Fractal Analysis of the Influence of Mesh Number of Sandpaper on Simulated Wear Process

Wei Jiang 1 *, Cuicui Ji 2, Hengjing Huang 2, Dandan Zhang 1, Yuntian Dai 1, Daixi Feng 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 analysis of worn surface topography is an important approach to study the wear mechanism of friction pairs. The influence of mesh number of sandpaper on simulated wear process was investigated based on fractal theory. The results indicate that cross-shear wear mode is appropriate for simulated wear, which is close to actual working condition and the resultant surface morphology has fractal characteristics. With the increase of the mesh number of sandpaper, the surface roughness \( R_a \) of stainless steel 0Cr18Ni9 and aluminum alloy 2A12 decreased while the fractal dimension \( D \) increased and showed a general linear relationship. However, the surface roughness \( R_a \) and fractal dimension \( D \) of the stainless steel were slightly greater than that of the aluminum alloy. Fractal dimension \( D \) may be related to the intrinsic physical properties of metallic materials and could be used to characterize the relative machinability of materials.

1. Introduction

The characteristic analysis of surface topography is an important method to study the wear mechanism, which has become a significant research subject in tribology. Traditionally, the surface morphology was characterized by statistical parameters, such as surface roughness \( R_a \). Many scholars have carried out the analysis of surface topography of metallic materials after traditional processing and non-traditional processes as well as the investigation of the influence of machining processing parameters on surface morphology [1-5]. With the deepening research of the surface morphology, the parameters used to characterize the surface morphology are constantly emerging but are sometimes overlapped. Some of the parameters are only applicable to special situations and sometimes even contradict each other, which brings great difficulty to the research of surface characterization. The traditional surface characterization parameter – roughness is scale dependent and would alter with the measurement scale [6]. The research shows that the contour height change of the rough surface is a nonstationary random process and has fractal characteristic [7]. Therefore, fractal theory was applied for the characterization of rough surface morphology widely by the scholars in recent years [8-10]. In this paper, the influence of mesh number of sandpaper on simulated wear process of metallic materials was investigated based on fractal theory.
2. Materials and Methods

In this study, two kinds of metal materials, stainless steel 0Cr18Ni9 and aluminum alloy 2A12 were selected for the simulated wear tests, including ferrous and non-ferrous metals. The initial surface morphology of the specimen was obtained using M7120A surface grinder, and the mesh number of sandpaper used in the simulated wear process was 180#, 600# and 1000# respectively. The simulated wear condition was dry friction with wear mode as cross-shear, and the wear length was 1000 mm. The surface morphology of the specimen after simulated wear tests was acquired via OLYMPUS DSX110 ultra-depth microscope. The eyepiece used was 20 times with the final image magnification of 277 times and the resultant size obtained was 980 µm×980 µm. Figure 1 and 2 demonstrate the morphology of initial and worn surface were obtained after simulated wear tests carried out using sand-paper with different mesh number of 180#, 600# and 1000# respectively.

![Figure 1. Surface morphology of aluminum alloy 2A12 before and after simulated wear test.](image-url)
3. Fractal Characterization

As an important fractal parameter, fractal dimension $D$ reflects the complexity of the surface morphology. In this study, pixel-covering method was applied for the calculation of the fractal dimension $D$ [11,12]. The basic procedure is as follows: the initial image was firstly transformed into grey-scale image and then image binarization process was applied to obtain a two grey-scale image, which means each pixel in the image would only show two colors, black or white. Afterwards, the boundary of the image was extracted and the two-valued image was then converted into digital data file, each of which represents the corresponding pixel and the value 0 and 1 represent black and white respectively. The number of each row and column was defined as $i$ and the block containing value 1 was marked as $N(i)$. The variable $j^*$ was defined as the pixel size and the block size would be $\varepsilon = ij^*$, then least square method was used for linear fitting in double logarithmic coordinates of data points $(\log(N(i)), \log(1/j))$ to calculate the fractal dimension $D$. Based on the pixel-covering method above, image binarization process and fractal dimension $D$ calculation was performed by programming in MATLAB (Version 8.4, Mathworks Inc, USA).

By taking the logarithm, an equation can be obtained as demonstrated in Eq.1:

$$\log(N(i)) = \log(C) + D\log(1/j)$$  \hspace{1cm} (1)

Then the fractal dimension $D$ could be calculated by taking the limit value $\varepsilon \rightarrow 0$ as shown in Eq.2:

$$D = \lim_{\varepsilon \rightarrow 0} \frac{\log(N(i))}{\log(1/j)}$$  \hspace{1cm} (2)
Figure 3 illustrates the image binarization process, boundary extraction and the calculation of fractal dimension $D$ of the surface morphology of stainless steel 0Cr18Ni9 after simulated wear test using sandpaper with mesh number of 180#.

![Initial surface morphology](image1.png) ![Image binarization process](image2.png) ![Boundary extraction](image3.png) ![Fractal dimension calculation](image4.png)

(a) initial surface morphology (b) image binarization process (c) boundary extraction (d) fractal dimension calculation

Figure 3. Calculation of fractal dimension $D$ of surface morphology using pixel-covering method.

4. Results and Discussion

The surface roughness $R_a$ and fractal dimension $D$ of aluminum alloy 2A12, stainless steel 0Cr18Ni9 before and after simulated wear tests with different mesh number of sandpaper were demonstrated in Tables 1, which were the average value after multiple measurements. Figure 4 illustrates the relationship between fractal dimension $D$, surface roughness $R_a$ and the mesh number of sandpaper (180#, 600# and 1000#). The original surface roughness $R_a$ obtained via surface grinder was 0.763 and 0.781 respectively. With the increase of the mesh number of sand paper, the surface roughness $R_a$ shows a decreasing trend (for aluminum alloy 2A12, the surface roughness is 0.691, 0.319, 0.303; for stainless steel 0Cr18Ni9, the surface roughness is 0.423, 0.414 and 0.409 respectively) while the fractal dimension $D$ increases. It is worth noting that the surface roughness of the stainless steel is slightly greater than that of aluminum alloy, which may due to the difference of the hardness. In the process of simulated wear, the surface of stainless steel would abrade less by the sandpaper than that of aluminum alloy, resulting in greater fractal dimension $D$, which indicated that the fractal parameters may be related to the intrinsic physical properties of metal materials. From the aspect of the difficulty
of the metal material processing, the fractal parameters may be able to reflect the relative machineability of the processed metal materials, which needs in-depth analysis.

Table 1. Fractal dimension and surface roughness of aluminum alloy 2A12, stainless steel 0Cr18Ni9 before and after simulated wear tests

| Material                  | Fractal Dimension $D$ | Surface Roughness $R_a$ |
|---------------------------|------------------------|--------------------------|
| Aluminum Alloy 2A12       |                        |                          |
| Original                  | 1.687                  | 0.763                    |
| 180#                      | 1.719                  | 0.691                    |
| 600#                      | 1.733                  | 0.319                    |
| 1000#                     | 1.740                  | 0.303                    |
| Stainless Steel 0Cr18Ni9  |                        |                          |
| Original                  | 1.709                  | 0.781                    |
| 180#                      | 1.721                  | 0.423                    |
| 600#                      | 1.735                  | 0.414                    |
| 1000#                     | 1.744                  | 0.409                    |

Figure 4. The relationship between fractal dimension $D$, surface roughness $R_a$ and the mesh number of sandpaper.

In addition, the mathematical relationship between fractal dimension $D$ and the mesh number of sandpaper was investigated. Linear fitting method was applied to establish the mathematical equation. As shown in Figure 5, for stainless steel 0Cr18Ni9, the relation between the fractal dimension and the number of sandpaper was $D = 1.72 + 2.57 \times 10^{-5}N$, for aluminum alloy 2A12, the relationship was $D = 1.72 + 2.81 \times 10^{-5}N$, and R-square was 0.976 and 0.939 respectively.

Figure 5. Mathematical relationship between fractal dimension $D$ and the mesh number of sandpaper.
5. Conclusions
In this paper, aluminum alloy 2A12 and stainless steel 0Cr18Ni9 were used to carry out the simulated wear test and the influence of the mesh number of sandpaper was analyzed during the simulate wear process. The wear mode of cross-shear was reasonable and appropriate, which is close to the actual wear condition. The corresponding surface morphology was analyzed based on fractal theory and the fractal dimension $D$ was calculated using pixel-covering method. With the increasing of mesh number of sandpaper from 180# to 1000#, the roughness $R_a$ decreases while the fractal dimension $D$ increases and showed a linear relationship to a certain extent. Both roughness $R_a$ and fractal dimension $D$ of the stainless steel were slightly greater than that of aluminum alloy due to the difference of the hardness, which indicated that fractal dimension $D$ could reveal the intrinsic physical properties of the metal materials and characterize the relative machineability.

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), the Applied Basic Research Programs of Changzhou (CJ20179044) and Scientific Research Foundation of Changzhou Institute of Technology (YN1512, YN1626, YN1715).

References
[1] S. A. Celik. Surface Roughness Investigation in the Electrical Discharge Machining of Powder Metal Material[J]. Journal of Applied Sciences, 2007, 7(12): 90-97.
[2] Y. D. Gong, X. L. Wen, Z. X. Zhu, J. Cheng, G. Q. Yin. Experiment Research on Surface Roughness in Micro-Grinding Metal Material[J]. Advanced Materials Research, 2014, 1017: 500-505.
[3] J. S. Lee. Evaluation of Surface Roughness of Metal and Alloy Material[J]. Journal of Materials Science & Chemical Engineering, 2016, 04(1): 90-97.
[4] E. Ünal. Influence of Drilling Parameters on Temperature and Surface Roughness of AISI O2 Steel[J]. Materialprufung, 2018, 60(2): 197-201.
[5] F. Ahmed, T. J. Ko, S. Ali. Analysis of the Influence of Input Parameters of EDM on Material Removal Rate and Surface Roughness for Machining Stainless Steel 304[J]. International Journal of Machining & Machinability of Materials, 2018, 20(1): 78.
[6] Sayles and T. R. Thomas. Surface Topography as a Non-Stationary Random Process[J]. Nature, 1978, 271: 431-434.
[7] L. He, J. Zhu. The Fractal Character of Processed Metal Surfaces[J]. Wear, 1997, 208: 17-24.
[8] Y. Wang, K.W. Xu. Characterization of surface morphology of copper tungsten thin film by surface fractal geometry and resistivity[J]. Thin Solid Films, 2004, 468 (1-2): 310-315.
[9] S. Prabhu, B. K. Vinayagam. Fractal Dimensional Surface Analysis of AISI D2 Tool steel Material with Nanofluids in Grinding Process using Atomic Force Microscopy[J]. Journal of the Brazilian Society of Mechanical Sciences & Engineering, 2011, 33(4): 129-143.
[10] W. Feng, X. Chu, Y. Hong, D. Deng. Surface Morphology Analysis Using Fractal Theory in Micro Electrical Discharge Machining[J], Materials Transactions, 2017, 58(3): 433-441.
[11] 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.
[12] 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.