Polymer Testing 32 (2013) 1045–1051

Contents lists available at SciVerse ScienceDirect

Polymer Testing

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

Material properties

Setup for evaluation of fatigue crack growth in rubber: Pure shear sample geometries tested in tension-compression mode

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ARTICLE INFO

Article history:
Received 2 May 2013
Accepted 10 June 2013

Keywords:
Rubber
Fatigue crack growth
Measurement setup
Tension-compression mode
Pure shear geometry
Tearing energy

ABSTRACT

A novel measurement setup is developed to determine fatigue crack growth and heat build-up in rubber. Loading conditions include tensile and compressional loads. Deviations in the crack shape are detected with special features (swivel arm and additional light sources) and provide the possibility of a subsequent manual correction of the shadow crack length. This results in improved reproducibility and a worst-case scenario is obtained.

Flat pure shear (PS) samples with 2 mm and 4 mm thickness are compared with faint waist pure shear (FWPS) samples. Especially due to the waisted shape and the corresponding non-uniform strain distribution, FWPS samples show augmented in-plane crack growth, but the validity of the tearing energy concept is questionable. PS samples with 4 mm thickness can easily support compressional loads but they show larger heat build-up at comparable tearing energies due to increased thickness. Thus, advantages and disadvantages are identified for each geometry.

1. Introduction

Rubber as an engineering material is not only used in everyday items but also in high performance products. Therefore, its application fields are widely spread and also its application conditions are various. Because of its resilient properties, rubber is often subjected to cyclic loading conditions which might initiate small cracks in the bulk material or on the surface of the component, or cause pre-existing cracks to grow until failure. The sum of these processes is called fatigue. Consequently, performance under quasi-static loads is insufficient for life time analysis. Fatigue life of rubber under cyclic loading smaller than the breaking strain has to be determined.

One factor influencing fatigue is the minimum strain, as described in [1–3]. It is expressed by the amplitude ratio or load ratio (i.e. minimum amplitude/load divided by maximum amplitude/load). A literature survey on the influence of the minimum load on fatigue can be found in [2]. Most studies focus on loading conditions with a ratio greater than or equal to zero [4–6]. Nevertheless, it is described in [7] that for negative load ratio the fatigue crack growth rate is strongly enhanced. Many engineering applications of rubber include compressional loading as well as tensile loading. Therefore, the fatigue behaviour under a negative ratio (tension-compression mode) is of interest and needs to be further investigated.

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http://dx.doi.org/10.1016/j.polymertesting.2013.06.003

Fatigue tests should run fully automatically and user-independently to reduce the user effort for the measurement. Usually, automatically operating fatigue testing systems for rubber specimens use shadow images to evaluate the crack growth. The crack length of such shadow images can be easily evaluated by particular evaluation software because of the high contrast. This kind of evaluation is only accurate as long as there are no deviations of the crack path. The focus of this study lies in tension-compression loading conditions. Due to the deleterious influence on fatigue, deviations in the crack shape and path might occur. Thus, an advanced measurement setup is developed which additionally takes pictures from the back side of the sample and fully illuminated images to detect and evaluate possible deviations.

Moreover, the measurement setup is flexible and extendable, and a complementary thermal imaging system is used to determine the heat build-up. The influence of two different types of pure shear sample geometries on fatigue crack growth and heat build-up during fatigue is determined, and advantages and disadvantages are identified.

2. Theory

The theoretical treatment of fatigue of rubber is based on two approaches [8]: The crack nucleation approach determines the lifetime until a crack appears as a function of parameters such as strain or strain energy density. On the contrary, the crack growth approach is based on the analysis of fatigue crack growth and resulting lifetime estimations [8,9].

One way to describe the crack growth approach is the energy based concept of the tearing energy. This concept was established by Rivlin and Thomas in order to quantify the crack growth rate as a function of a fracture mechanics parameter [10]. They used the Griffith criterion [11] to derive a material specific quantity i.e. the tearing energy. The formula for the tearing energy is specified in [10] for different sample geometries (tensile, trouser and pure shear samples). For pure shear samples, the formula for the tearing energy can be simplified to $T = W_0{}^*h_0$ and is, therefore, independent of the crack length. W_0 is the elastically stored energy per unit volume of the uncut sample and h_0 is the unstrained height of the sample. As also summarized in [8], Thomas showed in [12] that the tearing energy determined by global parameters is related to the local conditions at a crack tip, independently of the sample geometry. This fact was mathematically proved by the J-integral developed by Rice [13].

The approach of the tearing energy was extended to repeated loads and, therefore, to fatigue tests first by Thomas in [14]. Gent, Lindley and Thomas further showed that the fatigue crack growth curves are independent of the sample geometry and that the crack growth approach can be used to estimate fatigue life [9].

It is described in [1,6] how to determine dynamic tearing energies as it is also applied in this study. The force-deflection curve is measured on the cracked sample during testing and the strain energy U is determined with the following formula [15]:

$$U = \int (F|F \geq 0)ds.$$

Thus, the positive part of the area under the loading curve is taken into account for tension-compression loading conditions. The tearing energy is calculated with $T = W_0{}^*h_0 = U/A_{\mathrm{uncracked}}$ where $A_{\mathrm{uncracked}}$ is the area of the uncracked ligament in the plane of the notch.

3. Experimental

3.1. Measurement setup

The measurement setup used to measure fatigue crack growth curves of rubber samples mainly consists of two parts: a hydraulic testing system to apply the loads and a setup including an optical measurement and evaluation system to determine crack growth.

The hydraulic testing system is a MTS 858 MiniBionix. Special clamps have been made which allow form-fit gripping of the samples. The notching has to be reproducible and well-defined, as pointed out in [16,17]. This is achieved by using specially designed notching equipment with which a notch is introduced on one side of the sample. Both, the clamps and the notching equipment have form-fit guide rails, and the length of the notch can be adjusted by a limit stop.

The setup to determine fatigue crack growth is based on the optical measurement and evaluation system CV 5001 (KEYENCE). It is equipped with two cameras each with a resolution of 5 megapixels. The system is programmed and triggered in a way that it takes pictures at particular points during the measurement procedure.

Shadow images are generated with a background light panel at the backside of the sample. The optical measurement system automatically analyses the shadow images and evaluates the shadow crack length. This evaluation is, therefore, user-independent. In order to detect deviations in the crack shape or crack path, additional fully illuminated images are obtained with light sources illuminating the sample surface. Fully illuminated images are saved via ethernet because they cannot be evaluated automatically due to the poorer contrast compared to shadow images. Nevertheless, a correction of the shadow crack length can be performed, if necessary, by a subsequent manual evaluation of deviations. Thus, it can be ensured that the actual damage is taken into account.

Another special feature of the measurement setup is a swivel arm on which the usual background light panel on the back side of the sample and another one on the front side are attached. The swivel arm moves so that always one panel is on a level with the sample, as illustrated in Fig. 1. Hence, additional images from the back side of the sample are obtained. Quality control is ensured because deviations in the crack growth that are only visible on the back side can now be detected. Further, those images give the possibility of an additional evaluation of the strain distribution on the back side of the sample without negative interference of the crack evaluation on the front side. A white dot pattern is applied on the back surface and the strain distribution is evaluated by a subsequent full-field strain