FATIGUE LIFE PREDICTION IN RUBBER MATERIAL UNDER CYCLIC LOADS AT VARIABLE TEMPERATURES

C. S. Woo[1], H. S. Park[2]

[1,2]Korea Institute of Machinery & Materials, Department of nano-mechanics, 156 Gajeongbuk-Ro, Yuseong-Gu, Daejeon, 34103, Korea
Email: cswoo@kimm.re.kr, Web Page: http://www.kimm.re.kr

Keywords: Rubber material, Heat aging, Damage parameter, Fatigue, Lifetime prediction

Abstract
The interest of fatigue life evaluation for rubber component such as engine mount was increasing according to the extension of warranty period of the automotive components. A 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 mechanical rubber components. In this paper, the heat-aging effects on the material properties and fatigue life prediction of natural rubber were experimentally investigated. In order to investigate heat-aging effects on the material properties, the stress-strain curves were obtained from the results of tensile test. The rubber specimens were heat-aged in an oven at the temperature ranging from 50 to 100 C for a period ranging from 1 to 90 days. The stiffness increases as the heat-aging temperature and/or the heat-aging period increase. Also, the modulus at 100% increases as hardness increase. The elongation decrease as the heat-aging temperature and/or period increase, we known that variation of elongation is a function of period as well as temperature. Fatigue life prediction methodology of vulcanized natural rubber was proposed by incorporating the finite element analysis and fatigue damage parameter determined from fatigue test. Fatigue life prediction equation effectively represented by a single function using the Green-Lagrange strain. Predicted fatigue lives of the rubber component were in fairly good agreements with the experimental fatigue 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.

1. Introduction

Rubber's ability to withstand very large strains without permanent deformation or fracture makes it ideal for many applications including tires, vibration isolators, seals, hoses, belts, impact bumper, medical devices and structural bearing to name a few [1]. These rubber components subjected to fluctuating loads often fail due to the nucleation and growth of defects or cracks. To prevent such failures, it is necessary to understand the fatigue failure mechanism for rubber materials and to evaluate the fatigue life for rubber components. The fatigue lifetime prediction on the rubber components was increasing according to the extension of warranty period of the automotive components. A design of rubber components against fatigue failure is one of the critical issues to prevent the failures during the operation. Therefore, fatigue lifetime prediction and evaluation are the key technologies to assure the safety and reliability of mechanical rubber components [2]. Fatigue lifetime evaluation of rubber components has hitherto relied mainly on a real load test, road simulator test or bench fatigue test. Although above methods have advantages in accuracy of fatigue life, but cannot be used before the first prototype is made and the fatigue test should be always conducted whenever material or geometry changes are made. In order to get the excellent result of fatigue lifetime and have the short time test cycles, we expected the development of new method of fatigue test. As result, we have studied to obtain the new fatigue test, which is able to expect the fatigue life

Excerpt from ISBN 978-3-00-053387-7

for rubber component, by using of correlations with actual vehicle parts by conventional fatigue test, at the stage of material development test. This paper show the fatigue test by newly designed test piece, which is supposed to simulate actual parts strain by finite element analysis method, and also show the relationship between test piece fatigue life and actual parts, using finite element analyzed strain as a parameter. In this study, by using the parameter of maximum Green-Lagrange strains appearing at the locations, we can prove the relations between fatigue life and maximum Green-Lagrange strain, and the correlations between test piece test and bench test of actual rubber component. In order to predict the fatigue life of rubber components at the design stage, the simple procedure of life prediction is suggested in Fig.1.

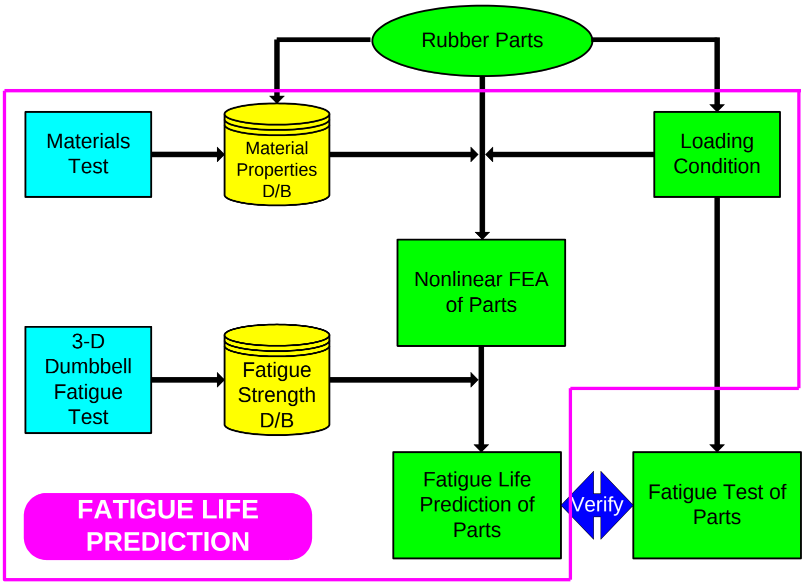


Figure 1. Procedure of fatigue life prediction system for rubber component

Rubber material was aged during its useful lifetime and the aging phenomena depended upon thermal and mechanical conditions. Thermal aging under engine room temperature and fluctuating mechanical loading by vehicle dynamic motion have affected the fatigue life of engine mount. When rubber is used for a long period of time, rubber becomes thermal aging it usually becomes hardened and loses its damping capability. This aging process results mainly from heat due to hysteric loss, and is affects not only the material property but also the fatigue life of rubber. The rubber materials show particular mechanical properties according to compounding ingredients and temperature conditions [3, 4]. Therefore, in order to evaluate the fatigue life of designed rubber components, it’s necessary to obtain the material properties at variable temperatures.

In this paper, the heat-aging effects on the material properties and fatigue life prediction of natural rubber were experimentally investigated. In order to investigate heat-aging effects on the material properties, the stress-strain curves were obtained from the results of tensile test. The rubber specimens were heat-aged in an oven at the temperature ranging from 50°C to 100°C for a period ranging from 1 to 90days. Also, Fatigue life tests were performed using the three dimensional dumbbell specimens, which were aged in different amounts. The Green-Lagrange strain at the critical location determined from the FEM was used for evaluating the fatigue damage parameter. Fatigue life prediction equation effectively represented by a single function using the Green-Lagrange strain. Predicted fatigue lives of the rubber component showed a fairly good agreement with the experimental fatigue lives. Fatigue lifetime prediction procedure employed in this study could be used approximately for the fatigue design of rubber components.

Excerpt from ISBN 978-3-00-053387-7

2. EXPERIMENT

2.1. Specimen

Rubber material used in this study is a carbon-filled vulcanized natural rubber, which have the hardness of the International Rubber Hardness Degree 45, 50, 55, 60, 65 (NR45, NR50, NR55, NR60, NR65). Compound recipes, including applied cure conditions, are summarized in Table 1. Vulcanized rubber sheet about 2mm thick were pressed and vulcanized with an electrically heated press at 150^{o}C for a given period of time. Dumbbell shaped specimen was cut from vulcanized rubber sheet for the measurement of stress and strain. Three-dimensional dumbbell specimen was used for the fatigue damage evaluation of the natural rubber. Three-dimensional 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 [5].

Table 1. Compound recipes of rubber material

Ingredient	NR45	NR50	NR55	NR60	NR65
SMR CV60	100	100	100	100	100
C/B FEF	13	22	27	40	40
C/B SRF	-	15	18	20	22
S/A	1	1	1	1	1
ZnO	5	5	5	5	5

2.2. Mechanical and fatigue test

To study the ageing propertie of the rubber material, specimens were aged in an air oven from 50℃ to 100℃ for 90day. Then specimens were conditioned at ambient temperature for at least 24h before testing. Axial tension test was loaded by UTM at a speed of 100mm/min, and the deflection was measured using a laser extensometer in Fig. 2(a). In order to evaluate a fatigue damage parameter of the natural rubber material and the experimental fatigue life, fatigue tests of three-dimensional dumbbell specimen in Fig. 2(b) were performed using the fatigue testing system as shown in Fig. 2(c). Fatigue tests were conducted in an ambient temperature and heat-aging(70℃) under the stroke-controlled condition with a sine waveform of 5 Hz and the mean displacement is 0, 3, 5, 8, 10mm at the displacement range is -11~21mm.

The fatigue failure was defined as a number of cycles at which the maximum load dropped by 20 percent. As increasing the cycles in initial phase, the maximum load decreased little by little. When the crack grew over the critical size, the maximum load decreased suddenly and the final failure reached.

(a) Mechanical test (b) 3-dimensional fatigue specimen (c) Fatigue test

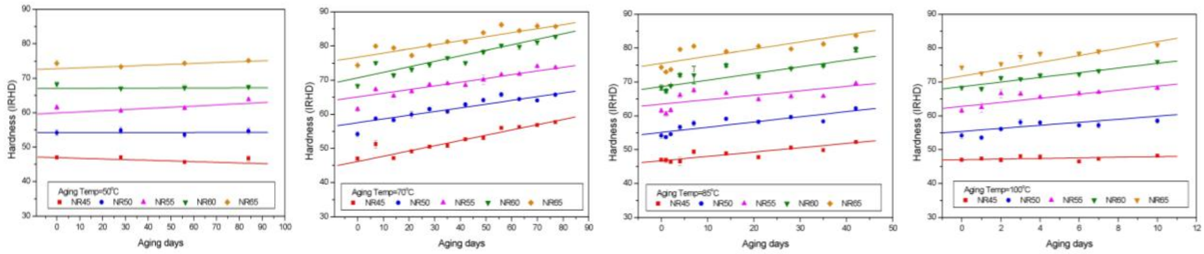
Figure 2. Mechanical and fatigue test

Excerpt from ISBN 978-3-00-053387-7

3. RESULT AND DISCUSSION

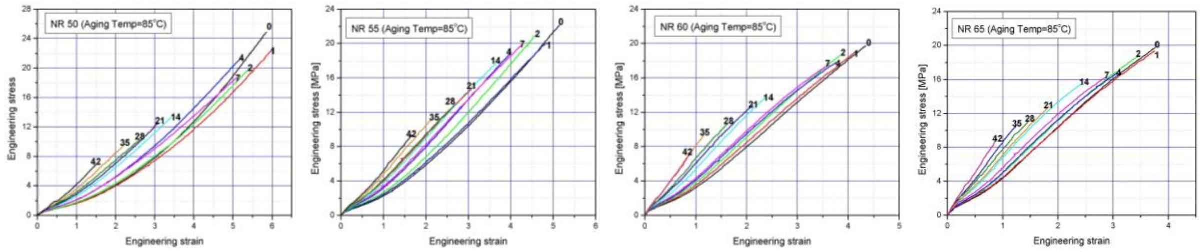
3.1. Mechanical property

The test data of hardness change for specimens heat-aged at different temperatures are shown as symbols in Figure 3 as functions of period. The hardness increases as the heat-aging temperature and/or the heat-aging period increase. In Fig. 4, the stress-strain curves obtained from the tensile test are shown for various temperature and heat aging days. The stiffness increases as the heat-aging temperature and/or the heat-aging period increase. Also, the modulus at 100% increases as hardness increase. Elongation at break(EB) is very important factor in material properties and fatigue life prediction of rubber components. Test data of elongation change for specimen heat-aged at different temperature are shown as in Fig. 5 as functions of period. The elongation decrease as the heat-aging temperature and/or period increase, we known that variation of elongation is a function of period as well as temperature.



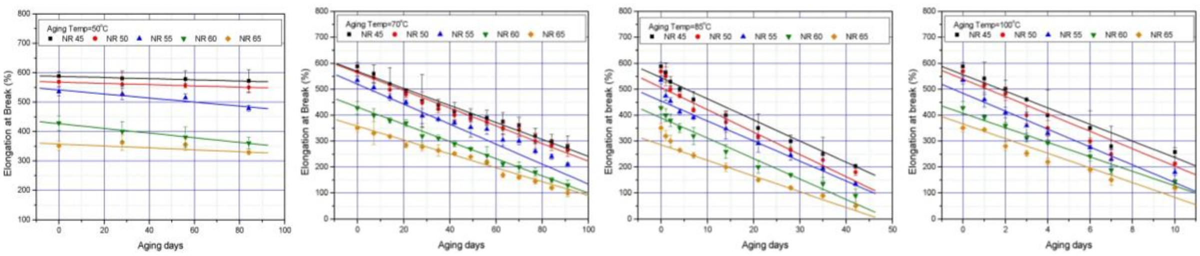
(a) 50°C (b) 70°C (c) 85°C (d) 100°C

Figure 3. Hardness after heat-aging



(a) NR50 (b) NR55 (c) NR60 (d) NR 60

Figure 4. Stress-strain curves



(a) 50°C (b) 70°C (c) 85°C (d) 100°C

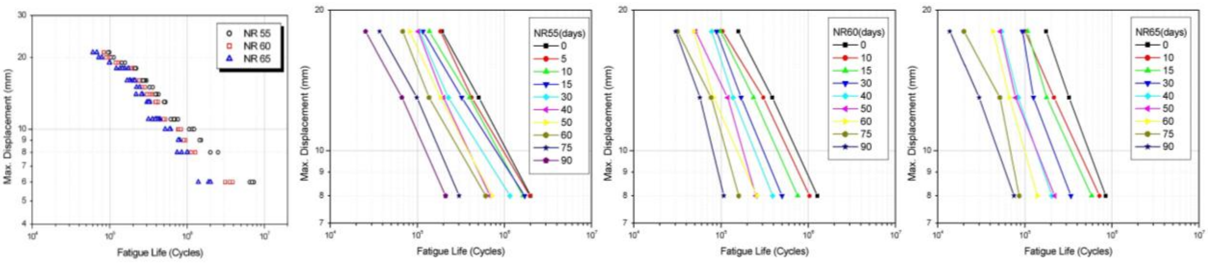
Figure 5. Elongation at break after heat-aging

3.2. Fatigue life prediction

Figure 6 shows the relationship between the displacement amplitude and the fatigue life at ambient temperature and 70℃. The fatigue lives decreased according to increasing the mean displacements and hardness. Fatigue life decreased as the tension displacement amplitude and heat aging days

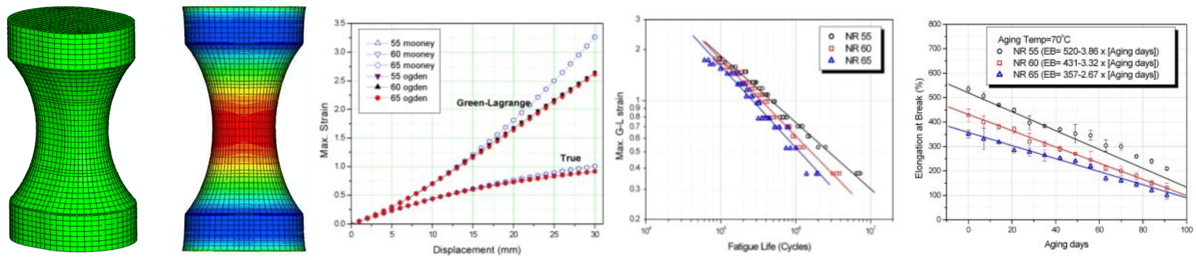
Excerpt from ISBN 978-3-00-053387-7

increased. It is possible to express the fatigue life with maximum displacement fairly good.
Figure 7(a) shows the Green-Lagrange strain distribution of the three-dimensional 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 three-dimensional dumbbell specimen under displacement was shown in Fig. 7(b). 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. Figure 7(c) shows the relation of maximum G-L strain with fatigue life. Fatigue life was effectively represented by the maximum G-L strain, where the G-L strain for each three-dimensional dumbbell specimen is calculated from the displacement versus G-L strain curve in Fig. 7(b). Elongation at break is very important factor in material properties and fatigue life prediction of rubber materials. The test data of elongation at break according to aging days at 70℃ are shown as in Fig. 7(d). Elongation at break was decrease as the hardness and heat aging day increase. Also, normalized strain was defined as dividing by maximum Green-Lagrange strain ($EB_{G\text{-}L}$) at break for the maximum Green-Lagrange strain ($\varepsilon_{G\text{-}L}$). Fig. 8(a) and (b) shows 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 was shown in Table 2.



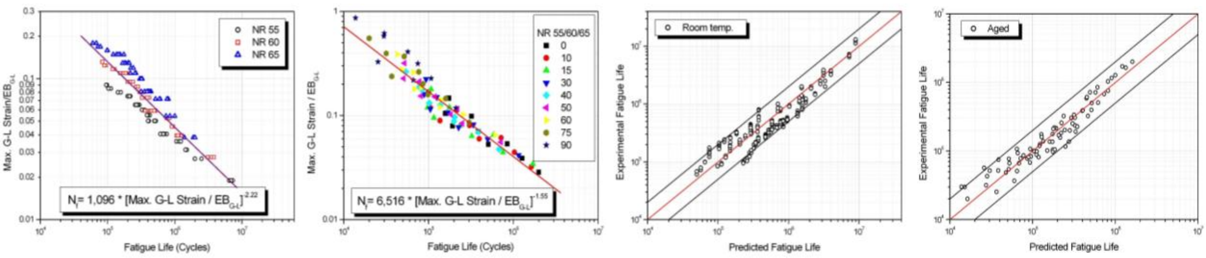
(a) Ambient temperature (b) NR55 at 70℃ (c) NR60 at 70℃ (d) NR 65 at 70℃

Figure 6. Fatigue life versus maximum displacement



(a) Finite element analysis (b) Strain-displacement (c) Max. G-L strain (d) Elongation at break

Figure 7. FEA of 3-dimensional fatigue specimen and maximum G-L strain versus fatigue life



(a) Ambient temperature (b) 70°C (c) Ambient temperature (d) 70°C

Figure 8. Fatigue life prediction using the normalized strain and

Table 2. Fatigue life prediction of natural rubber

Condition	Fatigue life prediction equation
Ambient temp.	$N_f = 1{,}096 \cdot [\ \varepsilon_{G\text{-}L} / EB_{G\text{-}L}\ ]^{-2.22}$
Heat-aging (70°C)	$N_f = 6{,}516 \cdot [\ \varepsilon_{G\text{-}L} / EB_{G\text{-}L}\ ]^{-1.55}$

It was observed that the maximum Green-Lagrange strain and normalized strain was a good fatigue damage parameter to account for hardness, amplitude effects. According to fatigue life prediction equation, fatigue life of ambient temperature was longer than at 70°C. Correlation between experimental and predicted fatigue life are shown in Fig. 8(c) and (d). Predicted fatigue lives are in a good agreement with experimental lives within a factor of two.

4. Conclusions

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. The Green-Lagrange strain at the critical location determined from the finite element method used for evaluating the fatigue damage parameter. Fatigue life prediction equation effectively represented by a single function using the Green-Lagrange strain. Predicted fatigue lives of the rubber component were in fairly good agreements with the experimental fatigue 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.

Acknowledgments

This research has been supported by Development of Materials and Component Program of Ministry of Knowledge Economy, Korea.

References

[1] A. N. Gent and G. J. Lake. Engineering with rubber, Hanser publication, 1992.
[2] G. J. Lake. Fatigue and fracture of elastomers, *Rubber Chem. & Tech.*, 68: 435-460, 1995.
[3] R. P. Brown. Rubber product failure, *RAPRA review reports*, 13(3), 2002
[4] R.P. Brown. Physical testing of rubber elastic, 3rd ed., Chapman & Hill, 1990.
[5] K.Takeuchi and M. Nagawaka. *Int'l Polymer Sci*. 20:10, 64-69, 1993.

Excerpt from ISBN 978-3-00-053387-7