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Heat and strain measurements at the crack tip of filled rubber under cyclic loadings using full-field techniques

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ABSTRACT

This study aims at characterizing heat sources during the deformation of the crack tip zone in carbon black filled Styrene Butadiene Rubber (SBR). For this purpose, the thermomechanical response of cracked specimens was investigated using coupled full thermal and kinematic field measurements and a suitable motion compensation technique. The kinematic analysis enabled us to define the zone of influence of the crack and to measure the maximum stretch ratio level. The maximum stretch ratio level at the crack tip is higher than that measured at specimen failure during uniaxial tensile tests, which can be explained by considering the maximum chain extensibility. The calorimetric analysis shows that the high heat source gradient zone is very much more confined than the high temperature gradient zone. The heat sources at the crack tip remain positive and small during unloading, which indicates that mechanical dissipation is high and confined to the crack tip. This result highlights that the material behaves very differently in the crack tip zone compared to homogeneous tests. This proves that it not possible to predict the behavior of the crack tip zone from homogeneous tests. Moreover, it is observed that the mechanical dissipation decreases with the number of first cycles, which highlights the fact that the material is increasingly accommodated. This study provides the first accurate measurement of heat sources at the crack tip of rubber, constituting a new experimental tool in the fracture mechanics of rubber.

1. Introduction

Elastomers are definitely one of the most versatile of materials, due to their entropic elasticity, their high damping properties, the nature of their thermal sensitivity, the ability of their filler network to reorganize, etc. These properties are all factors involved in mechanisms of deformation and damage, especially in high strain and stress gradient zones such as crack tips. More specifically as regards fracture mechanics in rubber, the tearing energy was defined by Rivlin and Thomas (1953) as the large strain counterpart of the elastic energy release rate previously proposed by Griffith (1921). This approach is still largely employed. The tearing energy is defined at the global scale by considering the balance of energy between the strain in a body and a crack. This is the total energy required to generate a unit fracture surface in a purely elastic body. Nevertheless, a significant part of this energy is dissipated mechanically by viscous effects and

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possibly stress softening at the crack tip. This is the reason why temperature, loading rate and the global loading applied also have significant effects on the tearing energy (Andrews, 1974; Andrews and Fukahori, 1977). Consequently, the local measurement of mechanical quantities such as mechanical dissipation is of paramount importance to improve our knowledge and prediction of crack growth. The present study focuses on the measurement of heat sources, especially mechanical dissipation, at the local scale in the zone of influence of the crack. For this purpose, full-field measurement techniques were used. Even though these techniques have recently spread to investigate crack propagation in rubber (this aspect is reviewed in Le Cam, 2012), no study reports accurate measurements of heat sources at the crack tip of a rubber specimen. The present study aims to perform such measurements by using coupled kinematic and thermal field measurements. For materials undergoing large deformations, such as elastomers, one problem consists of tracking points that undergo large displacements at their surface. Digital image correlation is probably the most suitable technique that can be used to tackle this issue. Temperature variation fields can be measured at the specimen surface using infrared thermography. As temperature fields are influenced by conduction as well as heat ex changes with ambient air and grips, it is not possible to distinguish heat sources due to the thermomechanical couplings (thermoelasticity, microstructural changes if any, etc.) from heat sources due to mechanical dissipation (viscosity, damage, etc.). This is the reason why we processed the temperature variation fields using a numerical strategy based on the heat equation in order to calculate the heat sources (the reader can refer to Toussaint et al., 2012 for further information). The paper is composed of three main parts. The first presents the experimental setup through the material formulation, the specimen geometry, the loading conditions and the full field measurement techniques. The second deals with image processing, including the motion compensation technique, the post-processing of the temperature fields and the heat source calculation. The third part presents the results and discussion. Concluding remarks close the paper.

2. Experimental setup

2.1. Material

The material was non-crystallizable Styrene-Butadiene Rubber (SBR) filled with 50 parts per hundred of rubber in weight (phr) of carbon black. The material was cured for 22 min. The mould temperature was set to 150 °C. The glass transition temperature was equal to −48 °C. Table 1 summarizes the chemical composition of the rubber, whose molar mass was 120,000 g/mol. The thermal diffusivity D_0, which is involved in the heat diffusion equation in Section 3.2.1, was equal to 1.81×10^{-7} m^2/s. The specific heat $C_p \approx C_E$, the coefficient of thermal expansion α and the thermal conductivity λ were equal to 1591 J kg^{-1} K^{-1}, 48.9×10^{-5} K^{-1} and 0.317 W m^{-1} K^{-1} at 25 °C, respectively. Finally, the density ρ_0 was equal to 1101 kg m^3 at the same temperature.

Table 1
Formulation in phr.

Ingredient	
Styrene-Butadiene Rubber (SBR)	100
Carbon black	50
Antioxidant 6PPD	1.9
Stearic acid	2
Zinc oxide ZnO	2.5
Accelerator CBS	1.6
Sulfur solution 2H	1.6

The specimen, whose geometry was 80 mm wide, 2 mm thick and 13 mm high, is presented in Fig. 1. It corresponded to classic pure shear (PS) geometry. It was notched on one of its sides using a razor blade. The initial crack length was about 8 mm. This geometry corresponding to the undeformed state of the specimen was chosen as the reference configuration.

2.2. Loading conditions

The global mechanical loading corresponded to cyclic uniaxial loading. In the present study we focus on the effect of stress softening in the zone surrounding the crack tip. As this phenomenon occurs between the first and the tenth cycle in case of a homogenous tensile test (see reference Diani et al., 2009), ten mechanical cycles were applied. The first and the tenth cycles were analyzed. Moreover, as stress softening mainly occurs between the first and second cycles, the second cycle was also analyzed. The global mechanical loading was applied under a prescribed displacement using a 500 N INSTRON 5543 testing machine (see Fig. 2). The signal shape was triangular in order to impose a constant global strain rate during loading and unloading. The displacement speed of the moving grip was equal to ±200 mm/min. The maximum global stretch ratio, defined as the ratio between the current and initial lengths of the gauge zone, was equal to 1.5.

2.3. Full thermal and kinematic field measurements

Temperature field measurements were performed on one side of the specimen using a Cedip Jade III-MWIR infrared camera, featuring a focal plane array of 320 × 240 pixels and detectors with a wavelength range of 3.5–5 μs. Integration time was equal to 1500 μs. The acquisition frequency f_a was set to 50 Hz. The calibration of the camera detectors was performed with a black body using a Non-Uniformity Correction (NUC) procedure. The thermal resolution, namely the noise-equivalent temperature difference (NETD), was equal to 20 mK. The spatial resolution of the temperature fields is the size of the pixel on the surface of the specimen. For the present test, it was equal to 62.5 μm. To ensure that the internal temperature of the camera was stabilized, it was switched on four hour before the experiment started. This camera temperature stabilization was necessary to avoid any drift in the measurements during the test. The thermal quantity considered in the present study was obtained by subtracting