International Journal of Fatigue 91 (2016) 322–327

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Study of the fatigue behavior of a synthetic rubber undergoing cumulative damage tests

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ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form 24 November 2015
Accepted 25 November 2015
Available online 5 December 2015

Keywords:
Fatigue
Rubber-like material
Cumulative damage test
Self-reinforcement

ABSTRACT

Fatigue damage tests were carried on polychloroprene rubber using a loading sequence with alternate blocks of two force amplitudes, one being damaging and the other not, and carried until the failure of the dumbbell-shaped samples. The duration of the blocks was investigated and chosen to be higher than 20% of the fatigue life of the damaging loading. The presence of cracks was assured by preliminary micro-tomography measurements on samples undergoing constant amplitude fatigue tests at the damaging solicitation. It was observed that the sum of cycles to failure at this damaging loading was more than 5 times the fatigue life at constant amplitude. The behavior of the hysteresis area, the maximal and the minimal strain hinted that the explanation of such an improvement of the fatigue characteristic was caused by the relationship between the crack growth, the strain-induced crystallized area at the tip of those cracks and the self-heating.

1. Introduction

Elastomers are widely used in the industry because of their ability to undergo large strain and to damp energy. Consequently, the knowledge of their mechanical characteristics is very important.

Fatigue behavior is one of those characteristics and requires understanding the damaging processes in order to predict fatigue life.

The studies of the fatigue behavior of the elastomers are very often divided between two approaches: crack nucleation and crack growth [1].

The crack growth considers a sample with already existing cracks or flaws. Studies in [2] proposed a fracture criterion based on the hypothesis that crack growth is caused by the conversion of a potential energy into a surface energy creating a new crack surface. Many authors developed this approach thereafter ([3–6] for example).

The crack nucleation approach considers that a material has an intrinsic fatigue life depending of the solicitation. It can therefore be defined as the time needed for a crack to reach a certain size. [7] and [8] adapted for the elastomers the ideas developed [9] in metals specimens. Several fatigue life criterion have been investigated such as: the maximum principal strain [10], the strain energy density [11], the cracking energy density [12], the Eshelby stress tensor [13] and the dissipated energy density [14,15].

The fatigue behavior of an elastomer is therefore subjected to the way cracks will grow. Studies in [16,17] confirmed that, for the natural rubber, this growth was inhibited by the appearance of a crystallized area at the tip of the crack induced by the deformation gradient. This is also observed by [18] where a Haigh diagram is drawn and showing an increase of fatigue load at a positive load ratio for the natural rubber.

When it comes to multilevel loading tests, the Miner's law is widely used, thanks to its simplicity. However, [19] show that it was not applicable for the natural rubber when subjected to a multilevel loading.

Those considerations led us to investigate fatigue tests where the solicitation alternates between two blocks (presented in a previous paper [20]): one at a damaging loading and the other one at a non-damaging loading. The elastomer investigated is a polychloroprene rubber (CR), which shows a very similar fatigue behavior as NR ([14], for example showed that it is subjected to strain-induced crystallization).

2. Experimental setup

2.1. Specimen, material and fatigue tests

The material studied during this research is a vulcanized polychloroprene rubber (CR) filled with N990 carbon black (Table 1).

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http://dx.doi.org/10.1016/j.ijfatigue.2015.11.026
0142-1123/

Table 1
Details about the formulation of the CR.

Elastomer	CR type G
Filler	Thermal carbon block (N990)
Curative system	S–ZnO–MgO

The specimen used were dumbbell-shaped (Fig. 1) made of a rubber part 30 mm long, bounded to two metal grip parts at each extremity that were subsequently attached to the fatigue machine with screws. Those specimens were molded at 175 °C by an injection press for 4 min. The fatigue tests were conducted with a servo-hydraulic fatigue-testing machine at room temperature. The fatigue campaign was focused on uniaxial force-controlled tests with a sinusoidal signal at a frequency of 5 Hz. All tests were conducted at a force ratio of $R = 0.1$ with R defined by (1):

$$R = \frac{F_{\min}}{F_{\max}} \tag{1}$$

where $F_{\min}$ and $F_{\max}$ are the minimal and maximal loading applied to the sample during a cycle.

2.2. Fatigue damage tests

The fatigue tests were set up by alternate blocks of N_b cycles in two force conditions (85 N and 175 N) and carried until the failure of the sample (Fig. 2) and at 5 Hz. The number of cycles during a block N_b is kept the same during the test. It must be noted that the first block of each test was at a loading of 85 N.

The two loadings were chosen as one being damaging and not the other. In this case, during constant amplitude fatigue tests [21], the fatigue life (defined as the number of cycles until failure of the specimen) for a maximal loading of 175 N is 10^4 cycles and for a maximal loading of 85 N is much greater than 10^6 cycles.

The durations of the blocks were chosen in order to be sure that the damaging blocks would be accompanied by cracks propagation. This aspect was verified by μ-tomography measurements that showed that from 10% of the fatigue life at 175 N, the porosity of the sample increases (Fig. 3). It appears that the size of the longer cracks is around 150 μm at 20% of the fatigue life, with the average crack size been around 30 μm during the whole fatigue test. The duration of the blocks were then chosen as 20%, 50% and 70% of the fatigue life at 175 N (or 2000, 5000 and 7000 cycles). Once the duration of the blocks settled, it was kept constant during the test.

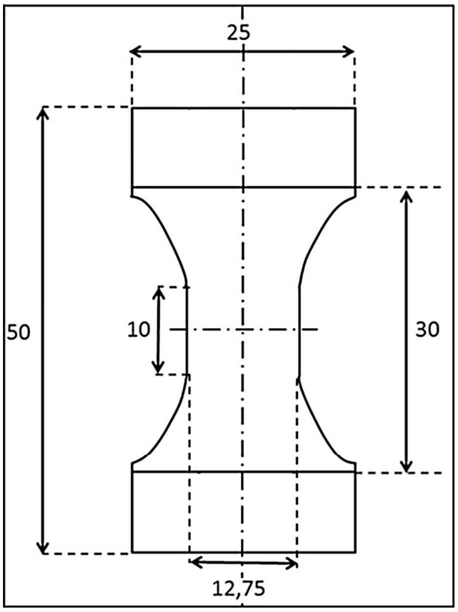

Fig. 1. Dumbbell-type specimen – lengths in mm.

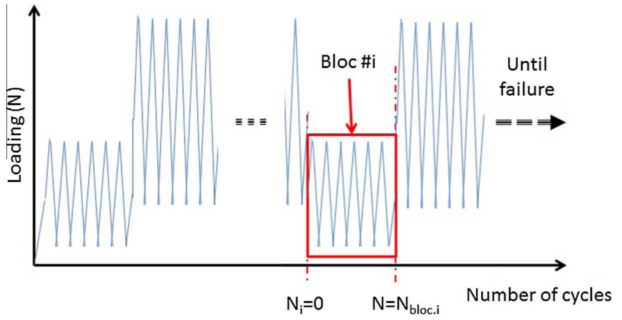

Fig. 2. Fatigue damage test protocole.

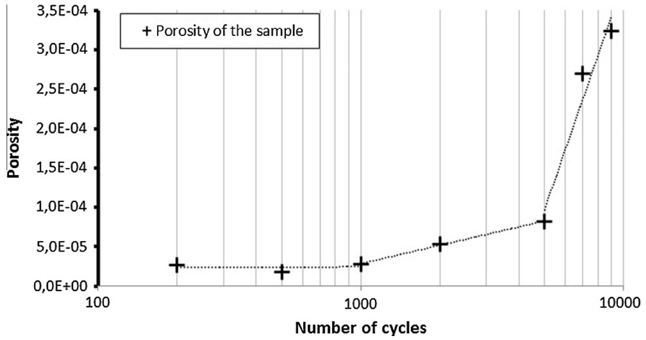

Fig. 3. Evolution of the porosity during a fatigue test at $R = 0.1$, $F_{\max} = 175$ N and $f = 5$ Hz.

The tests were carried until the failure of the sample. The total number of cycles at the more damaging loading (175 N) happens to be from 5 to 8.4 times higher than the fatigue life measured during the reference test at 175 N: 5×10^4 cycles for a block duration N_b of 2000 cycles, 7.2×10^4 cycles for $N_b = 5000$ cycles and 8.4×10^4 cycles for $N_b = 7000$ cycles [20].

3. Evolution of the fatigue parameters during the fatigue damage tests

The objectives of this campaign are twofold:

- Observing the influence of the duration of the blocks on the fatigue behavior of the CR.
- Comparing and understanding the differences between this test and a constant amplitude test.

The parameters investigated in this paper are the hysteresis area, the maximal and minimal global strain.

The reference tests which are shown in this paper are tests at constant amplitude in the same conditions.

The test with a block duration of 5000 cycles will be depicted, as the other block durations showed very close evolutions.

3.1. Hysteresis area

3.1.1. Evolution during the test

For both loading, the evolution of the hysteresis area shows two distinct behaviors between the first block and the other following blocks (Fig. 4).