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Material Properties

Effects of thermal aging on uniaxial ratcheting behavior of vulcanised natural rubber

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ABSTRACT

Vulcanised natural rubber (NR) tends to be hardened and lose damping capability as it is used at high temperature for a long period of time. Therefore, the thermal aging effects on the cyclic response of vulcanised NR need to be considered. In the present work, vulcanised NR sheets were thermally aged in an oven at a temperature ranging from 60 °C to 100 °C for aging time ranging from 24 h to 96 h. Subsequently, a series of uniaxial ratcheting tests were conducted on thermally aged vulcanised NR at room temperature. The thermal aging effects on the ratcheting behavior were experimentally investigated. The ratcheting strain can be restrained in thermally aged rubbers. The ratcheting strain decreases as the aging time or aging temperature increases. The reduction of ratcheting strain in thermally aged rubbers is attributed to the restrained ratcheting strain in the first cycle. Moreover, higher mean stress and stress amplitude cause faster ratcheting strain accumulation. Furthermore, the prior higher mean stress and stress amplitude can restrain the ratcheting strain in the subsequent cycles with lower ones. However, the loading rate has little influence on the ratcheting behavior of thermally aged rubbers.

1. Introduction

Owing to the excellent mechanical properties and good chemical and environmental resistance, vulcanised natural rubber (NR) products, such as automobile tires, dampers, seals and gaskets, have been widely used in the transportation industry [1–3]. In practice, these rubber components are often operated at high temperature. It is well-known that the mechanical properties of rubber components tend to be deteriorated when used for a long period of time [1,4–6]. Therefore, the thermal aging effects on the mechanical properties of vulcanised NR were considered in the past decades. It was found that the hardness increased with increasing aging temperature or aging time. Moreover, the increased aging temperature or aging time caused the decline of the ultimate tensile strength and ultimate strain [4]. South et al. [5] investigated the correlation between mechanical properties and various crosslink densities of vulcanised NR subjected to thermal aging. It was reported that the percentage of polysulfidic crosslinks was decreased and the percentage of monosulfidic crosslinks was increased by thermal aging process. The tensile properties increased linearly with increasing percentage of polysulfidic crosslinks. However, there was little correlation between tensile properties and total crosslink density. Furthermore, the dynamic mechanical properties of vulcanised NR were also influenced by thermal aging, which led to the increase of glass transition temperature (Tg) and loss factor (tanδ) [6].

In addition, many rubber components are often subjected to cyclic loading conditions in industry [7,8]. Therefore, the cyclic response and long-term behavior of rubbers are strongly influenced by the interaction between mechanical loading and thermal aging. Irreversible changes to the rubber due to elevated temperature and oxidative aging became important considerations [9]. Therefore, the thermal aging time affected significantly on the fatigue life of rubbers. The increased thermal aging time caused the deterioration of fatigue life [10]. The changes of molecular structure and crosslink density of rubbers were induced by thermal aging, which resulted in the reduction of fatigue resistance [11]. Therefore, the effects of thermal aging on the cyclic response and fatigue life of rubbers were significant and should be considered in the design of rubber components [9,12].

It is well-known that elastomers exhibit inelastic responses under cyclic loading conditions. A nonzero mean stress during cyclic loading may cause an accumulation of strain, which is termed as ratcheting strain [13–15]. In recent years, the ratcheting behavior of various polymers has been investigated [16–26]. The ratcheting behavior of

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Table 1
The formulations of vulcanised natural rubber.

Ingredient	Composition, phr[a]
NR	100.0
Carbon Black	68.0
Zinc Oxide	5.0
Softeners	2.0
Activator	2.0
Accelerator	0.5
Antioxidant	4.0
Sulfur	1.8

[a] Parts per hundred rubber, by weight.

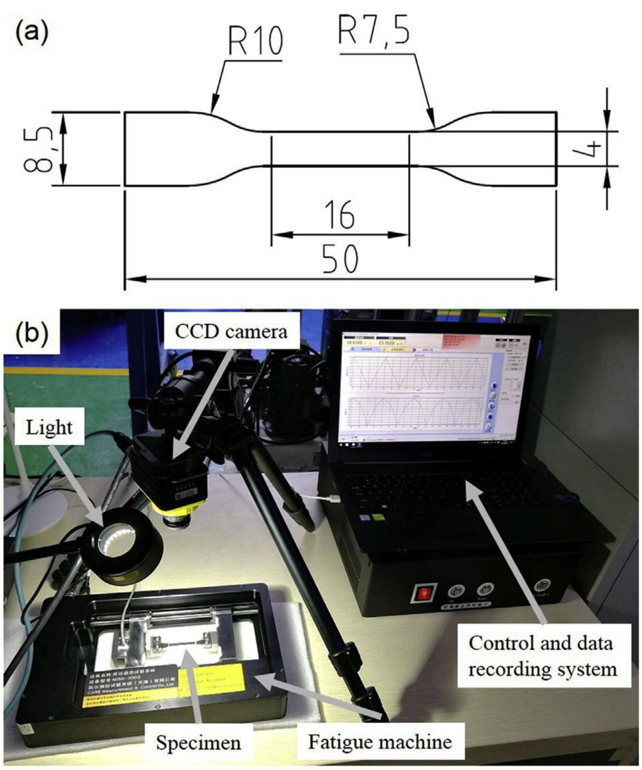

Fig. 1. Schematic of ratcheting test. (a) Specimen dimensions; (b) Experiment system setup.

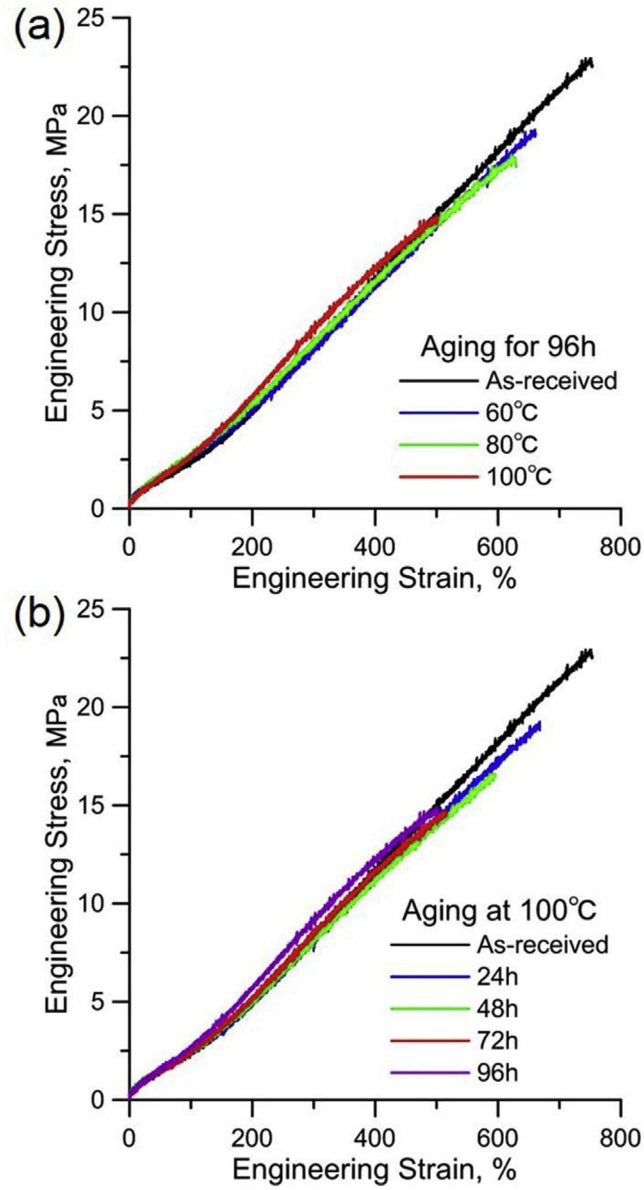

Fig. 2. Typical tensile stress-strain curves of thermally aged vulcanised NR: (a) Rubbers aged for 96 h at various temperatures; (b) Rubbers aged at 100 °C for various time.

rubbers [16–18], epoxy polymer [19], PTFE [20,21] and their components [22,23] was revealed under both uniaxial and multiaxial stress loading conditions. Based on these investigations, it was found that polymers exhibited hysteresis under cyclic deformation, which led to dissipation of mechanical energy and to the accumulation of ratcheting strain [14]. The mechanical loading conditions, such as mean stress, stress amplitude, stress loading rate and their loading history, affected the ratcheting strain accumulation. However, the tendency of ratcheting behavior was not identical for the various polymers. Moreover, the ratcheting behavior of polymer was also influenced by applied environments, which may cause the deterioration of mechanical properties [27,28]. The ratcheting behavior of thermally aged anisotropic conductive adhesive films (ACF) were investigated by Gao et al. [29]. The thermally aged ACF had lower ratcheting strain than the unaged ones. In addition, the ratcheting strains of thermally aged ACF decreased with the increase of hygrothermal aging time.

Until now, the ratcheting behavior of rubbers has been investigated under uniaxial or multiaxial loadings at room temperature. However, it was known that the mechanical properties of vulcanised NR tended to be deteriorated at high temperature for a long period of time [1,10,11]. Therefore, it is imperative to reveal the thermal aging effects on the ratcheting behavior of vulcanised NR for its practical applications. In the present work, the tensile properties and cyclic response of thermally aged vulcanised NR are investigated at room temperature. The effects of aging time and aging temperature on the ratcheting behavior of thermally aged vulcanised NR are clarified. Moreover, the effects of mechanical loading conditions, i.e. mean stress, stress, amplitude, stress loading rate and their loading history on the ratcheting behavior of thermally aged vulcanised NR are also discussed.

2. Experiment

The vulcanised NR sheets were synthesized by Inner Mongolia First Machinery Group Corporation. The formulations of the rubbers are shown in Table 1. Rubber sheets were heat-aged in an oven at a