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Material behaviour

Uniaxial ratchetting behaviour of cerium oxide filled vulcanized natural rubber

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ABSTRACT

The uniaxial ratchetting behaviour of cerium oxide filled vulcanized natural rubber (NR) was studied by cyclic asymmetric stress-controlled experiments at room temperature. The effects of mean stress, stress amplitude, loading history and stress rate on the ratchetting strain are discussed. The results show that cerium oxide filled vulcanized NR exhibits obvious ratchetting behaviour under cyclic asymmetric loading. The ratchetting strain increases with increase of mean stress or the decrease of stress rate. In addition, the subsequent loading conditions exhibit memory of the previous loading condition, which can influence the subsequent ratchetting strain.

1. Introduction

Rubber can withstand large strains and prolonged deformation, which makes it widely used in many applications. However, rubber products are often unavoidably subject to cyclic loading. Hence, the fatigue fracture properties of rubber material often determine the service life of these products. In order to ensure security and reliability in the use of rubber products, it is very important to study the fatigue properties and damage behaviour of the materials.

When materials and structures are subject to a cyclic stress with non-zero mean stress, a cyclic accumulation of inelastic deformation will occur (yielding occurs), which is called ratchetting or the ratchetting effect (cyclic creep). Uniaxial ratchetting effect means the accumulation of cyclic strain occur in the mean stress direction and the stress-strain hysteresis loops are not closed. The accumulation of ratchetting strain can damage the material and lead to reduction of fatigue life. Hence, the effects of ratchetting on the safe design of the structure and the fatigue life prediction of materials are significant. In the last 20 years, many scholars have done much research on the ratchetting behaviour of metals and alloys [1–13]. For example, Yang [1] studied the ratchetting effect and fatigue properties of 45 carbon steel. Kang et al. [3] studied the ratchetting effect and fatigue behaviour of SS304 steel, and found that the ratchetting behaviour of metal materials depends on the stress amplitude, mean stress, loading history and loading rate. Chen et al. [5] studied the uniaxial and multiaxial ratchetting of 63Sn-37Pb at room temperature. Their results show that the ratchetting strain of this material gradually increases at a relatively high ratchetting strain rate because of the cyclic softening of the material, which is different from metal materials. Lin et al. [6] studied the uniaxial ratchetting and low-cycle fatigue failure behaviour of AZ91 magnesium alloys, and they developed the stress-based fatigue life prediction models to evaluate the low-cycle fatigue failure life of the studied alloys under cyclic tension deformation. Their innovative work is very important for the reliability design of magnesium alloy components.

However, research on the ratchetting behaviour of polymers is relatively little [14–25]. For example, Lin et al. [15] studied the uniaxial ratchetting behaviour of anisotropic conductive adhesive film, and found that the effects of the mean stress, stress amplitude and loading history on the ratchetting strain are significant. Zhang et al. [19] studied

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Table 1
Experimental compound formulation used in this study.

Ingredient	PHR[a]	Weight%
NR	100.0	54.0
Carbon Black	68.0	36.7
Zinc Oxide	5.0	2.7
Softeners	2.0	1.1
Activator	2.0	1.1
Accelerator	0.5	0.3
Antioxidant	4.0	2.2
Sulfur	1.8	1.0
Cerium Oxide	2.0	1.1

[a] Parts per Hundred Rubber, by weight.

the uniaxial ratchetting behaviour of polytetrafluoroethylene (PTFE) under high temperature conditions. The results show that the ratchetting behaviour of this material is similar to the metal material and the ratchetting effect is very obvious with increase of temperature. Kang et al. [21] studied the ratchetting behaviour of polyester resin and glass fiber filled polyester resin. The results show that both materials have obvious ratchetting behaviour and the ratchetting behaviour is very time-dependence. Shariati et al. [22] studied the ratchetting effect and fatigue behaviour of POM under uniaxial cyclic loading conditions. Yu et al. [23] studied the uniaxial ratchetting behaviour of vulcanized NR. The results show that the uniaxial ratchetting behaviour of NR greatly depends on the stress amplitude and mean stress, and the rubber material exhibits strong memory of the previous high loading history. Wang et al. [24,25] studied the uniaxial and multiaxial ratchetting behaviour of nitrile rubber material and vulcanized NR at room temperature, and explored the effects of the load stress, load history, shear strain rate and creep on the ratchetting strain.

In this study, the uniaxial ratchetting behaviour of cerium oxide filled vulcanized NR was studied by the cyclic asymmetric stress-controlled experiments at room temperature. The effects of mean stress, stress amplitude, loading history and stress rate on the ratchetting strain are discussed.

2. Experiments

The material used in this study was cerium oxide filled vulcanized NR. The mechanical properties and formulation of the studied material are shown in Tables 1 and 2, respectively. The test piece geometry is shown in Fig. 1.

The cyclic stress-controlled deformation experiments were conducted on a micro uniaxial fatigue testing system (EUT1020) at room temperature, as shown in Fig. 2. Typical triangular wave loading is shown in Fig. 3.

Table 2
Mechanical properties of cerium oxide filled vulcanized NR.

Density (g/cm^3)	Shore hardness (A)	Tearing rate (%)	Tensile strength (MPa)	Permanent deformation (%)	Bounce rate (%)
1.152	65	615	20.8	18	44

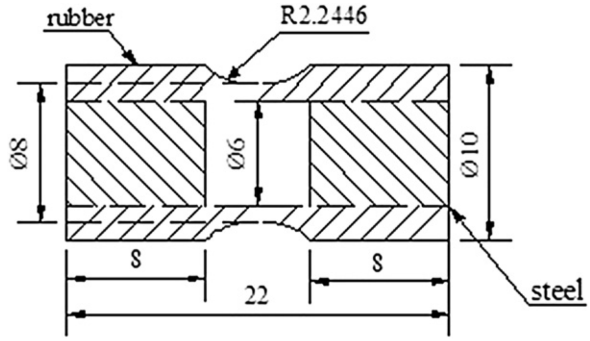

Fig. 1. Geometry of specimens.

The detailed loading conditions for the cyclic asymmetric stress-controlled experiments are listed in Table 3. From Table 3, it can be seen that the specs 1-2 focus on the loading history with variable stress amplitude, while specs 3-4 focus on the loading history with variable mean stress. In addition, spec 5 focuses on the loading history with variable stress rate, while specs 6-9 present the loading conditions of single-step cyclic stress-controlled tests.

3. Results and discussions

Ratchetting strain is the strain accumulation of material under asymmetric cyclic stress [25]. The following traditional definitions of the uniaxial ratchetting strain and its rate with cycles are introduced:

$$\varepsilon_r = \frac{1}{2}(\varepsilon_{\min} + \varepsilon_{\max}) \tag{1}$$

$$\dot{\varepsilon}_r = d\varepsilon_r/dN \tag{2}$$

where $\varepsilon_{\max}$ and $\varepsilon_{\min}$ are the maximum and minimum of the true strain in a cycle, respectively. The true strain and true stress are evaluated as $\varepsilon = \ln(1+\varepsilon_e)$ and $\sigma_e = \sigma_e(1 + \varepsilon_e)$, respectively. σ and ε are engineering stress and engineering strain, respectively. N is the number of cycles.

Fig. 2. Fatigue testing machine.