High-temperature fatigue life prediction method for rubber bushing of new-energy vehicles based on modified fatigue damage theory

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Abstract
Rubber bushing are important components in suspension of new-energy vehicles. It is of great practical engineering significance to conduct in-depth study of high temperature fatigue characteristics. On the high temperature fatigue test bench, the same batch of dumbbell rubber test pieces with the same material as rubber bushing and the same vulcanization process were subjected to fatigue test at different temperatures, then the arithmetic mean value of the fatigue life of each rubber test piece was taken as the fatigue life at given temperature. It was found that the fatigue life of the rubber test piece at each temperature can be well fitted when the peak of engineering strain is taken as the damage parameter. Moreover, on the basis of the fatigue damage theory, the Arrhenius high temperature aging factor was introduced to correct the fatigue damage formula considering the influence of temperature on fatigue life. The finite element analysis was used to determine the peak of engineering strain of the dangerous point of the rubber bushing at 70 °C, and the modified fatigue damage formula was employed. The prediction value of the rubber bushing fatigue life was calculated and compared with the bench test result. It is shown that the predicted fatigue life dispersion coefficient is less than 2, indicating the effectiveness of the proposed high temperature fatigue life prediction method. The research in this paper can provide reference for the durability design and fatigue life prediction of rubber parts in new-energy vehicles.

1. Introduction
Rubber is a non-metal material with excellent performance, so it is widely used in automotive vibration isolation systems. Commonly used rubber vibration isolator for vehicles including engine mount, suspension bushings, tires, and rubber ball hinges of thrust rods, etc [1–5]. The study of the mechanical properties of rubber materials has important engineering practical significance for enhancing the design level of automotive rubber parts and thus improving their performance. Rubber fatigue performance is a vital rubber mechanical property, thus in-depth research on the prediction method of rubber fatigue life would provide theoretical basis for the durability evaluation and reliability optimization of automotive rubber parts.

Scholars around the world had conducted a lot of research on the fatigue of automotive rubber parts, which has effectively promoted the improvement of the durability design level of automotive rubber parts. Literature [6] used the finite element method and equivalent stress method to predict the fatigue life of rubber shock absorbers, and verified the effectiveness of the method through experiments. Reference [7] based on the fatigue test of dumbbell-shaped rubber test columns, using different damage parameters to predict the fatigue life of rubber, on the basis of which the fatigue life of rubber isolator was predicted. References [8, 9] combined the finite element method and fatigue damage theory to predict the fatigue life of rubber ball hinges, and verified the accuracy of the life prediction method through bench tests. In [10], the maximum strain energy density was used as the damage parameter and the Monte Carlo method was used to simulate the road and engine excitations. Based on this, the random fatigue characteristics of the rubber bushing were analyzed. Based on the finite element analysis in [11], the fatigue initiation of automobile rubber suspensions was predicted using the crack
initiation method and crack propagation method, respectively. It can be known from the above literature that the research methods for fatigue life of rubber mainly include the crack initiation method based on continuum mechanics and the crack propagation method based on fracture mechanics, and the finite element method is commonly used in stress-strain analysis and fatigue damage parameter calculation for rubber parts [12–14].

In order to improve the accuracy of the fatigue life prediction of rubber parts and make the theoretical calculation fatigue life closer to the fatigue life of actual automotive rubber parts, the research on rubber fatigue has developed from uniaxial and multiaxial fatigue [15], and fatigue life prediction problems varied from constant amplitude load to variable amplitude load [16], also including both material sample fatigue and component bench fatigue, even vehicle fatigue [17]. Moreover, the influence of temperature on rubber fatigue is also researched [18–20]. In order to study the high-temperature fatigue life of a rubber bush for a new energy vehicle, this paper proposes a modified fatigue damage theory based on the high-temperature fatigue life test of a rubber test piece, and introduces the Arrhenius correction factor to the high temperature of the rubber test piece. The fatigue life was analyzed. Based on this, combined with the finite element analysis, the dangerous points and damage parameter values of the rubber bush were determined, and the high temperature fatigue life of the rubber bush was predicted by the modified damage model. The comparison with the measured fatigue life was conducted to verify the effectiveness of the proposed correction method.

2. High temperature fatigue test of rubber test piece

In order to study the fatigue law of rubber pieces at different temperatures, a batch of dumbbell-shaped standard rubber test strips were trial-produced, and their formulations and vulcanization processes were consistent with the rubber bushes studied. The high-temperature fatigue test was performed on the high-temperature fatigue test bench shown in figure 1. The geometry and size of the sample are shown in figure 2. The number of samples tested under each working condition was three, and the final fatigue cycle number of the arithmetic average of the three samples fatigue times was taken as the fatigue life of rubber pieces. In the fatigue test, the load was a sinusoidal displacement load and the frequency was 5 Hz. The engineering strain peaks of the load under different working conditions are shown in table 1. It must be pointed out the reason why the test peak engineering strain decreases as the temperature increases in table 1 is that as the strength of rubber weakens with
increasing temperature, in order to avoid strength failure rather than fatigue failure in high temperature fatigue tests, the stress amplitude of high temperature fatigue tests is reduced accordingly. Table 2 shows the fatigue cycle times of the rubber test pieces obtained in each test under different working conditions. The test conditions corresponding to the fatigue cycles in table 2 are related to the values in table 1 on a one-to-one basis.

3. Modified fatigue damage theory

3.1. Fatigue damage theory

When a damage parameter is selected, there is an inverse power relationship between the number of fatigue cycles and the damage parameter, as shown in equation (1), where \( N \) is the number of cycles, \( \varepsilon \) is the damage parameter, and \( k \) and \( b \) are fitting constants. According to related literature research [1, 2], several damage parameters such as peak engineering strain, maximum strain, maximum stress, and strain energy density had been considered. After comprehensively assessing the fitting accuracy and difficulty of obtaining these damage parameters, the engineering strain peak was selected as the damage parameter.

\[
N = ke^{-b}
\]

The logarithm of both sides of the formula (1) is taken simultaneously, and the S-N model can be linearized into the form shown in the formula (2) to facilitate the parameter identification of the model.
3.2. Theory of fatigue damage after temperature correction

Under the action of high temperature, the fatigue life of rubber is reduced due to the effects of aging and other factors. If the fatigue life model of formula (1) is used to model the fatigue life of rubber, the fatigue life data should be fitted at different temperatures, respectively.

In order to integrate the temperature into the fatigue life model, an Arrhenius correction factor is introduced to modify the fatigue damage life prediction formula (1), and the modified fatigue damage life formula is shown in formula (3).

\[ N = k e^b \exp\left(\frac{m}{T}\right) \]  

In formula (3), \( m \) is a constant related to the activation energy of rubber, and \( T \) is the Kelvin temperature. The physical meaning of activation energy is the energy required for a unit amount of substance to undergo a chemical reaction. The concept is derived from Arrhenius’s law. The research in this article finds that high temperature fatigue is related to the exponential temperature reciprocity, that is, to meet the Arrhenius law. The precise measurement of activation energy requires chemical means, and the activation energy obtained by fitting the experimental data is usually called table observation activation energy. In order to facilitate the parameter identification of the modified fatigue damage model, logarithms of both sides of equation (3) are taken simultaneously, and equation (3) is linearized into the form of equation (4).

\[ \ln(N) = \ln(k) + b \ln(\varepsilon) + \frac{m}{T} \]  

In order to separate the role of the temperature factor in the modified fatigue damage model, the Arrhenius factor in equation (3) is further moved to the left of the equation to obtain the form shown in equation (5). After transformation, equation (5) is exactly the same as the formula (1). The physical quantity on the left side of equation (5) is defined as the equivalent fatigue life \( N_e \) shown in equation (6), then there is a power exponential relationship between the equivalent fatigue life \( N_e \) and the damage parameter \( \varepsilon \), and it is independent of temperature \( T \). The relationship between them is shown in formula (7).

\[ N_e / \exp\left(\frac{m}{T}\right) = k e^b \]  

\[ N_e = N / \exp\left(\frac{m}{T}\right) \]  

\[ N_e = k e^b \]  

4. High temperature fatigue life prediction results of rubber pieces

The fatigue damage formula shown in formula (2) is used to model the high-temperature fatigue life of the measured rubber test pieces shown in tables 1 and 2, respectively. From the correlation coefficients between the life prediction results and the measured results in table 3, it can be known that each correlation coefficient is greater than 0.95, indicating that the fitting effect is good.

Figure 3 shows the relationship between fatigue life and damage parameters at different temperatures. As can be seen from figure 3, there is a clear linear relationship between logarithmic fatigue life and log damage parameters at different temperatures.

In order to further analyze the high temperature fatigue of rubber, the data in tables 1 and 2 are modeled by using formula (4), and the parameter recognition results shown in table 4 are obtained according to the least square method. From the correlation coefficient between the predicted life value and the measured value in table 4, we can see that the proposed modified fatigue damage theory has a good fitting effect. Compared with the
fitting effect in table 3, although the accuracy is slightly worse, the amount of identified parameters is reduced from 10 to 3, which greatly reduces the modeling workload. It also lays the foundation for predicting the fatigue life of rubber at different temperatures.

Figure 4 is a comparison chart between the measured high-temperature fatigue life and the predicted value of high-temperature fatigue life calculated from the modified fatigue damage theory. It can be seen from the figure that each sample point has a good fitting effect with all of the predicted values are within the 2 times dispersion lines.

In order to visually observe the prediction results of the modified fatigue damage theory, the measured fatigue life data at each temperature in table 2 is brought into equation (6) to obtain the actual equivalent fatigue life, and the data from equation (7) and table 4 was employed to calculated the predicted equivalent fatigue life, as shown in figure 5. It can be seen from figure 5 that the measured equivalent fatigue life at different

### Table 4. Parameter identification results of modified fatigue damage model.

| Parameters | m    | ln(k) | b    | Correlation coefficient |
|------------|------|-------|------|------------------------|
| Value      | 3396.9114 | 2.0936 | −2.9265 | 0.9431                 |

Figure 3. High temperature fatigue test results of rubber at different temperatures.

Figure 4. Comparison of prediction results and measured results of the modified fatigue damage model.
temperatures surrounds both sides of the predicted equivalent fatigue life line which indicating a high degree of agreement, verifying the modified fatigue damage formula proposed in this paper.

Figure 6 is a three-dimensional curved view of a modified fatigue damage model shown in equation (4). As can be seen from figure 6 the fatigue life decreases as the temperature increases, moreover the fatigue life decreases as the engineering strain increases. Figure 6 intuitively expresses the relationship between the temperature-fatigue damage parameter and the number of fatigue cycles.

5. Finite element analysis and fatigue life prediction of rubber bushing

Based on the fatigue test and life modeling of the rubber test piece, a finite element analysis model was established. A radial sinusoidal displacement load of 0–15 mm was applied to the rubber bushing under study, and the load application frequency was 5 Hz. The material model of the rubber in the finite element model is a mooney-Rivlin constitutive relationship model, and the parameters of the constitutive model are obtained by fitting the measured curve of the stress and strain of the rubber test piece at a high temperature of 70 °C. Under a given load, the stress-strain results of the finite element model are obtained, and the corresponding dangerous points and peak engineering strain peaks can be obtained, so that the engineering strain peak is brought into equation (4) to calculate the fatigue life at the corresponding temperature. In order to verify the accuracy of the finite element model and the modified fatigue damage model, a 70 °C high temperature fatigue bench test was performed on the rubber bushing. Figure 7 is a comparison diagram of the fatigue danger area obtained from the
finite element analysis and the measured fatigue crack position. It can be seen from figure 7 that the dangerous area obtained by the established finite element model is basically consistent with the actual cracking area.

Once the bushing breaks, its strength will drop significantly. Therefore, the suddenly changing of the measured force sensor value is chosen as the failure criterion of the bushing bench test, and the number of cycles at this time is used as the fatigue life value of the bushing. Table 5 shows the comparison between the predicted fatigue life of the rubber bushing and the measured fatigue life at a high temperature of 70 °C. As can be seen from table 5, the dispersion coefficient of the predicted fatigue life is 1.36, which meets requirements of the predicted fatigue life of the engineering needs, with the predicted results being more conservative, which is beneficial to actual engineering use.

6. Conclusions

This paper comprehensively uses the bench test, fatigue damage theory and finite element method to predict the high temperature life of a rubber bushing for a new energy vehicle, which can provide a reference for the fatigue durability design and evaluation of related rubber parts. The main conclusions of the research are as follows:

(1) A high temperature fatigue test of the rubber test piece was performed, and the peak value of the engineering strain was used as the damage parameter to fit the fatigue life at different temperatures.

(2) The Arrhenius factor was introduced and a modified fatigue damage formula was established to well characterize the effect of temperature on fatigue life.

(3) Based on the finite element analysis, combined with the modified fatigue damage formula, the fatigue life of the rubber bushing at 70 °C was predicted. Compared with the actual measurement results, the dispersion coefficient was 1.36, indicating that the prediction accuracy is high thus meets the engineering requirements.

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