Hindawi Publishing Corporation
Journal of Chemistry
Volume 2015, Article ID 427297, 6 pages
http://dx.doi.org/10.1155/2015/427297

Review Article

Review on Fractal Analysis of Porous Metal Materials

J. Z. Wang, J. Ma, Q. B. Ao, H. Zhi, and H. P. Tang

State Key Laboratory of Porous Metal Materials, Northwest Institute for Nonferrous Metal Research, Xi'an 710016, China

Correspondence should be addressed to H. P. Tang; hptang@c-nin.com

Received 24 September 2014; Revised 26 February 2015; Accepted 24 March 2015

Academic Editor: Gustavo Portalone

Copyright © 2015 J. Z. Wang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Porous metal materials are multifunctional lightweight materials and have been used widely in industry. The structural and functional characters of porous metal materials depend on the pore structure which can be described effectively by the fractal theory. This paper reviews the major achievements on fractal analysis of pore structure of porous metal materials made by State Key Laboratory of Porous Metal Materials, China, over the past few years. These include (i) designing and developing a set of novel fractal analytical software of porous metal materials, (ii) the influence of material characterization and image processing method on the fractal dimension, and (iii) the relationship between the material performance and the fractal dimension. Finally, the outlooks of fractal theory applied in porous metal materials are discussed.

1. Introduction

The fractal phenomenon is ubiquitous in a wide array of materials such as the growth of crystal, the fracture or martensite morphology, the quasicrystal structure, the deposited film, and the porous materials [1, 2]. These materials are a unique class of disordered materials and often display complex microstructures. Since the fractal theory was presented [3], it had been widely used in many fields of modern science, such as studying permeability of porous media [4, 5] or dual-porosity medium [6], investigating the mechanism of gas diffusion or fluid flow in porous media [7–10], evaluating dislocation structure [11], discussing positive pulsed streamer patterns in supercritical CO_2 [12], analyzing fracture surfaces or network [13, 14], simulating the failure of concrete [15], disclosing the temporal change of tropical cyclone Dan complex structure [16], and discussing the heat flux of subcooled pool boiling [17] and thermal conductivity performance [18].

For porous metal material, its performance is strongly affected by the pore structure, so the accurate description of pore structure has become a research hotspot in recent years [19]. The fractal theory is an effective method for discussing the pore structure of porous metal materials. This paper reviews the major achievements on fractal analysis of pore structure of porous metal materials made by State Key Laboratory of Porous Metal Materials, China, over the past few years, including a set of novel fractal analytical software of porous metal materials developed, the influence of material characterization and image processing method on the fractal dimension of pore structure of porous metal materials, and the relationship between the material performance and the fractal dimension. Finally, the outlooks of fractal theory applied in porous metal materials are discussed.

2. Novel Fractal Analytical Software

In order to analyze precisely the pore structure of porous metal materials, a set of novel fractal analytical software of porous metal materials was designed and developed by us based on the fractal theory and the computer image processing technology. Figure 1 shows the processing page layout view of the software. For the software, the shape factor and the sharpness factor of pore were introduced as discussed elsewhere [20, 21]. In addition, the characters and the processing steps of the software were described systematically in our previous works [22–24].

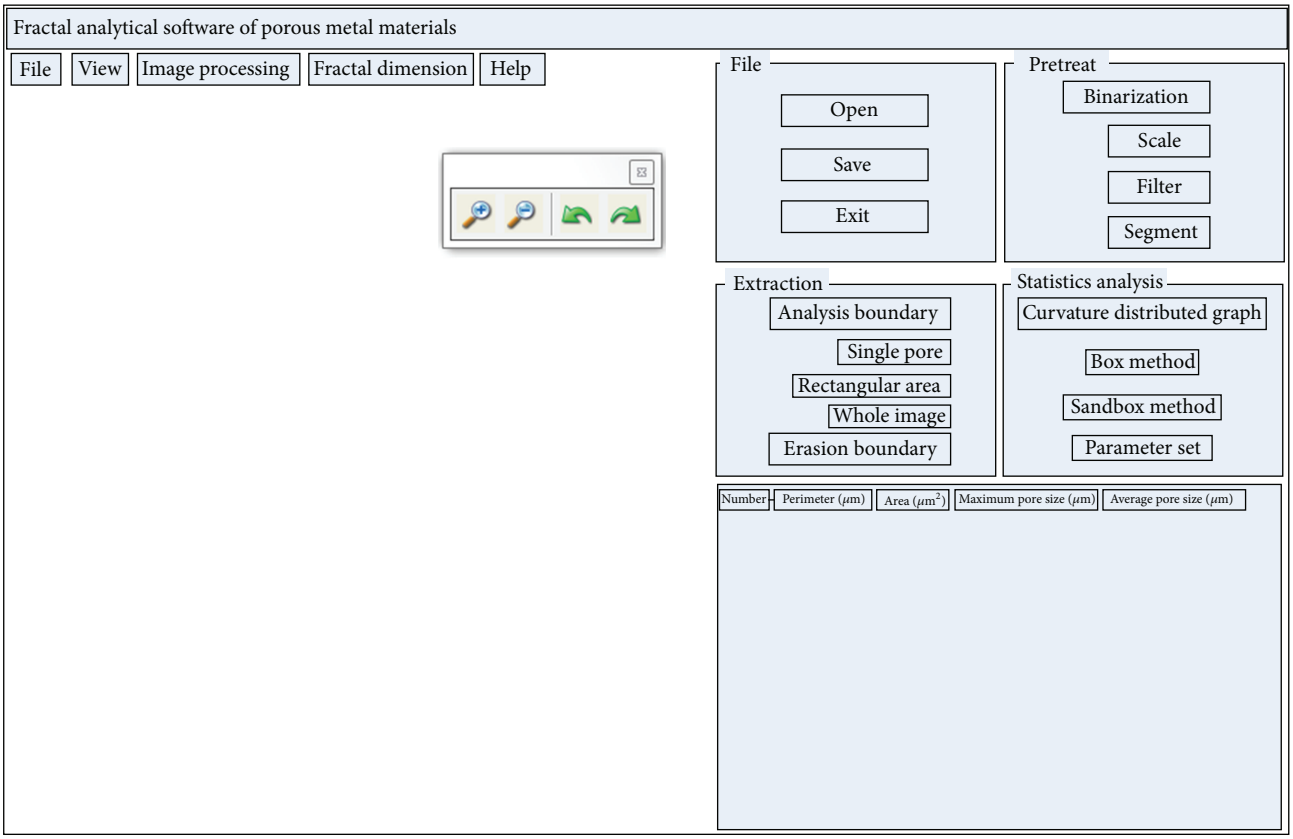


Figure 1: Layout view of software.

3. Analysis of Affecting Factors of Fractal Dimension

The fractal dimension of pore structure of porous metal materials was affected by the porosity, the image magnification, the powder particle size, the powder morphology, the image resolution, and the image region chosen [22–27].

3.1. Effects of Porosity and Powder Particle Size on Fractal Dimension. At the same image magnification, the quantity and the complexity of pore increase slowly as the porosity of porous metal materials increases, so the fractal dimension increases gradually with the porosity increasing [22, 24], shown in Figure 2.

In addition, the relationship between the fractal dimension, the volume porosity, and the surface porosity can be defined as [27]

$$\theta = M\left(1 + \frac{1}{D}\right)\varphi, \tag{1}$$

where θ is the volume porosity, D is the fractal dimension, φ is the surface porosity, and M is the emendatory coefficient.

According to (1), the volume porosity of porous metal materials made by irregular powder can be predicted and the calculated results are in good agreement with the tested ones, shown in Tables 1 and 2.

Table 1: Volume porosity of porous metal materials made by irregular powder with the particle size of 44~74 μm.

Fractal dimension	1.2304	1.2515	1.271	1.288	1.298
Volume porosity tested, θ/%	19.3	21.4	24.7	29.7	34.3
Volume porosity calculated, θ/%	17.07	19.06	21.44	26.17	30.29
$\Delta\theta$/%	2.23	2.34	3.26	3.53	4.01

Table 2: Volume porosity of porous metal materials made by irregular powder with the particle size of 74~150 μm.

Fractal dimension	1.1655	1.2072	1.2228	1.2441	1.2492
Volume porosity tested, θ/%	20.1	22.6	26.1	29.6	33.5
Volume porosity calculated, θ/%	18.43	21.23	24	26.59	31.85
$\Delta\theta$/%	1.67	1.37	2.1	3.01	1.65

It also can be seen from Figure 2 that the fractal dimension of pore structure of porous metal materials manufactured by fine powder is higher than that by coarse powder at the identical porosity.

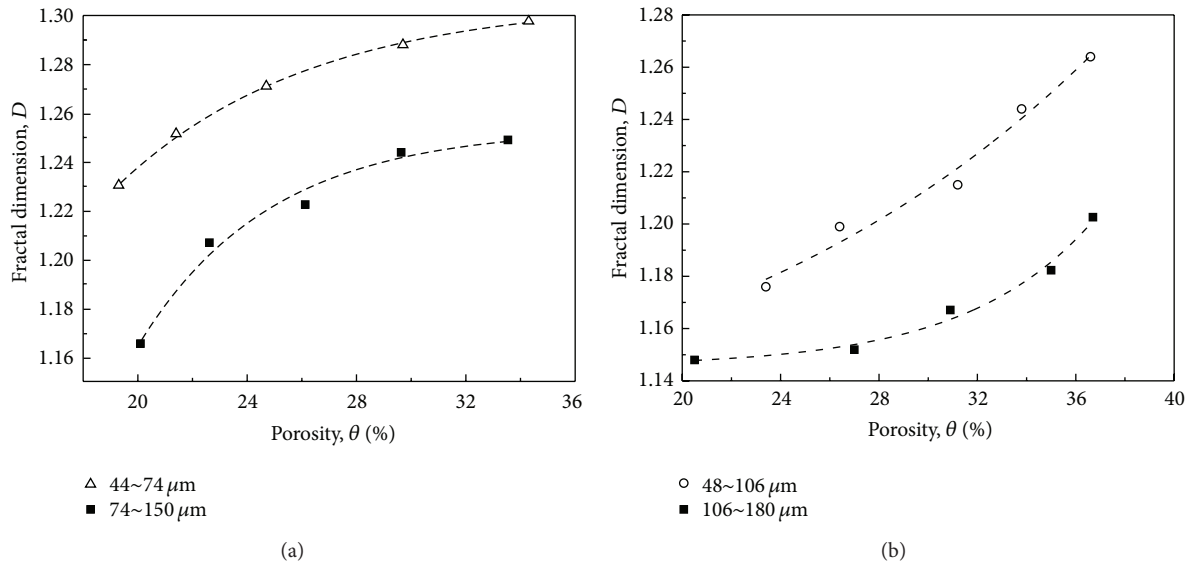


Figure 2: Fractal dimension versus porosity: (a) irregular powder and (b) spherical powder.

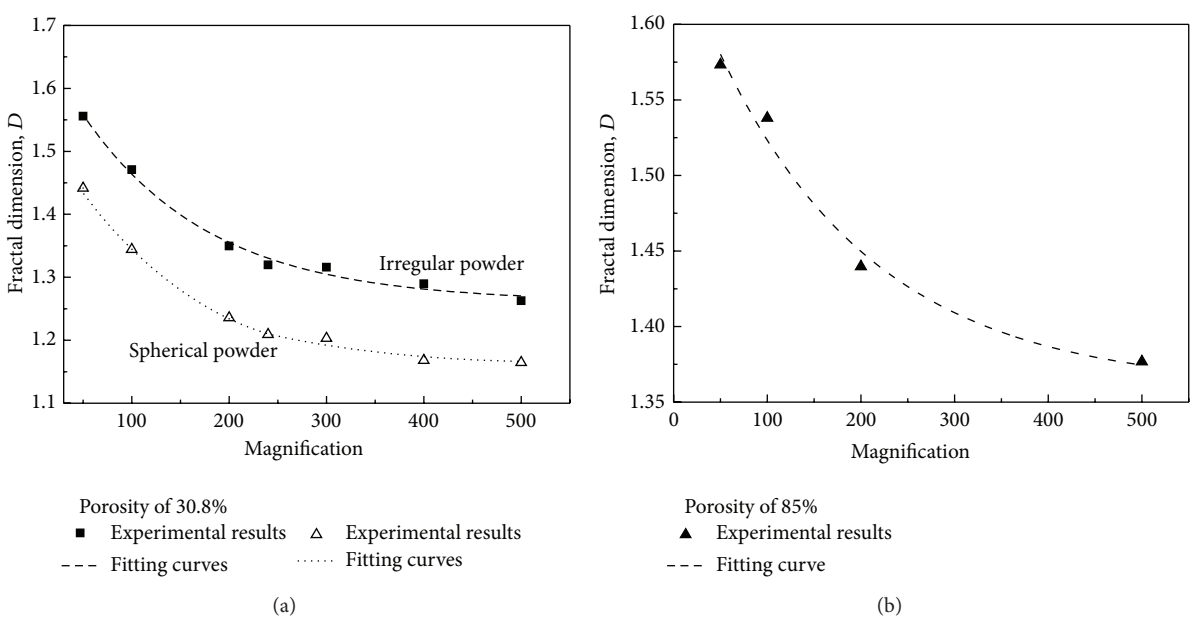


Figure 3: Fractal dimension versus image magnification for (a) porous metal powder materials and (b) porous metal fiber materials.

3.2. Effects of Image Magnification and Powder Morphology on Fractal Dimension. At the same porosity, the quantity of pore decreases slowly as the image magnification increases, so the fractal dimension decreases gradually with the image magnification increasing, shown in Figure 3 [23, 24].

Additionally, for porous metal powder materials (Figure 3(a)), the optimal image magnification ranges from 200 to 500. Furthermore, the relationship between the fractal dimension and the image magnification can be described by [23, 24]

$$D = a_0 \exp\left(-\frac{x}{a_1}\right) + a_2, \quad (2)$$

where x is the image magnification and a_0, a_1, and a_2 are the correlative coefficients.

In addition, it also can be seen from Figure 3(a) that the fractal dimension of pore structure of porous metal materials manufactured by irregular powder is higher than that by spherical powder at the identical image magnification and the same powder particle size.

3.3. Effect of Image Resolution on Fractal Dimension. The fractal dimension is also influenced by the image resolution, shown in Figure 4 [26, 27]. It can be seen from Figure 4 that the fractal dimension at the original image resolution is

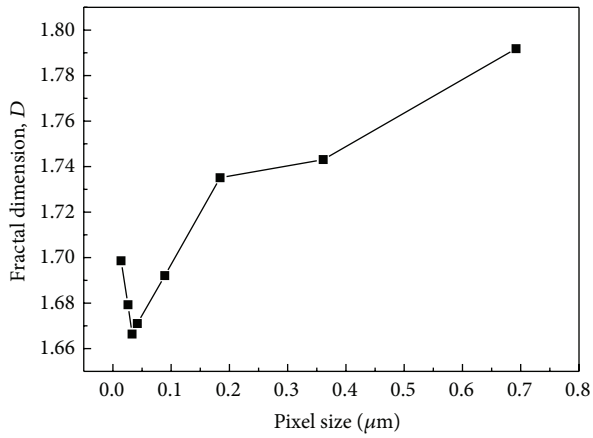


Figure 4: Fractal dimension versus image resolution for porous metal fiber materials.

Table 3: Fractal dimensions of pore structure for different regions chosen.

Porosity/%	73.1%			88.2%		
Region chosen	1	2	3	1	2	3
Fractal dimension/D	1.7609	1.7623	1.7671	1.8241	1.8284	1.8251

the lowest, about 1.665, while it increases gradually with the image resolution increasing or decreasing.

3.4. Effect of Image Region Chosen on Fractal Dimension. The effects of different image regions chosen on the fractal dimensions are shown in Table 3. It can be seen from Table 3 that the difference between the fractal dimensions is very small, lower than 1%, so the fractal dimension is not almost affected by the image region chosen. The results show that the microstructure of porous metal materials is homogeneous.

4. Relationship between the Material Performance and the Fractal Dimension

The performance of porous metal materials is strongly affected by the pore structure. In the paper, the relationships between the mechanical properties, the acoustic properties, the air permeability, and the microresistance of porous metal materials and the fractal dimension were reviewed.

4.1. Relationship between the Mechanical Performance and the Fractal Dimension. The relationships between the compressive strength, the tensile strength, and the fractal dimension are shown in Figure 5 [22, 28]. The results show that the compressive or the tensile strength decreases gradually with the fractal dimension increasing.

For porous metal powder materials, the relationship between the compressive strength and the fractal dimension can be regarded as

$$\sigma_c = a\left(1 - \exp\left(k\left(D - b\right)\right)\right), \tag{3}$$

Table 4: Air permeability (K) of porous metal materials made by irregular powder with the particle size of 44~74 μm.

Fractal dimension	1.2304	1.2515	1.271	1.288	1.298
K_{tested} (m^3/m^2·kPa·h)	14.20	15.30	19.50	30.01	47.90
$K_{\text{calculated}}$ (m^3/m^2·kPa·h)	11.33	13.60	17.73	28.75	46.04
ΔK/%	2.87	1.70	1.77	1.26	1.86

where σ_c is the compressive strength and a, k, and b are the correlative coefficients.

For porous metal fiber materials, the relationship between the tensile strength and the fractal dimension can be regarded as

$$\sigma_b = a - k \cdot D, \tag{4}$$

where σ_b is the tensile strength and a and k are the correlative coefficients.

4.2. Relationship between the Sound Absorbing Performance and the Fractal Dimension. The relationship between the sound absorption coefficients and the fractal dimension is shown in Figure 6 [28]. The results show that the sound absorption coefficients of porous metal fiber materials decrease little by little as the fractal dimension increases.

4.3. Relationship between the Air Permeability and the Fractal Dimension. The relationship between the air permeability and the fractal dimension is shown in Figure 7 [28]. The results show that the air permeability of porous metal fiber materials increases linearly as the fractal dimension increases. In addition, the relationship between the air permeability and the fractal dimension can be presented by

$$K = \frac{C \cdot \left(6.15 d_f \theta^{3.35}\right)^2 \cdot M\left(1 + 1/D\right)\varphi}{16}, \tag{5}$$

where K is the air permeability, C is the Kozeny Carman constant, d_f is the diameter of metal fiber, θ is the volume porosity, φ is the surface porosity, and M is the emendatory coefficient.

According to (5), the air permeability of porous metal powder materials is calculated and the calculated results are in good agreement with the tested ones, shown in Table 4. So the air permeability of porous metal materials can be predicted using (5).

4.4. Relationship between the Microresistance and the Fractal Dimension. The relationship between the microresistance of porous metal materials and the fractal dimension is shown in Figure 8 [29]. The results show that the microresistance increases slowly as the fractal dimension increases.

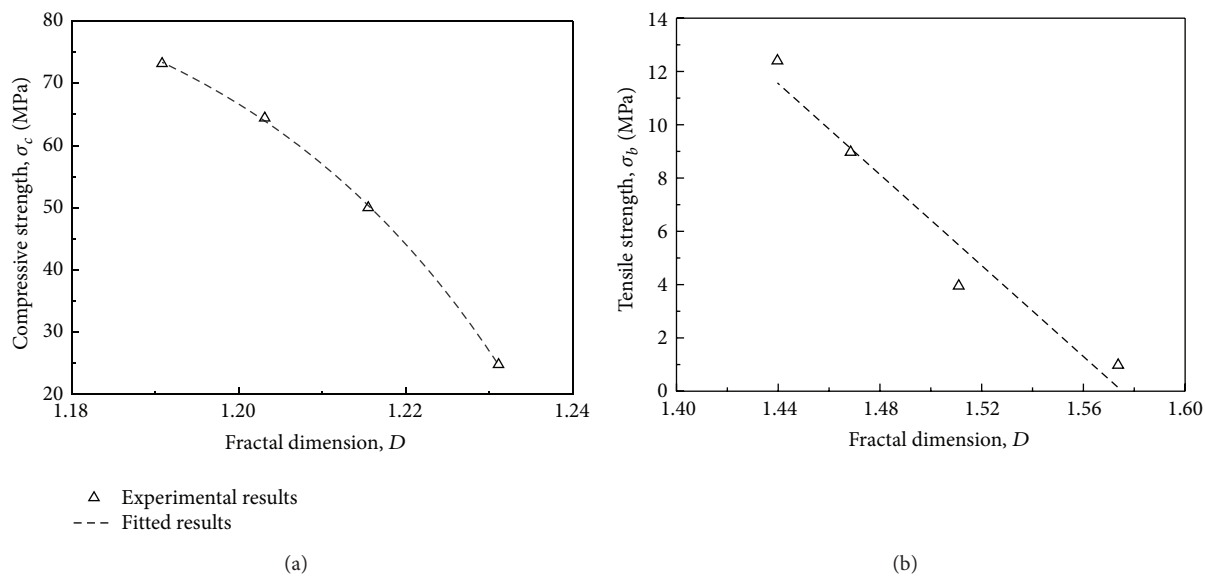


Figure 5: Mechanical properties versus fractal dimension for (a) porous metal powder materials and (b) porous metal fiber materials.

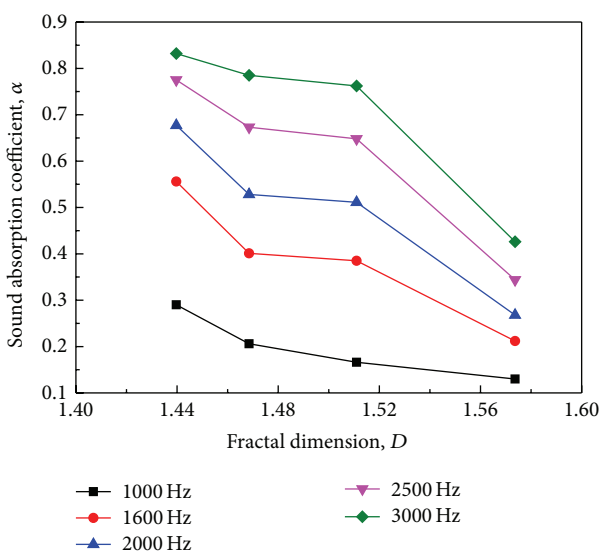


Figure 6: Sound absorption coefficient versus fractal dimension for porous metal fiber materials.

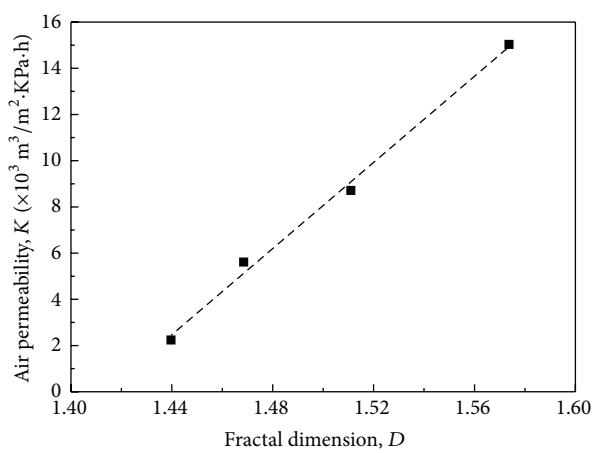


Figure 7: Air permeability versus fractal dimension for porous metal fiber materials.

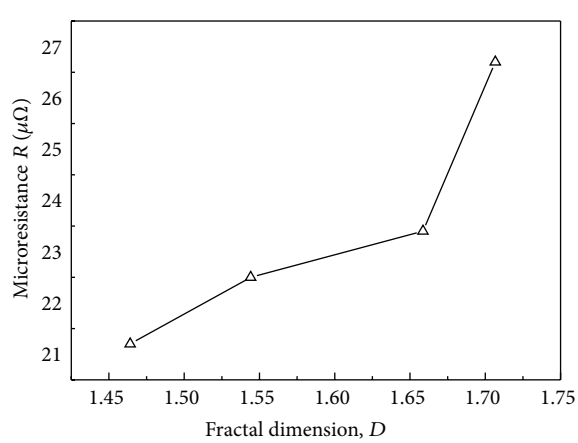


Figure 8: Microresistance versus fractal dimension for porous metal powder materials.

5. Summary and Conclusions

The fractal theory is a promising method for studying the pore structure of porous metal materials. The paper attempts a reasonably comprehensive review about our achievements covering the affecting factors analysis of fractal dimension, the relationships between the fractal dimension and the compressive strength, the tensile strength, the sound absorption coefficient, the air permeability, and the microresistance. Most of the future research on fractal theory application in porous metal materials will be driven by material structure and properties. Furthermore, more accurate description of

pore structure based on the fractal theory is indispensable for optimizing the pore structure for obtaining excellent material performance.

Conflict of Interests

The authors declare that they have no financial and personal relationships with other people or organizations that can inappropriately influence their work, and there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in the paper. In addition, they have no potential conflict of interests regarding each other.

Acknowledgments

Authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (51301141, 51074130) and the Youth Scientific Star Project of Shaanxi Province (2014KJXX-24) and the Opening Project of State Key Laboratory of Explosion Science and Technology (Beijing Institute of Technology) (KFJJ15-02M).

References

[1] A. S. Kulkarni, *Nature of Branching in Disordered Materials*, University of Cincinnati, 2007.

[2] W. Y. Chu, Y. J. Su, K. W. Gao et al., *Fractal in Materials Science*, Chemical Industry Press, Beijing, China, 2004, (Chinese).

[3] B. B. Mandelbrot, *The Fractal Geometry of Nature*, W. H. Freeman and Company, New York, NY, USA, 1977.

[4] B. M. Yu and P. Cheng, "A fractal permeability model for bidispersed porous media," *International Journal of Heat and Mass Transfer*, vol. 45, no. 14, pp. 2983–2993, 2002.

[5] X. H. Tan, X. P. Li, J. Y. Liu, G. D. Zhang, and L. H. Zhang, "Analysis of permeability for transient two-phase flow in fractal porous media," *Journal of Applied Physics*, vol. 115, no. 11, pp. 113502–113507, 2014.

[6] Q. Zheng and B. Yu, "A fractal permeability model for gas flow through dual-porosity media," *Journal of Applied Physics*, vol. 111, no. 2, Article ID 024316, 2012.

[7] L. Ma and R. He, "Steady-state gas diffusion in fractal porous media," *Journal of Tsinghua University (Science and Technology)*, vol. 53, no. 10, pp. 1459–1463, 2013 (Chinese).

[8] M. Liang and H. Rong, "Unsteady state gas diffusion in fractal porous media," *CIESC Journal*, vol. 64, no. 9, pp. 3139–3144, 2013 (Chinese).

[9] J. C. Cai, "A fractal approach to low velocity non-Darcy flow in a low permeability porous medium," *Chinese Physics B*, vol. 23, no. 4, Article ID 044701, 2014.

[10] Y. Ju, Q. G. Zhang, Y. M. Yang, H. P. Xie, F. Gao, and H. J. Wang, "An experimental investigation on the mechanism of fluid flow through single rough fracture of rock," *Science China Technological Sciences*, vol. 56, no. 8, pp. 2070–2080, 2013.

[11] A. Vinogradov, I. S. Yasnikov, and Y. Estrin, "Stochastic dislocation kinetics and fractal structures in deforming metals probed by acoustic emission and surface topography measurements," *Journal of Applied Physics*, vol. 115, no. 23, pp. 233506–233515, 2014.

[12] T. Furusato, T. Ihara, S. Kameda et al., "Fractal analysis of positive pulsed streamer patterns in supercritical carbon dioxide," *IEEE Transactions on Plasma Science*, vol. 40, no. 10, pp. 2425–2430, 2012.

[13] W. J. Yuan, Q. Y. Zhu, C. J. Deng, and H. X. Zhu, "Fractal analysis of fracture surfaces in refractories," *China's Refractories*, no. 1, pp. 27–31, 2014.

[14] M. Z. Gao, W. C. Jin, Z. X. Dai, and J. Xie, "Relevance between abutment pressure and fractal dimension of crack network induced by mining," *International Journal of Mining Science and Technology*, vol. 23, no. 6, pp. 925–930, 2013.

[15] Q. Xu, J. Y. Chen, J. Li, and M. M. Wang, "Multi-scale numerical model for simulating concrete material based on fractal theory," *Acta Mechanica Solida Sinica*, vol. 26, no. 4, pp. 344–352, 2013.

[16] Z. X. Luo, Y. Wang, G. L. Ma et al., "Possible causes of the variation in fractal dimension of the perimeter during the tropical cyclone Dan motion," *Science China: Earth Sciences*, vol. 57, no. 6, pp. 1383–1392, 2014.

[17] B. Q. Xiao, Y. Yang, and X. F. Xu, "Subcooled pool boiling heat transfer in fractal nanofluids: a novel analytical model," *Chinese Physics B*, vol. 23, no. 2, Article ID 026601, 2014.

[18] F. L. Zhu, S. Z. Cui, and B. H. Gu, "Fractal analysis for effective thermal conductivity of random fibrous porous materials," *Physics Letters A*, vol. 374, no. 43, pp. 4411–4414, 2010.

[19] H. P. Tang, J. L. Zhu, Z. P. Xi, X. B. Di, J. Y. Wang, and Q. B. Ao, "Impact factors of fractal analysis of porous structure," *Science China Technological Sciences*, vol. 53, no. 2, pp. 348–351, 2010.

[20] N. Chawla and X. Deng, "Microstructure and mechanical behavior of porous sintered steels," *Materials Science and Engineering A*, vol. 390, no. 1-2, pp. 98–112, 2005.

[21] P. Beiss and M. Dalgic, "Structure property relationships in porous sintered steels," *Materials Chemistry and Physics*, vol. 67, no. 1–3, pp. 37–42, 2001.

[22] J. Z. Wang, H. P. Tang, J. L. Zhu, Q. B. Ao, H. Zhi, and J. Ma, "Relationship between compressive strength and fractal dimension of pore structure," *Rare Metal Materials and Engineering*, vol. 42, no. 12, pp. 2433–2436, 2013.

[23] J. Z. Wang, Z. P. Xi, H. P. Tang, W. D. Huang, J. L. Zhu, and Q. B. Ao, "Fractal dimension for porous metal materials of FeCrAl fiber," *Transactions of Nonferrous Metals Society of China*, vol. 23, no. 4, pp. 1046–1051, 2013.

[24] H. P. Tang, J. Z. Wang, J. L. Zhu et al., "Fractal dimension of pore-structure of porous metal materials made by stainless steel powder," *Powder Technology*, vol. 217, pp. 383–387, 2012.

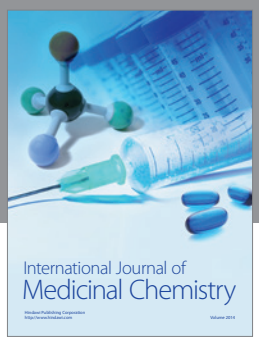
[25] X. B. Di, Z. P. Xi, H. P. Tang, and J. L. Zhu, "Analysis of pore-structure by fractal in sintered porous stainless steel fibres," *Rare Metal Materials and Engineering*, vol. 36, supplement 3, pp. S571–S573, 2007.

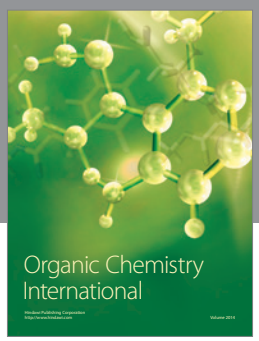
[26] H. P. Tang, J. L. Zhu, Z. P. Xi, X. B. Di, J. Y. Wang, and Q. B. Ao, "Impact factors of fractal analysis of porous structure," *Science China Technological Sciences*, vol. 53, no. 2, pp. 348–351, 2010.

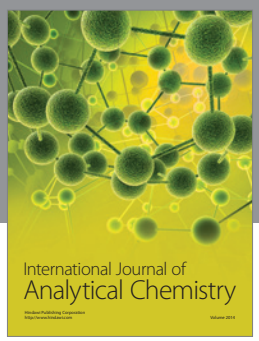
[27] X. B. Di, *Research on Pore-Structure Fractal Characterization in Porous Metals*, Northeastern University, Shenyang, China, 2008, (Chinese).

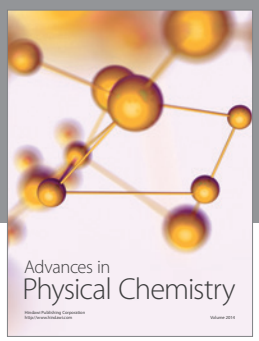
[28] H.-P. Tang, J.-Z. Wang, Q.-B. Ao, and H. Zhi, "Effect of pore structure on performance of porous metal fiber materials," *Rare Metal Materials and Engineering*. In press.

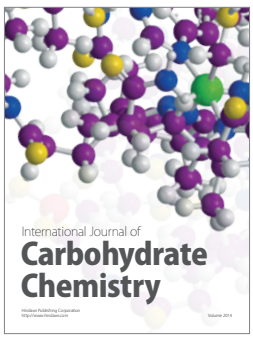
[29] C. Li, H. P. Tang, J. L. Zhu, Q. B. Ao, and H. Zhi, "Fractal characterization of ultra-thin porous Ti plate," *Heat Treatment of Metals*, vol. 36, no. 10, pp. 15–18, 2011.











Hindawi

Submit your manuscripts at
http://www.hindawi.com