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Property Modelling

Modeling of the heat build-up of carbon black filled rubber

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ABSTRACT

Rubber is a typical viscoelastic polymer and has a low thermal conductivity. The main consequence is heat generation and leads to a temperature rise called heat build-up of the rubber material when subjected to cyclic deformation. Cylindrical carbon black (CB) filled rubber specimens were sinusoidally compressed with a Gabo Eplexor 500N dynamic mechanical analyzer, under various frequencies (10, 30, 50, 70 and 90 Hz) and dynamic strain amplitudes (1%, 2%, 3%, 4% and 5%). A ThermaCAM SC3000 infrared camera was used to capture the surface temperatures of the specimens. To predict the influence of two main influent factors (loading strain amplitude and frequency) on the heat build-up (HBU), relations of the dynamic properties with the strain and frequency were constructed based on the Kraus and General Maxwell model, respectively. And effect of rising temperature on the loss modulus was investigated. Combine with the heat equation, an analytical method for calculating the HBU was established. The comparison between calculated results and experimental data shows that the proposed analysis method provides a satisfactory way to predict HBU for rubber compounds.

1. Introduction

The rubber material is widely used in the industry because of their good abrasion resistance, damping behavior, and ability to undergo very large deformation with nearly no permanent deformation [1,2]. In many common applications, dynamic loads are usually presented causing the rubber materials to exhibit their viscoelastic behavior. Viscoelastic is one of the important properties of many polymers, which leads to energy dissipation of polymers and consequent heat generation [3–6]. Moreover, the rubber components tend to be poor conductor of heat, and therefore a significant rise in temperature can be observed when it is subjected to cyclic loading [7]. The high temperature leads to a decrease in ultimate strength or even severe failures before the designed service life of rubber components.

Since Joule published the paper showing the temperature increase of rubber during deformations [8], lots of papers were published to explain the mechanism of the phenomenon [9]. And, by considering the effect of filler type and dispersion, interfacial bonding, rubber matrix and processing method on the HBU, many works were also made to make low heat build-up (HBU) rubber [10–14].

Nevertheless, to develop low HBU rubber, computational methods are indispensable in the product development cycle in order to reduce costs of experimental methods. Finite element analysis (FEA) and theoretical calculation are reliable methods to predict HBU of polymer materials under cyclic deformation. For the finite element analysis method, Ebbott et al. developed a FEA approach to predict tire rolling resistance and temperature distributions, which mainly focused on the material properties and constitutive modeling, and the steady state temperature distribution was obtained [15]. Lin and Hwang applied a numerical procedure to calculate the heat generation rate for investigating the temperature distribution of a tire worked under different conditions [16]. Rao et al. developed a finite element algorithm in cylindrical coordinates to predict the three-dimensional operating temperatures for axisymmetric tires through a simple decoupled procedure, and the computation results was compared with the results obtained from a standard finite element solver [17]. Lima and Rade developed a hybrid numerical–experimental methodology to investigate the influence of frequency, amplitude and preload on the HBU phenomenon in a two-dimensional translational viscoelastic mount [18,19]. Rodas first developed a finite strain thermo-viscoelastic constitutive model to describe the self-heating in elastomeric materials during low-cycle fatigue, and then modified the model by using a stretch amplification factor to account for the effect of carbon black (CB) filler on the heat build-up [20,21]. Futamura et al. introduced the concept of deformation index, which could be effectively used to determine the relevant dynamic viscoelastic properties. The deformation index concept was applied to thermomechanical analysis, simplifying the fully coupled iterative FEA method into a noniterative

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computational method [22]. Li and Zhang et al. studied the mechanisms of HBU and the transient temperature distributions in a cylindrical rubber specimen by using FEA. In their work, the heat build-up analysis of a rubber specimen under cyclic loading was performed based on nonlinear viscoelastic theory and coupled thermo-mechanical approach. Creep effect and dynamic property softening effect on heat build-up were firstly considered. They proposed that dynamic property softening effect should be considered to obtain accurate calculation results [23]. In addition, theoretical research in this area was established by Karnaukhov and Senchenkov [24]. They proposed heat governing equations of thermoviscoelasticity for polymers under cyclic deformation, and a series of works concerning on axially loaded cylinders were done by them and other authors [25,26].

Note that many works were done to predict the steady or transient temperature distributions of rubber components, but to simplify the model, almost all of the works neglected the mechanical properties dependence on the temperature. In fact, the hysteresis loss and consequent heating within the material are generally described in the term of the loss modulus (i.e. the imaginary part of the complex dynamic modulus). Due to the viscoelastic nature of the rubber material, its dynamic behavior is significantly dependent on the load amplitude, frequency and temperature [27–32]. For this reason, the present paper intends to propose and validate a theoretical method, which considers the influence of temperature rise on the material property, based on the heat governing equations for the characterization of HBU in rubber cylinder. And, the solution of the theoretical method was discussed in detail.

In the view of this, we aim to develop a theoretical method to predict the HBU of the rubber. Firstly, cylindrical CB filled rubber specimens were sinusoidally compressed with a Gabo Eplexor 500N dynamic mechanical analyzer, under various frequencies (10, 30, 50, 70 and 90 Hz) and dynamic strain amplitudes (1%, 2%, 3%, 4% and 5%). The surface temperatures of the specimens were measured using a ThermaCAM SC3000 infrared camera. Secondly, based on the heat equation, an analytical method for calculating the HBU was established. And finally, the proposed method to predict the HBU of rubber component was verified by comparing with the experimental data.

2. Experimental

2.1. Material

The samples for the mechanical and thermal tests were provided by Zhuzhou Times New Material Technology Co., Ltd, in China. The formulation was as follows: 100 phr NR (Thailand RRS3), 20 phr carbon black (N550), 10 phr zinc oxide, 5 phr antioxidant, 2.5 phr sulfur, 2 phr stearic acid, 2 phr micro crystal wax, 2 phr solid coumarone resin and 1.4 phr vulcanization activator.

2.2. Heart build-up (HBU) test

To investigate the strain amplitude and frequency effects on the temperature rise behaviors of the CB-filled rubber, tests under various strain amplitudes and frequencies were carried out with a Gabo Eplexor 500N working in the compression mode. The rubber specimen was solid with a diameter of 10 mm and a height of 10 mm. The HBU tests were performed at different strain amplitudes ranging from 1% to 5% at fixed prestrain −20% and frequency 50 Hz, and under various frequencies, i.e. 10, 30, 50, 70, 90 Hz, at fixed prestrain −20% and dynamic strain amplitude 5%. A ThermaCAM SC3000 infrared camera was used to capture the surface temperatures of the specimens. The FLIR ThermaCAM SC3000 has a thermal sensitivity of 20mK at 30 °C, an accuracy of 1% for temperatures up to 150 °C and 2% for temperatures above 150 °C. For all the tests, the initial temperature was kept the same (27 °C). The experimental setup is shown in Fig. 1.

3. Heat build-up (HBU) calculation

According to the law of conservation of energy, the heat conducting differential equation of a solid can be written as [26]:

$$\rho c\dot{\theta} - k\nabla^2\theta = \dot{Q} \tag{1}$$

where ρ is the volumetric mass, c the specific heat capacity, k the heat conductivity, θ the changed temperature and $\dot{Q}$ is the rate of calorific energy produced by the dissipation per unit volume.

For the viscoelastic rubber material, energy loss which is ultimately converted into heat is inevitable when a continuous cyclic deformation is applied on a rubber specimen, and cause a relative high increases in temperature within the specimen [33]. In order to investigate the energy loss, the specimen is supposed to be loaded with a sinusoidal strain controlled process $\varepsilon(t)$ of the following form:

$$\varepsilon(t) = \varepsilon_0 + \Delta\varepsilon \sin(2\pi ft) \tag{2}$$

where f is the frequency, ε_0 is the prestrain and $\Delta\varepsilon$ is the strain amplitude of excitation. If the strain amplitude $\Delta\varepsilon$ is sufficiently small, the stress response $\sigma(t)$ of the specimen is in a good approximation also a harmonic function and can be written as:

$$\sigma(t) = \sigma_0 + \Delta\sigma[\cos(\varphi)\sin(2\pi ft) + \sin(\varphi)\cos(2\pi ft)] \tag{3}$$

where φ is the phase angle between the applied strain and the resulting stress, σ_0 is the static stress and $\Delta\sigma$ is the stress amplitude.

If we define the storage and dissipation moduli E' and E'' as:

$$E'(\varepsilon_0, f, T, \Delta\varepsilon) = \frac{\Delta\sigma}{\Delta\varepsilon}\cos(\varphi) \tag{4}$$

and

$$E''(\varepsilon_0, f, T, \Delta\varepsilon) = \frac{\Delta\sigma}{\Delta\varepsilon}\sin(\varphi) \tag{5}$$

The dynamic stress response can be rewritten as:

$$\sigma(t) = \sigma_0 + \Delta\varepsilon[E'(\varepsilon_0, f, T, \Delta\varepsilon)\sin(2\pi ft) + E''(\varepsilon_0, f, T, \Delta\varepsilon)\cos(2\pi ft)] \tag{6}$$

And the strain energy is given over one period by:

$$\begin{aligned} W(t) &= \int_0^{1/f} \sigma(\tau)\dot{\varepsilon}(\tau)d\tau \\ &= 2\pi f\Delta\varepsilon^2\int_0^{1/f} [E' \sin(2\pi ft)\cos(2\pi ft) + E'' \cos^2(2\pi ft)]dt \end{aligned} \tag{7}$$

It is well known that the energy consists of the stored energy and dissipated energy. If the inertial effect is negligible in the process of deformation, the stored energy is stain potential energy only. This potential energy is stored in the stretching of the molecular configuration and subsequently released completely after unloading. Therefore, the first term of the integral does not contribute to the dissipation of energy during the cycle, and the expression for the dissipated energy Q is given as follows:

$$Q = \int_0^{2\pi/\omega} \sigma(t)\dot{\varepsilon}(t)dt = \pi\Delta\varepsilon^2E'' \tag{8}$$

The dissipated energy, named hysteresis loss, represents the area of the hysteresis loop and causes the temperature rise of the material [34,35].

Heat generation rate ($\dot{Q}$), the amount of heat generated per unit volume per unit time, can be written as follows [16]:

$$\dot{Q} = \frac{Q\cdot\omega}{2\pi} = \frac{1}{2}\omega\Delta\varepsilon^2E'' \tag{9}$$

So, Eq. (1) can be rewritten as:

$$\rho c\dot{\theta} - k\nabla^2\theta = \frac{1}{2}\omega\Delta\varepsilon^2E'' \tag{10}$$

To simplify the calculation, the heat is assumed to conduct along the radial direction of the cylinder, and there is no heat transfer at both