roughness $R_a$ for ferrous metal materials; for non-ferrous metal materials the fractal dimension $D$ increases with the decrease of surface roughness $R_a$.

4. The fractal dimension $D$ may be related to the intrinsic physical properties of metal materials and can be used to reveal the relative machinability of metal materials, which needs to be further studied.
6. Conflict of interest statement
The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgements
This work was financially supported by the Applied Basic Research Programs of Science and Technology Commission Foundation of Jiangsu Province (BK20150256), the National Natural Science Foundation of China (51505126) and Scientific Research Foundation of Changzhou Institute of Technology (YN1512, YN1626).

References
[1] Sayles and T. R. Thomas. Surface Topography as a Non-Stationary Random Process[J]. Nature, 1978, 271: 431-434.
[2] B. B. Mandelbrot. The Fractal Geometry of Nature[M]. New York: W. H Freeman and Co. 1982.
[3] L. He, J. Zhu. The Fractal Character of Processed Metal Surfaces[J]. Wear, 1997, 208: 17-24.
[4] S.R. Ge, K. Tonder. The Fractal Behavior and Fractal Characterization of Rough Surfaces[J]. Tribology, 1997, 17(1): 73-80.
[5] P. Sahoo, T. Barman, J.P. Davim. Fractal Analysis in Machining[J]. Springerbriefs in Applied Sciences & Technology, 2011, 3: 69-81.
[6] C.C. Ji, H. Zhu, W. Jiang. Running-in Test and Fractal Methodology For Worn Surface Topography Characterization[J]. Chinese Journal of Mechanical Engineering, 2010, 23(5): 600-605.
[7] D.S. Li, Y.D. Zhang, Q. Wu, P. Wang. Identification of Fractal Scale Parameter of Machined Surface Profile[J]. Applied Mechanics and Materials, 2011, 42: 209-214.
[8] R. D. Peng, H. P. Xie, and Y. Ju. Computation Method of Fractal Dimension for 2-D Digital Image[J]. Journal of China University of Mining & Technology, 2004, 33(1): 19-24.
[9] W. Jiang, C. C. Ji, and H. Zhu. Fractal Study on Plant Classification and Identification[C]. International Workshop on Chaos-fractals Theories & Applications, 2009: 434-438.