Revisiting the deformation mechanisms in rubbers from surface calorimetry-based energy characterization

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Abstract. Complete energy balances carried out during cyclic deformation of rubbers (especially filled rubbers) show that viscosity is not systematically the preponderant contribution to the hysteresis loop: the mechanical energy brought to the material is not entirely dissipated into heat but can be predominantly used by the material to change its microstructure. A ratio in terms of energy has been defined to fully characterize the energetic behaviour of rubbers and opens new way of interpretation of the resistance of rubbers through their ability to store mechanical energy.

Introduction

Elastomers are widely used in many industries such as automotive, nuclear, or civil engineering for their high deformability, high damping and resistance to fatigue. Such properties are generally obtained by adding fillers in the rubber matrix, which induces or increases the hysteresis loop in the mechanical response. Classically, the mechanical energy involved in the hysteresis loop is assumed to be mainly dissipated into heat. Nevertheless, several observations question this assumption: (i) the mechanical response of some elastomers exhibits a hysteresis loop only when strain-induced crystallization (SIC) occurs. In this case, no self-heating accompanies the mechanical cycles [1] (ii) the mechanical hysteresis can be not time-dependent [2-5] (iii) if all the energy contained in the hysteresis loop were due to viscosity, the self-heating would be much higher than that observed experimentally. One can therefore wonder about the nature and the time dependency of the phenomena involved in the formation of the hysteresis loop and about the real contribution of the intrinsic dissipation to it. Three recent studies investigate the energetic behaviour and the energy storage during deformation of rubbers [1,6,7]. The present paper presents and discusses on the results reported in these studies.

Energy balance

The energy balance is carried out from the mechanical and the calorific responses obtained during mechanical cycles. The mechanical response provides the energy and its rate P_{stored}^{cycle} corresponding to the hysteresis loop. Integrating the heat source with respect to time over one cycle gives the mean intrinsic dissipation:

$$\tilde{\mathcal{D}}_{int} = \frac{1}{t_{cycle}} \int_{cycle} s \, dt$$

The difference between P_{hyst}^{cycle} and the intrinsic dissipation gives the energy rate stored at each cycle:

$$P_{stored}^{cycle} = P_{hyst}^{cycle} - \tilde{\mathcal{D}}_{int}$$

To further discuss on the relative contribution of the energy stored in the hysteresis loop of rubbers, a ratio γ_{se} has been proposed. It is written in terms of energy as follows:

$$\gamma_{se} = \frac{W_{stored}^{cycle}}{W_{hyst}^{cycle}}$$

When tends to 0, no energy is stored during the deformation, when tends to 1, the whole hysteresis loop is due to energy stored and no intrinsic dissipation is detected.

Experimental setup

Three materials were considered: an acrylonitrile butadiene rubber (NBR) unfilled and carbon black filled, an unfilled natural rubber and a polyurethane (TPU). Further information on the materials and the specimens used is provided in [7], [1] and [6], respectively. The mechanical tests consist in applying sets of several cycles at an increasing maximum stretch λ_{max}. The number of cycles at a given maximum stretch is chosen in such a way that the last one is mechanically and thermally stabilized. Several loading rates were applied. Temperature measurements were carried out by using FLIR infrared cameras.

Results and discussion

The heat source s (in $W.m^{-3}$) is calculated for each stabilized cycle at different maximum stretches. A diagram is proposed to summarize the energetic behaviour of the three materials considered. It will be fully presented and discussed during the talk.

Concluding remarks

Recent studies reviewed in this paper investigate the energetic behaviour and the energy storage during deformation in different types of elastomers. A ratio γ_{se} has been proposed to relativise the energy stored at each cycle. Results show that viscosity is not systematically the preponderant contribution to the hysteresis loop: the mechanical energy brought to the material is not entirely dissipated into heat and can be mainly used by the material to change its microstructure. This ratio is of a first importance for designing rubber parts as it characterizes the greater or lesser ability of the rubber to absorb mechanical energy without damaging, typically in the case of fatigue [8].

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