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# MICROCALORIMETRY AT THE CRACK TIP OF RUBBER

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## ABSTRACT

This study deals with the experimental determination of heat sources in the crack tip vicinity of notched rubber specimens. The determination of heat source evolution at the stretched crack tip is an important issue to understand the physical mechanisms involved in the crack growth of such materials. Indeed, heat sources are a more relevant quantity than the temperature variations because the latter are influenced by the heat conduction as well as the heat exchanges with the outside of the specimen. Due to large deformations undergone by rubbery materials, a motion compensation technique has been developed in order to track material points at the surface of the specimen during the loading. For that purpose, during the experiments, the displacement and the temperature fields are measured by using both kinematic and infrared cameras. Measurements are then processed to associate a temperature and a strain level to each material point on the specimen surface. Then, the heat sources produced or absorbed by the material due to the deformation processes are derived from the corresponding temperature variation maps using the heat diffusion equation. The first results obtained by applying such a methodology open a new route in the study of crack growth in rubber.

**Keywords:** Notched rubber specimen, crack tip, heat sources, full-field measurement, motion compensation technique

## INTRODUCTION

Full-field measurement techniques have recently spread in the experimental mechanics community. For materials undergoing large deformations, such as elastomers, one problem consists in tracking points at their surface that undergo large displacements. Digital Image Correlation (DIC) is probably the most suitable technique [1] that can be used to tackle this issue. When thermo-mechanical couplings occur, temperature variation fields can be measured at the surface of specimens subjected to mechanical loads using infrared thermography. However, the temperature fields are influenced by conduction as well as heat exchanges with ambient air and grips. This is the reason why we use the heat sources, which are deduced from the temperature variation fields using a numerical strategy based on the heat equation. When large deformations occur, the calculation of heat sources is complicated. Recent work [2] has been performed in case of large deformations using both displacement and temperature fields that were measured simultaneously during the test. They were combined to obtain heat source maps. In the present paper, the procedure to combine displacement and temperature fields to calculate heat sources is

first presented. This procedure is applied to the calculation of heat sources in the crack tip vicinity of a notched rubber specimen.

## METHODOLOGY

A motion compensation technique is required to calculate heat sources. This compensation enables us to associate a displacement and a temperature at any point of the specimen surface in the reference configuration, which is chosen as the undeformed state. For this purpose, four steps are necessary:

Step 1: two back-to-back cameras are employed. Displacement field is calculated using DIC technique. The number of measurement points is equal to the number of ZOIs (zones of interest), which is different from that of the IR camera. For displacement fields, Eulerian or Lagrangian configuration can be used, whereas thermal fields are measured in the current configuration. It can be noted that the sensor of each camera does not capture exactly the same zone and the dimension of the pixels of both cameras is not the same.

Step 2: the displacement field is interpolated in such a way that this quantity becomes known over the same grid as that of the infrared camera.

Step 3 : the temperature field is plotted in the reference coordinate. The infrared camera sensor remains fixed whereas the physical points of the surface (where the temperature measurement is performed) move during the test. Since both the temperature and displacement fields are known exactly on the same grid (thanks to the preceding step), a new map is obtained by combining both fields.

Step 4: the same procedure as previously is applied to the reference temperature field. The temperature variations field  $\theta$  is therefore known in the undeformed configuration by merely subtracting the initial temperature field to the current one.

## THERMOMECHANICAL FRAMEWORK

Temperature fields measured at the flat surface of a specimen by an IR camera are 2D, *i.e.* bidimensional. At a given point on the surface, the temperature is nearly homogeneous through the thickness. In fact, a small temperature gradient exists close to the specimen faces due to the heat exchange by convection with the air, but the surface temperature can be considered as very close to the mean temperature in the thickness. Then, by integrating the 3D heat diffusion equation over the specimen thickness [3] and defining the mean thermal disequilibrium through the thickness between the specimen and its surroundings by  $\theta(x, y)$ , the following bidimensional formulation of the heat diffusion equation is obtained:

$$\dot{\theta} + \frac{\theta}{\tau} - D \Delta_{2D} \theta = \frac{s}{\rho C_{E,V_k}} \quad (1)$$

where  $\tau$  is a time constant characterizing the heat exchanges by convection with ambient air along the direction perpendicular to the specimen plane,  $D$  is the thermal diffusivity,  $s/\rho C_{E,V_k}$  is the "heat source" expressed here in  $^{\circ}\text{C}/\text{s}$ .

## EXPERIMENTAL SETUP

The material considered here is a filled styrene-butadiene rubber. The sample geometry is a typical pure shear shaped sample, with a 90 mm width, 13 mm height and 2 mm thick. It is notched on one side using a razorblade. The test was performed using an Instron 5543 uniaxial testing machine with a capacity of 500 N under imposed displacement and triangular signal. The displacement rate of the moving grip was set at  $\pm 200$  mm/min. A set of 10 cycles with a maximum global stretch ratio of 1.5 is performed. Figure 1 presents the experimental set-up. Two cameras were used during the test:

- a cooled 16-bit dynamic Pco-Edge sCMOS camera with 5.5 million pixels. DIC was performed with a resolution of 0.05 pixels and a spatial resolution of 10 pixels corresponding to the distance between two independent points. The acquisition frequency was set at 50 Hz.
- a Cedip Jade infrared camera. The detector size is 320 x 240 (76800) pixels. The integration time and the acquisition frequency were set at 1500  $\mu\text{s}$  and 50 Hz, respectively. The thermal resolution, namely the noise-equivalent temperature difference, is equal to 20 mK for a temperature range of 5 – 40  $^{\circ}\text{C}$ .

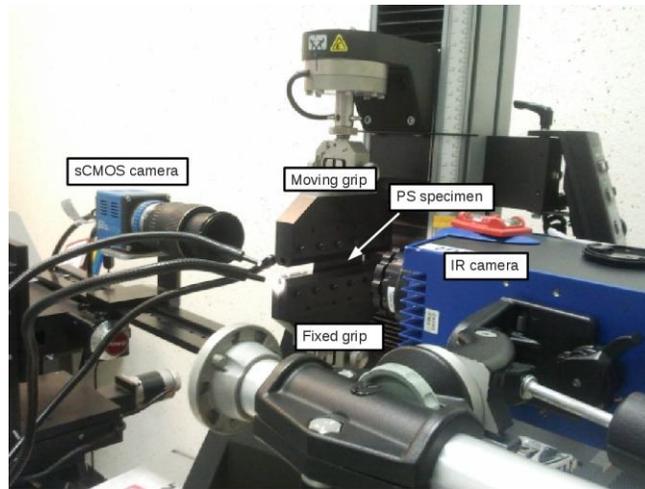


Fig. 1: experimental setup

## RESULTS

The evolution of displacement field and the corresponding temperature variation fields were measured during the two first cycles of the test. The displacement fields that occur during the test are needed to establish the correspondence between the location of the material points of the specimen at any stage of the loading (in the current configuration) and at the beginning of the test (in the reference configuration). Logically, the maximum temperature variation is located in the vicinity of the crack tip. The zone of influence of the crack undergoes highly large strains.

## CONCLUSION

Measuring simultaneously the displacement and the temperature variations and calculating the corresponding heat source fields on the surface of elastomeric specimens subjected to mechanical loading provides information of importance on the complex thermo-mechanical behavior. Specific practical problems have been solved in this work for the determination of these fields. One of them concerns the mapping of all quantities in the reference configuration. A motion compensation technique using both kinematic and thermal fields measurement has been developed. The procedure was then used to determine heat source field, in the crack tip vicinity of notched rubber specimens.

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