Fatigue life prediction of vulcanized natural rubber subjected to heat-aging

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Abstract

Fatigue life prediction and evaluation are the key technologies to assure the safety and reliability of automotive rubber components. In this paper, fatigue life prediction methodology of vulcanized natural rubber was proposed by incorporating the finite element analysis and fatigue damage parameter determined from fatigue test. Heat-aging effects on the fatigue life prediction of natural rubber were experimentally investigated. Fatigue test were performed using the 3-dimensional dumbbell specimen, which were aged different amounts. The Green-Lagrange strain at the critical location determined from the finite element analysis was used for evaluating the fatigue damage parameter. Fatigue life prediction equation effectively represented by a single function using the Green-Lagrange strain. According to fatigue life prediction equation, fatigue life ambient temperature was longer than at 70°C. Predicted fatigue lives of the rubber component were in fairly good agreements with the experimental fatigue lives within factor of two.

Keywarsds : Vulcanized natural rubber ; Heat-aging, Fatigue test ; Finite element analysis ; Green-Lagrange strain ; Fatigue life prediction

1. Introduction

The interest of the fatigue life for rubber components increasing to the extension of warranty period of the automotive components [1]. Design of rubber components against fatigue failure is one of the critical issues to prevent the failures during the operation. Therefore, fatigue life prediction and evaluation are the key technologies to assure the safety and reliability of automotive rubber components [2,3].

In this paper, the heat-aging effects on the material properties and fatigue life prediction of natural rubber were experimentally investigated. Fatigue life obtained from the results of physical and fatigue test. The rubber specimens were heat-aged in an oven at 70°C for a period ranging from 1 to 90 days. Fatigue life prediction methodology of vulcanized natural rubber was proposed by the finite element analysis and fatigue damage parameter determined from fatigue test. Fatigue life tests were performed using the 3-dimensional dumbbell specimen was aged different amounts. The Green-Lagrange strain at the critical location determined from the finite element analysis was used for

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evaluating the fatigue damage parameter. Fatigue life prediction equation effectively represented by a single function using the Green-Lagrange strain and normalized strain. Predicted fatigue lives are in a good agreement with the experimental fatigue lives within factor of two.

2. Experiment

The material used in this study is a carbon-filled vulcanized natural rubber, which has the hardness of the International Rubber Hardness Degree 55, 60, 65 (NR55, NR60, NR65). Three-dimensional dumbbell specimen in Fig. 1(a) is used for the fatigue life evaluation of the natural rubber. The 3-D dumbbell specimen has an elliptical cross-section and parting lines are located on the minor axis of specimen to avoid undesirable failure at the surface discontinuities [4,5].

Finite element analysis was performed to investigate the deformation behavior of 3-D dumbbell specimen. Material constants representing the Mooney-Rivlin and Ogden strain energy potential of order 3 was used for defining a constitutive relation of the natural rubber. The 3-D dumbbell specimen is modeled with 10-noded tetra hyper-elastic element and one eighth of the dumbbell specimen was modeled due to the geometric symmetry. For materials like rubber which experiences a large deformation, Green-Lagrange strain ($\varepsilon_{G-L}$) has been used as a strain measure [6].

Fig. 1(b) shows the Green-Lagrange strain distribution of the 3-D dumbbell specimen. The maximum Green-Lagrange strain was found at the surface of the major axis in the dumbbell specimen. The Green-Lagrange strain at the critical location determined from the finite element analysis was used for evaluating the fatigue damage parameter of the natural rubber. The displacement and maximum Green-Lagrange strain curve was used for generating a fatigue life equation of the natural rubber expressed by the maximum Green–Lagrange strain as a damage parameter. The maximum Green-Lagrange strain distribution of the 3-D dumbbell specimen under displacement shown in Fig. 1(c).

Fatigue tests were conducted in an ambient temperature and 70°C under the stroke-controlled condition with a sine waveform of 5Hz and the mean displacement is 0, 3, 5, 8, 10mm at the displacement range -11~21mm. As the automotive rubber components for vibration isolators are loaded compressively, the minimum strain is below zero generally. Therefore, to evaluate the effect of minimum strain on the fatigue life that the test results which the minimum displacements are below zero. The fatigue failure was defined as number of cycles at which the maximum load dropped by 20 percent. Increasing cycles in initial phase, the maximum load decreased. When the crack grew over the critical size, the maximum load decreased suddenly and the final failure reached as shown Fig. 1(d).

Fig. 2 shows the relationship between the displacement amplitude and the fatigue life for ambient temperature and 70°C. The fatigue lives decreased increasing mean displacements and hardness. Fatigue life decreased as the tension displacement amplitude and heat aging days increased. It is possible to the fatigue life with maximum displacement fairly.

![Fig. 1. Fatigue test; (a) 3 dimensional fatigue test specimen (b) finite element analysis of 3 dimensional dumbbell specimen (b) maximum strain versus displacement (d) definition of fatigue failure of specimen](image-url)
3. Result and Discussion

By using the result of the fatigue test and finite element analysis, fatigue life can express the maximum Green-Lagrange strain instead of maximum displacement. Fig. 3(a) shows the relation maximum Green-Lagrange strain fatigue life. Fatigue life effectively maximum Green-Lagrange strain, where the Green-Lagrange strain for each 3-D dumbbell specimen is calculated from the displacement versus Green-Lagrange strain curve in Fig. 1(c).

Elongation at break is very important factor in material properties and fatigue life prediction of rubber materials. The test data elongation at break according aging days at 70°C shown as in Fig. 3(b). Elongation at break decrease as the hardness and heat aging increase. Also, normalized strain was defined as divide by maximum Green-Lagrange strain ($EBG_L$) at break. Fig. 4(a) and (b) show relation of normalized strain and fatigue life. Fatigue life prediction equation effectively represented by a single function using the normalized strain.

Fatigue life prediction equation ($N_f$) of natural rubber material shown in Table 1. It was observed that the maximum Green-Lagrange strain and normalized strain was a good fatigue damage parameter to account for the hardness, amplitude effects. According to fatigue life prediction equation, fatigue life ambient temperature was longer than at 70°C. Relation between experimental and predicted fatigue life shown in Fig. 4(c) and (d). Predicted fatigue lives are in a good agreement with experimental lives within a factor of two.
Fig. 4. Fatigue life prediction using the normalized strain: (a) ambient temperature (b) heat-aging at 70°C (c) and (d) correlation between experimental and predicted fatigue life at ambient temperature and 70°C

Table 1. Fatigue life prediction of natural rubber

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Fatigue life prediction equation</th>
<th>Fatigue life ($\varepsilon_{G-L}/\varepsilon_{EBG-L}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature (at 25°C)</td>
<td>$N_f = 1,096 \times [\varepsilon_{G-L}/\varepsilon_{EBG-L}]^{-2.22}$</td>
<td>2,633,912 847,417 565,347</td>
</tr>
<tr>
<td>Heat aging (at 70°C)</td>
<td>$N_f = 6,516 \times [\varepsilon_{G-L}/\varepsilon_{EBG-L}]^{-1.55}$</td>
<td>1,494,318 676,982 510,324</td>
</tr>
</tbody>
</table>

4. Conclusion

Fatigue life prediction and evaluation of rubber material are very important in design procedure to assure the safety and reliability of automotive rubber components. In this paper, fatigue life prediction methodology of vulcanized natural rubber was proposed by the finite element analysis and fatigue damage parameter determined from fatigue test. Fatigue tests were conducted by using the 3-D dumbbell specimen at various hardness, displacement amplitude and heat-aged period. Fatigue life was effectively represented the maximum Green-Lagrange strain and normalized strain. According to fatigue life prediction equation, fatigue life of ambient temperature was longer than at 70°C. Predicted fatigue lives of the rubber component were in fairly good agreements with the experimental lives within factors of two. Therefore, fatigue life estimation procedure employed in this study could be used approximately for the fatigue design of the rubber components at the early design stage.

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Reference

5. Yamaguchi H, Nakagawa N, *Fatigue test technique for rubber materials of vibration insulator*, Int. polymer Science and Technology; 1993, 20, p. 64-69