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Research on Fractal Feature of Wear Surface Topography Based on Gray Images of Rubber Surfaces

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Abstract Abrasion performance is an important index for evaluating the performance of rubber products. The surface morphologies of rubber composites under different temperatures and loads were characterized based on fractal theory. The abrasion performance and characteristics of the surface morphology of rubber were investigated. Images of surface morphology of rubber samples were collected by a 3D measuring laser microscope and converted to black-and-white binary images. Based on the multifractal model, the relationship between the experimental conditions and the characteristic parameters of the abrasion surfaces, such as the width of multifractal spectrum $\Delta\alpha$, the change in the multifractal spectrum $\Delta f(\alpha)$, wave length, wave height and the root mean square deviation of the outline were quantitatively analyzed. The results show that abrasion volume increased as the temperature increased. Similarly, abrasion volume increased as load increased. As the temperature or the load increases, the abrasion of the rubber surface increases in intensity and volume, the abrasion surface becomes more uneven, and the abrasive grain becomes more complex. The characteristic parameters, such as the wave length and wave height of the abrasive grain, the arithmetic mean deviation of the outline, the root mean square deviation of the outline and the 3D arithmetic mean deviation, increase in certain regularity.

Keywords Fractal theory · Rubber abrasion · Surface morphology · Multifractal spectrum curve

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1 Aims and Background

Abrasion performance is an important index for evaluating the performance of rubber products; it is not only connected to physical and mechanical properties, but also closely associated with factors such as working loads and temperatures. However, commonly used methods of abrasion evaluation ignore the working condition and abrasion surface morphology of rubber, which are crucial factors in the comprehensive evaluation of rubber abrasion properties. This thesis focuses on the investigation of rubber surface properties under different loads and temperatures, uses fractal theory to describe the complex morphology of rubber abrasion surfaces, and conducts a qualitative and quantitative analysis of the macroscopic characteristics and microstructure of rubber composite abrasion surfaces.

Many research studies have focused on the abrasion mechanism of rubber. In 1958, Schallamach [1, 2] found that when relative slip existed between smooth rubber and a hard smooth surface, a series of ridges formed (called the Schallamach abrasion pattern) that were perpendicular to the sliding direction and mutually parallel and that moved with the extension of cracking. In studies of rubber composites, Schallamach and Grosch [3–5] found a positive correlation between the abrasion volume and the reciprocal of its damage energy density. Persson [6, 7] established an elastic and plastic friction contact theory between rubber and a rough road surface. Southern and Thomas [8] proposed a fatigue abrasion theory combined with abrasion and fracture mechanics. Muro [9] established the correlation between the rate of abrasion and contact pressure.

Xu and Karger-Kocsis [10], as well as Bhattacharya and Bhowmick [11] tested abrasion properties of rubber composites with different fillers (nano-carbon black, alumina, etc.) and base materials (natural rubber, silicone rubber, etc.), and employed an atomic force microscope and a scanning electron microscope to investigate the abrasion surfaces, but did not take into account the influence of temperature on abrasion properties. The depth and breadth of research has improved from the preliminary explorations of abrasion patterns to more recent studies of abrasion properties that incorporate the methods of mechanics and material science. However, the research work described above focused on the results of abrasion without considering the abundant information about surfaces in the process of abrasion and the important effect of temperature on abrasion performance. Rubber products are frequently used at high temperatures. Due to periodic hysteresis loss, the temperature of a tire shoulder can reach 100 °C, and the temperature of a tire crown reaches 70–80 °C in the rolling process. Compared to room temperature, tire rubber properties change significantly when the tire is at a high temperature for a long time. When studying the price fluctuation of stock in 1974, Mandelbrot [12, 13] found a certain self-similarity in the wave scale of the stock price, and proposed the fractal theory. Fractal theory is widely applied to characterize and analyze the constitutive relations between the part and the whole of an irregular shape. Ge and Zhu [14, 15] applied fractal theory to study abrasion surfaces, introducing a new concept of fractal parameters of characteristic roughness and a fractal interpolation theory of a rough surface profile, and established a prediction model for the fractal parameters of abrasion surfaces. The abrasion surfaces of rubber have the fractal characteristics of randomness and multi-scale properties. Therefore, fractal theory can be used to describe and evaluate the morphology characteristics of rubber abrasion surfaces.

Abrasion testing instruments are designed for measuring the abrasion value under different loads and temperatures. The 3D measuring laser microscope is used to characterize abrasion surface morphology and obtain the microstructure parameters of rubber samples. The computer program processes images of rubber surface morphology, and analyzes the multifractal spectrum. This paper studied the microstructure characteristics of rubber sample surfaces under different experimental conditions, comparing the variation of abrasion volume, analytical results of fractal theory and the characteristics of abrasion surface morphology parameters, which can directly reflect the abrasion properties and characteristics of rubber surfaces under high temperature.

2 Experimental

2.1 Experimental Materials

The tread rubber of an all-steel radial tire with the following composition was used:

Hainan smoke sheet rubber, N330 carbon black, white carbon black, ZnO, steric acid (SA), plasticizer, Antioxidant RD, Antioxidant 6PPD, Silane coupling agent, accelerant NOBS, and sulphur. All materials listed were available industrial products.

2.2 Experimental Instruments

The experimental equipment included a rubber mixer (XSM-500), roll mill (BL-6175-BL), plate vulcanizing apparatus (HS-100T-FTMO-2PT), rotorless curemeters (GT-M2000-A), densimeter (GT-XS-365M), double end grinding machine (MZ-4101), 3D measuring laser microscope (LEXT OLS4100) and a new type of abrasion tester that is designed for more realistic abrasion studies.

2.3 Experimental Procedure

1. Rubber samples were prepared and pasted to heatable wheels. They were placed in the vulkameter for 2.5 h at 115 °C, and then cooled for 24 h at room temperature.
2. The rubber wheel was installed on the rubber abrasion tester. After the experimental temperature and load were set, the heating system heated the wheel.
3. The rubber abrasion tester was run for 500 revolutions for pre-grinding, then turned off. The rubber wheel was taken off the tester and cleaned. The total mass of the rubber wheel and rubber scrip was measured and recorded as m_1.
4. The rubber wheel was installed on the tester again. The test was continued for 1709 revolutions (500 m). The rubber wheel was taken off the tester, cleaned, and weighed; this measurement was recorded as m_2.
5. The density ρ of rubber was measured. The abrasion volume was calculated according to the following formula:

$$V = (m_1 - m_2)/r \tag{1}$$

V—abrasion volume of samples, cm^3. m_1—mass of samples after pre-grinding, g. m_2—mass of samples after test, g. ρ—density of samples, g/cm^3.

3 Experimental Results

Abrasion volumes were calculated for samples under different experimental conditions, as shown in Table 1.

As Table 1 indicates, the abrasion volume of rubber grew with the increase of temperature: abrasion volume at 80 °C > abrasion volume at 60 °C > abrasion volume at 25 °C. Abrasion volume also grew as load increased: abrasion volume under 37.38 N > abrasion volume under 32.04 N > abrasion volume under 26.70 N.

4 Results and Discussion

4.1 Fractal Theory

Multifractal distribution is used to describe the uneven random probability distribution of fractal geometry at different levels. The box-counting method is used in the multifractal spectrum to analyze and characterize surface morphology. The statement $\Delta\alpha = \alpha_{max} - \alpha_{min}$ defines the disorder of probability measures in the overall fractal area and the complexity of the surfaces, and characterizes the wave. A larger value of $\Delta\alpha$ corresponds to a less uniform rubber surface, more dispersed distribution of surface height, rougher abrasion surface, and more severe abrasion.

Because of the direct correspondence between α and $f(\alpha)$, a dimension spectrum called the multifractal spectrum is used to describe the multifractal properties. By definition, $\Delta f(\alpha) = f(\alpha_{min}) - f(\alpha_{max})$. The complexity and irregularity of the abrasion surfaces are mainly shown by $\Delta f(\alpha)$. When $\Delta f(\alpha) > 0$, the multifractal spectrum curve is left-hook-shaped, so the subset of maximum probability numbers is smaller than the subset of minimum probability numbers. Thus, most of the abrasion surface is valley with the relatively lower height. When $\Delta f(\alpha) < 0$, the multifractal spectrum curve is right-hook-shaped, so the subset of maximum probability numbers is larger than the subset of minimum probability numbers. Hence, most of the abrasion surface is peak with relatively higher height. When $\Delta f(\alpha) = 0$, the multifractal spectrum curve is symmetric, so the subset of maximum probability numbers is equivalent to the subset of minimum probability numbers. The peaks and valleys are equal in area. Therefore, the physical significance of the multifractal spectrum is to measure the degree of complexity, irregularity and uniformity of the fractal structure of the studied object [16].

Based on the box-counting method, a program for multifractal spectrum analysis was written in the Matlab environment to analyze the abrasion surface images collected by the

Table 1 The rubber strip abrasion results

Temperature (°C)	Load (N)	Angle (°)	P (g/cm^3)	m_1 (g)	m_2 (g)	Δm (g)	ΔV (cm^3)
25	26.70	15	1.124	71.727	71.425	0.302	0.2687
25	32.04	15	1.113	68.990	68.674	0.316	0.2839
25	37.38	15	1.124	70.541	70.201	0.340	0.3025
60	26.70	15	1.123	79.886	79.543	0.343	0.3054
80	26.70	15	1.121	71.462	71.030	0.432	0.3854

3D measuring laser microscope. The multifractal spectrum α–$f(\alpha)$ curve and related parameters were obtained. The paper [17] was used as a reference for detailed analysis of the principle.

4.2 Research and Analysis of Abrasion Mechanism Based on Fractal Theory

Abrasion tests of rubber samples under different temperatures and loads were conducted by a high-temperature abrasion tester. Images of the surface morphology of the rubber samples were collected by the 3D measuring laser microscope and converted to black-and-white binary images. Based on fractal theory, the abrasion surface morphology data were analyzed to obtain the multifractal spectrum α–$f(\alpha)$ curves.

4.3 The Effect of Temperature on the Surface Morphology of Rubber Samples

Under the working conditions of a 15° angle, $^{\#}$40 granularity, and 26.70 N load, the rubber abrasion experiment was conducted at 25, 60, 80 °C. The 2D and 3D images captured by OLS4100 of the abrasion surface of rubber are shown in Fig. 1.

Figure 2 shows that the multifractal spectrum α–$f(\alpha)$ curves are convex functions related to α, with varying degrees of left-hook-shape. It means that more pixel points of fractal phenomenon deposit in low position. The "valleys" of rubber abrasion surface occupy a bigger probability. The abrasion pattern is relatively steep. The opening sizes of the curves vary under different temperatures, indicating different multifractal spectrum widths $\Delta\alpha$ and different degrees of abrasion.

Under the working conditions of a 15° angle, $^{\#}$40 granularity, and 26.70 N load, values of $\Delta\alpha$ and $\Delta f(\alpha)$ were calculated at different temperatures, as shown in Table 2.

Table 2 indicates that with the increase of temperature, $\Delta\alpha$ increased, the surface height became more heterogeneous, abrasive cracks became more complex, and abrasion of the rubber surface became more pronounced. The abrasion volume also grew as the load increased, according to the following relationships: abrasion volume at 80 °C > abrasion volume at 60 °C > abrasion volume at 25 °C. The results of the analysis are consistent with experimental results.

4.4 The Effect of Load on the Surface Morphology of Rubber Samples

Under the working conditions of a 15° angle, $^{\#}$40 granularity, and 25 °C, the rubber abrasion experiment was conducted under the loads of 26.70, 32.04 N, and 37.38 N. The 2D and 3D images of the abrasion surfaces of the rubber samples captured by OLS4100 are shown in Fig. 3.

The images above were analyzed with the multifractal spectrum method to obtain the multifractal spectrum α–$f(\alpha)$ curves, which are shown in Fig. 4.

Figure 4 shows that the multifractal spectrum α–$f(\alpha)$ curves are convex function related to α with left-hook-shaped. It means that more pixel points of fractal phenomenon deposit in low position. The "valleys" of rubber abrasion surface occupy a bigger probability. And the abrasion pattern is relatively steep. The opening sizes of the curves varies under different loads, indicating different values of multifractal spectrum width $\Delta\alpha$ and different dregrees of abrasion.

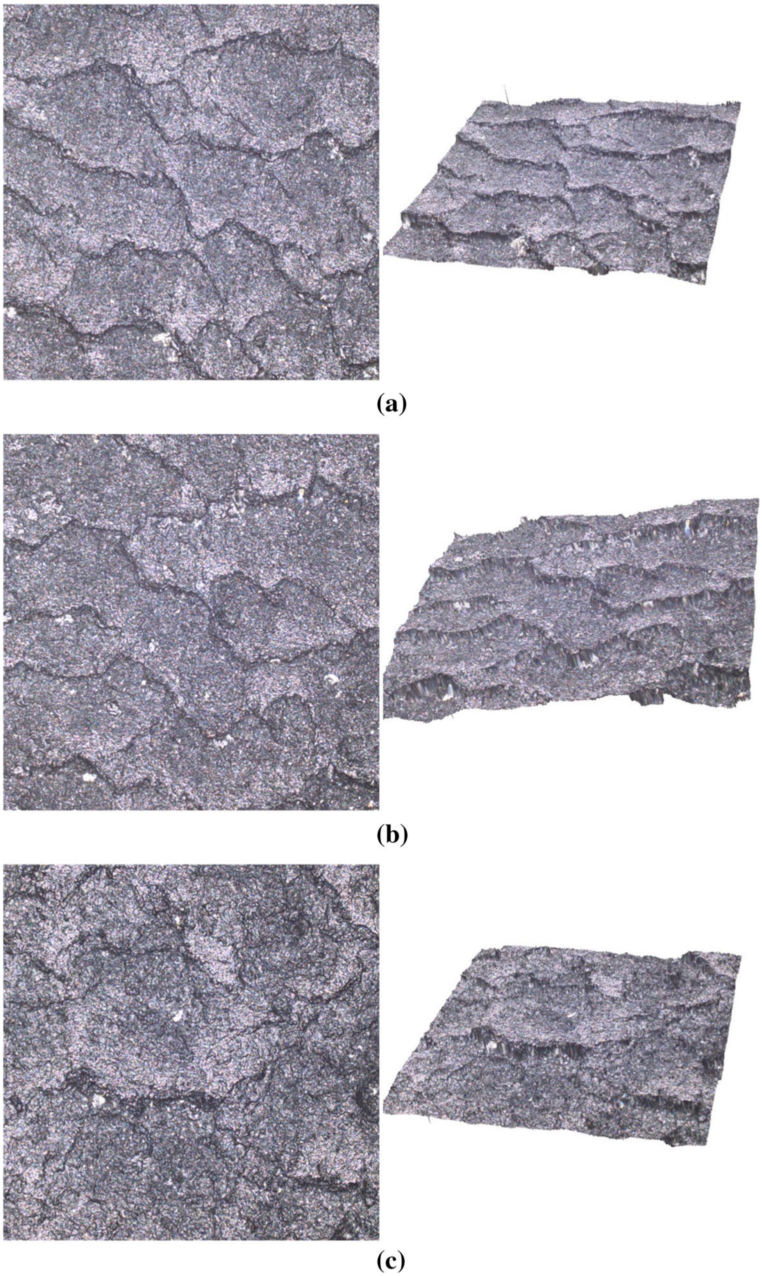


Fig. 1 2D and 3D microscope images of abrasion surface at different temperatures
The images shown above were analyzed with the multifractal spectrum method to obtain the multifractal spectrum α–$f(\alpha)$ curves shown in Fig. 2. **a** 25°C, **b** 60°C, **c** 80 °C

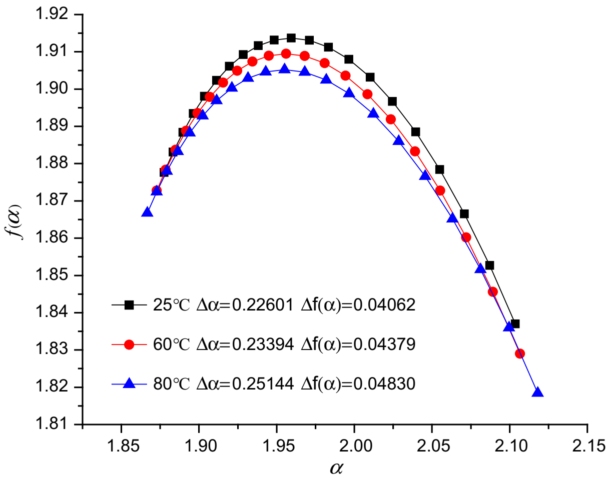


Fig. 2 α–$f(\alpha)$ curves under different temperatures

Table 2 The parameter values of the multifractal spectrum α–f(α) curves

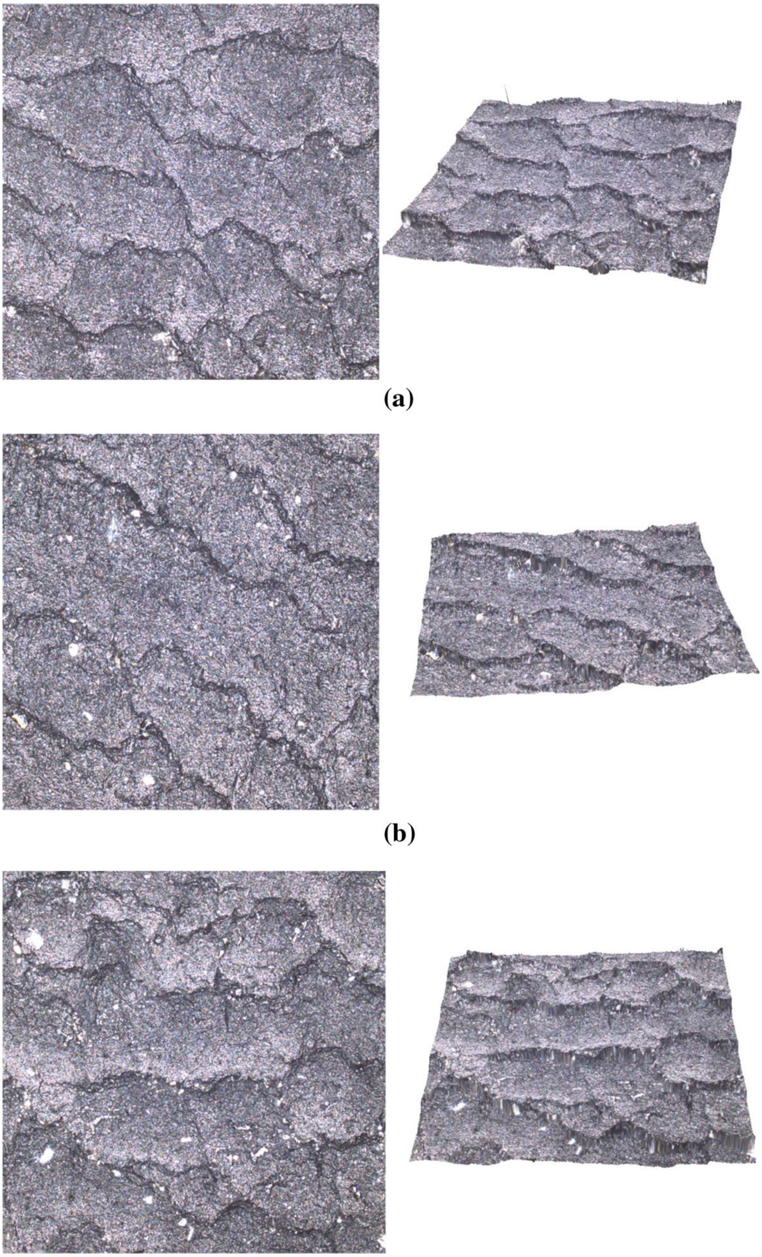
Temperature (°C)	α_{min}	α_{max}	$\Delta\alpha$	$f(\alpha_{min})$	$f(\alpha_{max})$	$\Delta f(\alpha)$
25	1.87761	2.10363	0.22601	1.83700	1.91369	0.04062
60	1.87276	2.10670	0.23394	1.82897	1.90947	0.04379
80	1.86671	2.11815	0.25144	1.818 41	1.90521	0.04830

Under the working conditions of a 15° angle, #40 granularity, and 25 °C temperature, the values of $\Delta\alpha$ and $\Delta f(\alpha)$ for different loads are shown in Table 3.

Table 3 depicts that with the increase of load, $\Delta\alpha$ increased, the surface height became more heterogeneous, the abrasive grain became more complex, and the abrasion of the rubber surface became more pronounced. The abrasion volume increased as the load increased, according to the following relationships: abrasion volume at 37.38 N > abrasion volume at 32.04 N > abrasion volume at 26.70 N. The analytical result is consistent with the experimental result.

4.5 Study of the Surface Outline of the Rubber Samples

The wavelength of an abrasive crack is the horizontal distance between two continuous troughs (as shown in Fig. 5, line BC). The wave height is the smaller one of the two vertical distances between the two continuous troughs and the middle peak (as shown in Fig. 5, line DE). The characteristic parameters of abrasion surfaces, such as the wave length and wave height of the abrasive grain, the arithmetic mean deviation of the outline, the root mean square deviation of the outline and the 3D arithmetic mean deviation, were studied. The effects of temperature and load on the surface morphology and properties of rubber were analyzed.



(a)

(b)

(c)

Fig. 3 2D and 3D microscope images of abrasion surfaces under different loads. **a** 26.70 N, **b** 32.04 N and **c** 37.38 N

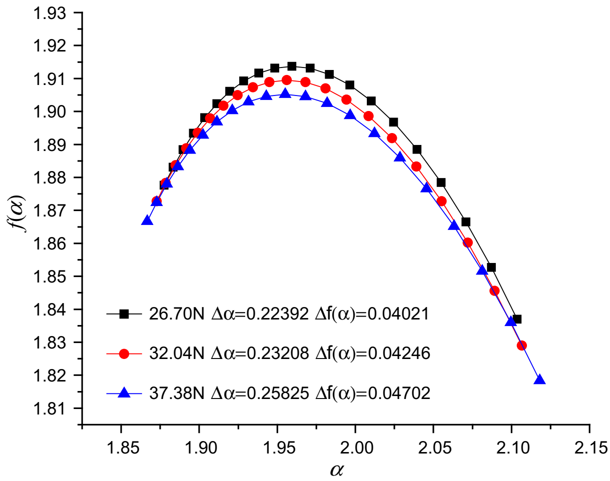


Fig. 4 α–$f(\alpha)$ curves under different loads

Table 3 The parameter values of the multifractal spectrum α–$f(\alpha)$ curves

Load (N)	α_{min}	α_{max}	$\Delta\alpha$	$f(\alpha_{min})$	$f(\alpha_{max})$	$\Delta f(\alpha)$
26.70	1.88417	2.10809	0.22392	1.84516	1.92024	0.04021
32.04	1.87472	2.10680	0.23208	1.83338	1.91191	0.04246
37.38	1.86260	2.12085	0.25825	1.81558	1.90266	0.04702

4.6 The Effect of Temperature on the Surface Contour Curves of Rubber Samples

Under the working conditions of a 15° angle, #40 granularity, and 26.70 N load, rubber abrasion was tested under different temperatures (25, 60, 80 °C). The surface contour curves of the rubber captured by OLS4100 are shown in Fig. 5 and the characteristic parameters are shown in Table 4.

Figure 5 and Table 4 depict that with the increase of temperature, the abrasion of the rubber surface became more pronounced, while the wave length and wave height of abrasive cracks, R_a, R_q and S_a increased with certain regularity.

4.7 The Effect of Load on the Surface Contour Curves of Rubber Samples

Under the working conditions of a 15° angle, #40 granularity, and 25 °C, the rubber abrasion was tested under loads of 26.70, 32.04 and 37.38 N. The surface contour curves of the rubber captured by OLS4100 are shown in Fig. 6 and the characteristic parameters are shown in Table 5.

Figure 6 and Table 5 depict that with the increase of load, the abrasion of the rubber surface became more pronounced, while the wave length and wave height of the abrasive grain, R_a, R_q and S_a increased with certain regularity.

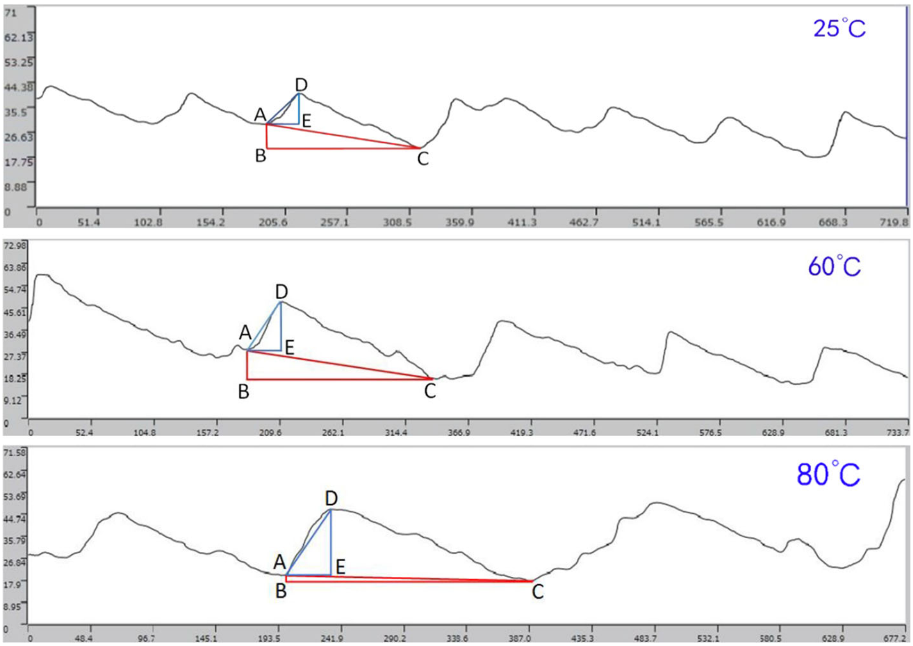


Fig. 5 The abrasion surface contour curves under different temperatures

Table 4 The surface profile parameters under different temperatures

Temperature (°C)	Wave length (μm)	Wave height (μm)	R_a (μm)	R_q (μm)	S_a (μm)
25	131.354	12.624	1.037	1.308	1.368
60	154.819	19.685	1.091	1.436	1.445
80	189.092	25.725	1.452	2.006	1.621

4.8 Experimental Results and Analysis

Both abrasion volume measurement and the multifractal spectrum method were applied to explore the abrasion properties of rubber at different angles. The results have a high degree of consistency. The abrasion properties of rubber under different temperatures and loads were qualitatively and quantitatively analyzed.

Temperature influences the abrasion properties of rubber. The intensity of the thermal movement of molecules varies with the temperature. Temperature influences the strength, elastic modulus and viscoelasticity of rubber, and affects the abrasion properties and the characteristics of abrasion surface morphology of rubber. With the increase of temperature, the thermal movement of molecules becomes more rapid, the intermolecular force weakens, the cohesive energy decreases, the tensile strength and tear strength of rubber decrease, the abrasion properties of rubber degrades, the abrasion of the rubber surface becomes more pronounced, and the abrasion surface becomes rougher. The abrasion volume, wave length, wave height, R_a, R_q and S_a increase with certain regularity as temperature increases.

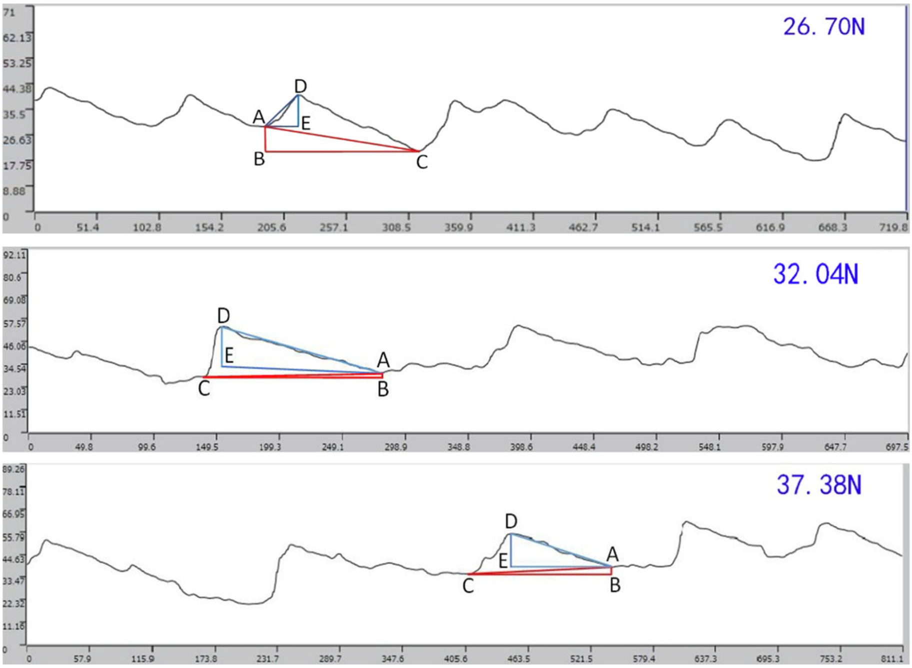


Fig. 6 The abrasion surface contour curves under different loads

Table 5 The surface profile parameters under different loads

Load (N)	Wave length (μm)	Wave height (μm)	R_a (μm)	R_q (μm)	S_a (μm)
27.70 N	131.354	12.624	1.037	1.308	1.368
32.04 N	145.648	16.828	1.112	1.463	1.445
37.38 N	151.320	18.478	1.291	1.626	1.589

Load also has a significant impact on the abrasion properties of rubber. The pressure applied to rubber varies with load and determines the amount of friction on the rubber surface and the abrasion volume. When the load is below the critical value, no abrasion pattern is observed. At this time, it's adhesive abrasion that abrasion rate is low. When the load exceeds the critical load, a series of parallel abrasion patterns are generated on the abrasion surface, perpendicular to the sliding direction. The experimental results show that the experimental loads were larger than the critical load. With the increase of load, the friction on the rubber surface increased and the trend of adhesive abrasion and the capacity of crack extension increased, so the abrasion properties of rubber degrades, the abrasion of the rubber surface became more pronounced, and the abrasion surface became rougher. The abrasion volume, wave length, wave height, R_a, R_q and S_a increased with certain regularity.

5 Conclusions

The abrasion properties of rubber samples under different temperatures and loads were tested. The experimental results were qualitatively and quantitatively analyzed based on the fractal theory and the multifractal spectrum method. The results show that:

1. The rubber abrasion surface has obvious fractal characteristics. Fractal theory can be used as an effective method to describe the abrasion surface of rubber. The characteristic parameters can be applied to quantitatively describe the abrasion properties. This improves upon previous methods by producing a more comprehensive and accurate evaluation of the abrasion properties of rubber.
2. The value of $\Delta\alpha$ is an effective parameter for investigating the roughness of a rubber abrasion surface. The observation that $\Delta\alpha$ increases with increasing temperature indicates that as the abrasion temperature increases, the abrasion of the rubber surface becomes more pronounced, the surface becomes rougher, the abrasion surface becomes more uneven, and the abrasive crack becomes more complex.
3. The characteristic parameters of abrasion surfaces present a certain regularity: with the increase of temperature or load, the molecular chains of rubber are broken more easily, the surface abrasion debris falls off more easily, the abrasion surface becomes rougher, the abrasion pattern becomes more prominent, and the wave length and wave height of abrasive cracks, R_a, R_q and S_a increase with certain regularity.
4. The experimental results show that temperature and load have significant impact on the abrasion properties of rubber. Based on the abrasion volume, it can conclude that the abrasion properties of rubber exhibit obvious regularity under different temperatures and loads.

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