Research on fatigue failure mode and failure theory of rubber

Zhanbin Wang

1 AECC Beijing Institute of Aeronautical Materials, Beijing 100095, China
2 Failure Analysis Center of Aviation Industry Corporation of China, Beijing 100095, China
3 Beijing Key Laboratory of Aeronautical Materials Testing and Evaluation, Beijing 100095, China

a284495778@qq.com, b zhanbin.wang@biam.ac.cn

Abstract. The rubber products are usually used in the condition of periodically complicated stresses, and their anti-fatigue function is simultaneously dependent on their viscoelasticity and the emergence and propagation of cracks directly effecting on the life of rubber products. Therefore, the research on fatigue failure of rubber products has important significance to improve their durability and safety. The research on fatigue failure of rubber has important significance to improve the durability and safety of rubber products. The fatigue failure mechanism of natural rubber was explained from the point of molecular motion theory and phenomenological theory. The application of test research methods in the study of rubber fatigue microstructure and the influence of environmental factors on the fatigue properties of natural rubber were studied, and the future development direction of natural rubber fatigue was also forecasted.

1. Introduction

As the only widely used non-synthetic elastomer, natural rubber has very unique physical and chemical properties, high elasticity, wear resistance, flexural resistance and other advantages make it able to withstand a large strain and will not lead to permanent deformation and fracture. It is widely used in producing vibration isolators, elastic bearings, tires, seals, gaskets and other products [1-4]. In general, rubber products mostly served under the condition of cyclic loading, it is easy to produce fatigue failure under the action of cyclic stress, vibration and currently about 90% since the elasticity of the products are natural rubber or natural rubber and other rubber and plastic, so the fatigue properties of natural rubber directly relational columns vibration function failure or not and all kinds of equipment running status. Therefore, it is very important to study the fatigue characteristics of natural rubber to improve the safety and reliability of rubber products.

As early as the middle of the 20th century, Mullins, Gent et al. [5-6] started to study the situation of crack nucleation and propagation in rubber fatigue process using fracture mechanics theory, but it was only limited to uniaxial fatigue analysis. After decades of development, the application of rubber components has become more and more extensive, and the working environment has become more and more complex, which may be subjected to the repeated action of multi-axial stress at the same time. Due to the complexity of natural rubber structure, packing, processing technology, working environment and other factors will affect its mechanical properties, which increases the difficulty of rubber multi-axial fatigue performance and failure mechanism research. It was not until the beginning
of this century [7-8] that the research on rubber multiaxial cyclic stress fatigue really began. In just over ten years, great progress has been made in both experimental research methods and theoretical explanations, but more in-depth discussion is still needed.

In this paper, the causes of fatigue failure of rubber based on molecular kinematics and phenomenology are reviewed. The application of experimental research methods in the study of rubber fatigue microstructure, the influence of environmental factors on the fatigue properties of rubber and the main characteristics of fatigue fracture morphology are described emphatically. In addition, the development direction of rubber fatigue problems in the future is prospected.

2. Fatigue failure mechanism of rubber

At present, the research on rubber fatigue failure mechanism is still in the initial stage, mainly including mechanical failure theory, thermal fatigue theory and mechanical theory [9-10].

2.1 Mechanical failure theory

According to mechanical failure theory, rubber fatigue is not a chemical reaction process, but the mechanical force applied to rubber makes its structure and properties change, and finally leads to its fatigue failure. The chemical reaction occurring in the fatigue process of rubber can only be regarded as one of the factors affecting the fatigue properties of rubber. The theory divides rubber fatigue into three stages: the first stage, the stress and deformation decrease sharply after bearing the load (stress softening phenomenon); In the second stage, the change of stress or deformation is slow, and the rupture core stage occurs on the surface or inside. In the third stage, the ruptured nucleus increases until the global destruction stage (destruction phenomenon).

2.2 Thermal fatigue theory

According to thermal fatigue theory, rubber products under long-term dynamic load, internal molecular chain friction heat, resulting in a sharp rise in the internal temperature, thermal oxygen aging, and fatigue failure.

2.3 Mechanical theory

According to the mechanical theory, the fatigue process of rubber is a chemical reaction process under the action of force, which is mainly an active oxidation process under the action of force. The molecular chain of rubber material is broken by mechanical force in the fatigue process, and the resulting free radicals react with oxygen to trigger oxidative aging, resulting in molecular chain fracture, and then micro-cracks are generated, which gradually expand with time.

3. Fatigue failure causes of rubber

Fatigue damage of rubber material refers to the phenomenon that the physical and mechanical properties of the material are decreased under the action of periodic deformation or external force. Fatigue crack growth and wear are two important forms of fatigue failure of rubber products. The former is that the crack continues to expand until the component breaks under the action of external force, and the latter is the damage directly caused by sliding friction. At present, there are mainly two theories to explain the fatigue failure of rubber: molecular kinematics theory and phenomenology theory [11].

3.1 Kinetic theory of molecules

According to molecular kinematic theory, the fracture of chemical bonds is the main cause of rubber fatigue failure. Under the action of dynamic load, the stress concentrates on the weak bond parts of the sample, resulting in micro-cracks. The micro-cracks continue to expand until the fracture under the action of external force, which is a viscoelastic non-equilibrium process of continuous fracture of molecular chain, showing a strong time-temperature effect. The rubber molecular chains were aligned along the stress direction, and part of the chain structure gradually changed from the previous network
to a straight line. Due to the non-uniformity of the network structure, the non-uniform load of each part was directly caused. A small strain is not enough to break the molecular chain. With the increase of strain, the most fragile network chain breaks first, and the stress it bears is distributed to the surrounding molecular chains rapidly and evenly, so that it breaks due to overload. At this time, only the network structure of the molecular chain is destroyed, and no macroscopic destruction phenomenon is shown. The macroscopic failure is based on the accumulation of a large number of chain breaks. The microcracks are most likely to initiate at the first chain break, where more chain breaks occur. The elastic potential energy of the molecular chain is gradually transformed into the form of heat energy, which is macroscopic thermal effect in the process of crack expansion until fracture. The molecular kinematics theory explains the causes and propagation of fatigue cracks from the molecular point of view and explains the nature of rubber fatigue fracture mechanism and experimental phenomena in fatigue process. However, the microscopic explanation is inevitably abstract, and the constitutive behavior of rubber is complex and changeable, and there are many influencing factors, so there are still unknown experimental phenomena to be explained.

3.2 Phenomenological theory
As with all solids, rubber has internal defects of various shapes and sizes. Under the action of cyclic stress, the stress on the ends of these defects is far greater than the average stress level and becomes the stress concentration point. When a certain defect reaches the failure limit due to mechanical load and chemical action, it evolves into a micro-crack and fatigue failure begins. Phenomenological theory from the perspective of internal structural damage materials, rubber materials under the action of load, stress softening phenomenon (Mullins effect), the material internal defects, such as micro cracks as the origin of the fatigue damage, in the process of fatigue stress is focused on the damage caused by micro cracks, micro cracks growing crack formation, eventually lead to material damage. The propagation mode and propagation speed of the crack are determined by the viscoelasticity of the material, and are also affected by the external environmental factors. Temperature, oxygen, ozone and other factors can independently or jointly affect the fatigue process of the rubber material and shorten its fatigue life. Based on a large number of experiments, phenomenology explains the causes of fatigue sources by studying the evolution process of fatigue characteristics, and the results are reliable and intuitive. However, it only stays at the level of experimental phenomena, does not start from the microstructure of the material, and ignores the influence of the properties of the material itself on the fatigue performance.

Both view that fatigue failure is caused by crack propagation, but the origin of the crack is different. Once the micro-crack is formed, both view that the chemical bond fracture promotes the expansion of the micro-crack until the rubber member is completely broken. With the enrichment of scientific research means, the changes in the microstructure of materials become more and more clear, and the molecular kinematics theory is more favored by scholars. But the pure theoretical research is inevitably too thin, there are certain limitations, can not fully explain all the experimental phenomena, only with the combination of experimental research, can in-depth study of rubber fatigue mechanism, continuous theoretical improvement.

4. Factors influencing the fatigue life of rubber
Under cyclic loading, rubber fatigue can be divided into two stages: crack nucleation and crack propagation. Because the mechanical behavior of rubber is changed by viscoelastic, hysteresis, stress-induced crystallization, non-linearity and other factors, and the rubber material is sensitive to temperature, composition, surrounding environment, loading frequency and the magnitude of stress variables, the fatigue failure process of rubber is very complex and variable.

4.1 Should be variable
Cadwell et al. [12] found that increasing the minimum strain can increase the fatigue life of natural rubber. Beatty[13] also showed that the energy input decreased when the minimum strain increased,
which prolonged the fatigue life of the sample. Roberts et al. [14-15] found in uniaxial and equibiaxial tensile tests that uniaxial tensile fatigue life of natural rubber was larger than equibiaxial fatigue life from the Angle of maximum principal elongation. But butyl rubber this rule is not obvious.

Jbl Cam et al. [16] conducted universal and multi-axial fatigue tests on carbon black filled natural rubber, and observed fatigue damage from macro and micro points of view. It was found that fatigue cracks sprout at micro-structural defects with actual size less than 400um, and the crack initiation at macro scale was corresponding to the crack propagation at micro scale. The shape of the fatigue strip is different under different loading conditions.

In order to research of rubber fatigue failure mechanism, Ryan J Harbour, etc. [17,18] and torsional Angle, by adjusting the strain amplitude on the crystallization of natural rubber and strain of strain not crystallization of styrene-butadiene rubber ring multiaxial fatigue tests were carried out, observe the test in the process of crack initiation and development rule, to their own fatigue life are analyzed and predicted. The crack energy density and conventional strain were used to evaluate the crack propagation ability of two kinds of rubber. G Berton et al. [19] used the same method to have an in-depth understanding of the fatigue properties of neoprene rubber, to determine the stress amplitude at the time of the most serious fatigue damage, and to measure the hysteresis energy and stiffness in the experimental process, so as to compare the influence of stress-induced crystallization and crack growth on the stiffness.

Mars W V et al. [20] carried out tension-torsion fatigue tests on short-walled cylindrical specimens of natural rubber and studied the nucleation and growth of fatigue cracks under multiaxial stress. It was found that cyclic stress and strain could significantly soften vulcanized natural rubber, and the greater the maximum strain, the higher the degree of softening. At the maximum load, the specimen has special deformation, and the occurrence of strain crystallization is related to the maximum load. Lion et al. [21] carried out a multi-step relaxation test of rubber and a loading test at a certain strain rate in the temperature range of -20℃-100℃, and the results showed that, within this temperature range, the fixed extension modulus of rubber increased with the increase of temperature, while the hysteretic loss decreased with the increase of temperature at a certain strain rate.

4.2 Environmental factors

The fatigue performance of rubber materials is greatly affected by environmental factors when applied in different environmental conditions, such as oxygen, ozone, chemical media, light, heat and so on, which can reduce the fatigue life of rubber, especially in the long fatigue process of rubber. The unsaturated carbon-carbon double bond in the molecular chain of natural rubber is easy to interact with oxygen and ozone in the air. Oxygen leads to the degradation and cross-linking of the molecular chain, while ozone can only lead to degradation, and the rise of temperature can accelerate the oxidative aging of rubber.

K. N. Arynbek et al. [22] conducted uniaxial fatigue test and crack propagation test on natural rubber to study the influence of air and seawater on the fatigue properties of natural rubber, and found that the fatigue life of rubber in sea water is longer than that in air under high stress. Because the heat generated during sample fatigue is more easily conducted in seawater, the high temperature of the sample in air destroys the stress-induced crystallization that limits crack propagation and accelerates the oxidation of the rubber molecular chains.

Gent et al. [23] compared the crack growth rates of natural rubber, styrene butadiene rubber and butadiene rubber under static and cyclic loads in air and vacuum. At the same temperature and oxygen concentration, it was found that the crack growth rate of NR was increased by two times, while that of SBR and SBR was increased by eight times. In addition, the crack propagation rate increases with the increase of oxygen concentration and decreases with the decrease of oxygen concentration, but oxidative aging causes irreversible damage to rubber mechanical properties.

Kuzuminski [24] to find out the connection between the oxidation and rubber material fatigue, styrene butadiene rubber was studied under different reaction time consumption of antiager, found after fatigue test stabilizer consumption than before fatigue test, reactive oxygen species and the
rubber macromolecule chain to form the activity of superoxide free radicals, antiager capture peroxides reactive oxygen species in the process of fatigue. To a certain extent, the fracture of rubber sample was alleviated. Gent[25], through the fatigue test of natural rubber, found that in the fatigue process, the rubber macromolecular chain in the rubber material breaks under the mechanical force, and the active free radical end of the macromolecule is easy to oxidize with oxygen, and the microcrack formed becomes the stress concentration position, and continues to expand until the fracture under the action of stress.

4.3 Formulation factors
Rubber formula has always been the focus of product research and development, and rubber materials with different mechanical properties can be obtained by changing the formula and processing technology. According to different accelerant and sulfur dosage ratio, the vulcanization system can be divided into ordinary vulcanization system, semi-effective vulcanization system and effective vulcanization system. The vulcanization system of semi-effective vulcanization system contains an appropriate amount of single sulfur bond and multi-sulfur bond at the same time, which can not only ensure the stability of the rubber material, but also improve the crosslinking efficiency. Carbon black as the most important reinforcing filler, its particle size, dispersion, and bonding strength between the matrix, seriously affect the fatigue failure resistance of rubber products.

5. Factors test method for rubber
The early fatigue failure research methods of rubber materials are mainly based on fracture mechanics, but the causes and development process of fatigue failure cannot be described from the micro point of view. In the process of cyclic stress fatigue, the physical properties and chemical compositions of natural rubber have changed in different degrees. With the rapid development of modern technology, Fourier transform infrared spectroscopy (IR), scanning electron microscopy (SEM), X-ray diffraction (XRD), energy spectrum analysis (EDS), nuclear magnetic resonance (NMR) and other advanced microscopic testing techniques are helpful to understand the changes of physical properties and chemical composition before and after fatigue. It is convenient to reveal the fatigue failure mechanism of rubber.

The observation of fatigue fracture morphology is of great significance to the study of fatigue crack initiation, propagation and fracture mechanism. Saintier N et al. [26-28] conducted uniaxial tensile fatigue experiments of rubber under both constrained and unconstrained conditions. SEM observation showed that crystallization could make the crack tip blunt or branch. In addition, the natural rubber after multiaxial tensile fatigue was analyzed by SEM and energy dispersive spectrum (EDS). It was found that the microcracks originated from the cavitation formed after the debonding of zinc oxide particles and rubber, and zinc oxide aggregates were found around the cracks. Sun Xiaorong et al. [29] compared the influence of fatigue properties of nano-sized zinc oxide and ordinary zinc oxide NR rubber, and found that nano-sized zinc oxide was more likely to aggregate and form microscopic holes, which gradually led to macroscopic damage of the material under the action of fatigue stress.

Guan Bingfeng et al. [20] compared the tensile fatigue life of filled natural rubber obtained by different mixing methods, and studied the macroscopic dispersion and microscopic dispersion of fillers under two mixing methods by means of optical microscope, SEM and other means. The results show that the dispersion degree of filler has a serious effect on the fatigue life of rubber samples with different mixing methods. The lower the viscosity of rubber, the higher the dispersion degree of filler and the better the fatigue performance of rubber products.

Gengsheng Weng et al. [30] studied the initiation and propagation of nano-cracks in natural rubber at 85℃ and small strain amplitude. Through infrared spectroscopy, it was found that the thermal oxidation effect destroyed the crosslinking structure of rubber. It was determined that the crack originated at the aggregation place of zinc sulfide and was caused by the falling off of zinc sulfide particles. The crack turned into a large cavity in the fatigue test, and the high temperature accelerated the speed of the process.
As the most typical strain crystalline elastomer, natural rubber can inhibit mechanical chain breaking, protect the molecular chain from oxygen and reduce the crack growth rate. Especially in the case of large strain fatigue, natural rubber has better fatigue resistance and longer fatigue life. Therefore, it is very important to analyze the crystallization of natural rubber in the fatigue process to explain its fatigue mechanism.

6. Morphological characteristics of rubber fatigue fracture

The fracture morphology shows the fracture process and mechanism of the material. In most cases, the failure causes of rubber seals and the corresponding solutions can be found by analyzing the fracture morphology of rubber seals. Especially in the process of failure analysis of some small rubber seals which are inconvenient to carry out routine physical and chemical performance test, the fracture morphology analysis plays an important role[31].

The macro characteristics of the fatigue fracture of rubber are similar to those of metal and plastic materials: (1) the cross section of the source area is flat, smooth and fine, most of which have outward radiating steps and radial patterns, and the fatigue arc cannot be seen in the source area. (2) The section of the expansion zone is flat and perpendicular to the principal stress. The most basic macroscopic feature left on the fracture during the fatigue fracture expansion stage is the fatigue arc (concentric arc strip centered on the crack source, also known as beach pattern or shell pattern), which is also the main basis for identifying and judging the fatigue failure of rubber materials. (3) The macroscopic morphology of the final fracture zone presents herringbone or radial stripe, which is similar to the fracture of one-time fracture [40]. Typical morphology is shown in Fig. 1.

![Fig.1 The macro-characteristics of fatigue fracture about rubber materials](image)

Rubber material fatigue fracture of the micro characteristics vary widely with metal or plastic material, has the duty of unique characteristic, mainly displays in:

(1) Rubber materials generally add curing agent, strengthening agent, etc during the preparation of particulate matter and the porosity, etc., makes the rubber materials on micro expansion shows the phenomenon of uneven material; In addition to the stress relaxation and the change of external load, the crack propagation constantly changes the direction and can not form a stable fatigue band. Therefore, fatigue curves can be observed at most fatigue fractures of rubber materials, especially rubber actual components, while no obvious fatigue bands can be observed. Fatigue bands are usually only obvious at the interruptions of regular fatigue tests, as shown in Figure 2 and Figure 3.

(2) The strength of rubber material is lower than that of metal, the crack propagation is usually faster, the number of fatigue arcs or strips is usually much less than that of metal, and the spacing is wider; Shapes usually don't have metal rules.

(3) Herringbone lines or radial stripes in the transient fault zone, without obvious dimple morphology.
7. Conclusion and prospect

In the past two decades, rubber materials have been widely used in aerospace, weapons, automobiles and other fields. The rise of commercial simulation software provides convenience for the study of rubber fatigue failure forms. The research on its fatigue performance and life prediction has also made great progress at home and abroad. However, due to the complex and changeable rubber fatigue process and numerous influencing factors, the experimental methods and experimental mechanism still need to be further explored. To this end, put forward the following several aspects of research recommendations.

(1) Fatigue properties of rubber, fracture analysis, organic combination of microstructure. The difference of fatigue properties of rubber is the result of the direct effect of microstructure. Most scholars still remain in the simple property calibration, and have not systematically combined fracture analysis and microstructure characterization. The qualitative and quantitative combination of fatigue properties, fracture analysis and microstructure is of great significance to the life evaluation and improvement of rubber components.

(2) Study on fatigue products of rubber. Rubber can produce different fatigue products under specific loading conditions, and the research on fatigue products is relatively few. Therefore, more efforts should be made to study the generation mechanism, chemical composition and the influence of fatigue products on the fatigue process.

(3) An in-depth study on the theory of rubber constitutive behavior. Due to the complexity of the constitutive behavior, there are many factors affecting the fatigue performance of rubber materials, so
it is necessary to improve the sample design scheme, further the fatigue mechanism and microstructure of rubber, enrich the theoretical basis of the constitutive behavior.

(4) Quantitative study of rubber fatigue fracture, according to the fatigue strip arc and other characteristics of the establishment of rubber material fatigue fracture quantitative analysis and life evaluation technology.

References
[1] Gent AN, Mars WV. Strength of elastomers[J]. Science Technology Rubber,2013:473-516.
[2] Sun Shu, Li Xiu-jie, Li Wei-yu. Hydrothermal Aging Test and Storage Life Prediction of GD414 Silicone Rubber for Spacecrafts[J]. Failure Analysis and Prevention,2020,15(2):78-83.
[3] Jiang Bintao, Wang Lei. Fatigue Life Analysis of Carbon Fiber Reinforced Metal Matrix Composites [J]. Failure Analysis and Prevention, 2019, 14(3):153-156.
[4] Feng Baodong, Huang Yansong, Ma Junwen et al. Analysis and Prevention of Engine Seal Apron Crack [J]. Failure Analysis and Prevention, 2009, 4(3):165-167.
[5] Mullins L. Rupture of Rubber. Role of Hysteresis in the Tearing of Rubber [J]. Transactions of the Institution of the Rubber Industry, 1959, (35):213-222.
[6] Gent A N, Lindley P B, Thomas A G. The relationship between cut growth and fatigue [J]. Journal of Applied Polymer Science, 1964, 8(1):446-455.
[7] Mars WV, Fatemi A. Multiaxial fatigue of rubber part I: equivalence criteria and theoretical aspects [J]. Fatigue Fracture Engineer Material Structure, 2005, 28(5):515-522.
[8] Saintier N, Caillietaud G, Piques R. Multiaxial fatigue life prediction for a natural rubber [J]. International Journal of fatigue, 2006, 28:530-539.
[9] Ouyang Sufang, Wang Lijing. Research Progress on Fatigue Failure Behavior of Rubber [J]. Rubber Science and Technology, 2015(3):5-10.
[10] Sun Xiaorong, Li Fuping, Jiang Honggang. Research progress of fatigue properties of natural rubber [J]. Special rubber products, 2007, 28(5):53-56.
[11] Isayev A I, Deng J S. Nonisothermal vulcanization of rubber compounds [J]. Rubber Chemis- try and Technology, 1988, 61(2):340-381.
[12] Cadwell SM, Merrill RA, Sloman CM, et al. Dynamic fatigue life of rubber [J]. Industrial and Engineering Chemistry, 1940, 12(1):19-23.
[13] Beatty J R. Fatigue of rubber [J]. Rubber Chemistry and Technology, 1964, 37(5):1341-1364.
[14] Roberts BJ, Benzies J B. Relationship between uniaxial and equi-biaxial fatigue fatigue in gum and carbon-black-filled Vulcanizates [J]. Plastics and Rubber: Materials and Applications, 1978, 3(2):49-54.
[15] Roach JF. Crack growth in elastomers under biaxial stresses [D]. USA: University of Akron, 1982.
[16] JBL Cam, BHuneau, EVerron. Fatigue damage in carbon black filled natural rubber under uni and multiaxial loading conditions [J]. International Journal of Fatigue, 2013, (3):82-94.
[17] Shangguan Wenbin, Wang Xiaoli, Ye Bijun. Experimental Study on the Influence of Strain Ratio on Fatigue Characteristics of Filled Natural Rubber and the Method of Life Prediction [J]. Journal of Mechanical Engineering, 2013(4):849-857.
[18] Ryan J Harbour, Ali Fatemi, Mars W V. Fatigue crack orientation in NR and SBR undervariableamplitude and multiaxial loading conditions [J]. Rubber Chemistry and Technology, 2008, 43(6):1783-1794.
[19] GBerton, CCruanes, FLacroix, et al. Study of the fatigue behavior of the poly-chloroprene rubber with stress variation tests[J]. Procedia Engineering, 2015, 101(2):413-420.
[20] Mars WV, Fatemi A. Multiaxial stress effects on fatigue behavior of filled natural rubber [J]. International Journal of Fatigue, 2006, 28(5):521-529.
[21] Lion A. On the large deformation behavior of reinforced rubber at different temperatures [J]. Journal of the Mechanics and Physics of Solids, 1997, 45(11):1805-1834.
[22] KNarynbe, BHuneau, EVerron. Influence of air and seawater on fatigue behavior of natural rubber [J]. Materials and Design, 2015, 403-409.
[23] Gent, Sirisinaba C, Thepsuwan U. Comparison of reinforcing efficiency between Si-69 and Si-264 in a conventional vulcanization system. Polymer Testing, 2004, 23(9): 871-879.

[24] Kuzuminski A S. Fatigue of rubber. Rubber Chemistry and Technology, 1995, 28: 429.

[25] Gent AN, Hindi M. Effect of oxygen on the tear strength of elastomers. Rubber Chemistry and Technology, 1989, 63(1): 123-134.

[26] Saintier N, Cailletaud G, Piques R. Crack Initiation and Propagation under Multiaxial Fatigue in a Natural Rubber. International Journal of Fatigue, 2006, 28(1): 61-72.

[27] N Saintier, G Cailletaud, R Piques. Cyclic loadings and crystallization of natural rubber: An explanation of fatigue crack propagation reinforcement under a positive loading ratio. Material Science & Engineering, 2011, 528(3): 1078–1086.

[28] Gengsheng Weng, Guangsu Huang, Hangxin Lei. Crack initiation and evolution in vulcanized natural rubber under high temperature fatigue. Polymer Degradation and Stability, 2011 (12): 2221-2228.

[29] S Beurrot-Borgarino, BHuneau, EVerron, et al. Strain-induced crystallization of carbon black-filled natural rubber during fatigue measured by in situ synchrotron X-Ray diffraction. International Journal of Fatigue, 2013, 47(2): 1-7.

[30] PRublon, BHuneau, EVerron, NSaintier. Multiaxial deformation and strain-induced crystallization around a fatigue crack in natural rubber. Engineering Fracture Mechanics, 2014, 123(3): 59-69.

[31] Xu Shixian, Su Zhentao, Wu Jian. Analysis on Sealing Performance of VL seals based on mixed lubrication theory. Industrial Lubrication and Tribology, 2019, 71(1): 54-60.