Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 21
ISSUE 1
March
2007

Failure mechanisms in thin rubber sheet composites under static solicitation

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Received 26.10.2006; accepted in revised form 15.11.2006

Properties

ABSTRACT

Purpose: Mechanical behaviour and damage mechanisms in thin rubber sheet composites were investigated under static solicitation at room temperature. Two types of rubber are used in this study; Natural rubber, NR vulcanised and reinforced by carbon black and Synthetic rubber (styrene-butadiene-rubber, SBR).
Design/methodology/approach: A comprehensive study has been carried out in order to identify a threshold criterion for the damage mechanism to explain a tearing criterion for the concept of tearing energy of the elastomers and also to give a detail for the damage mechanism depending on the loading conditions. A typical type of specimen geometry of thin sheet rubber composite materials was studied under static tensile tests conducted on the smooth and notched specimens with variable depths. In this way, the effects of the plane stress on the damage mechanism are characterized depending on the rubber materials.
Findings: Damage mechanisms during tensile test have been described for both of rubber types and the criteria which characterize the tearing resistance, characteristic energy for tearing (T) was explained. Damage in the specimens were evaluated just at the beginning of the tearing by means of the observations in the scanning electron microscopy (SEM).
Practical implications: A tearing criterion was suggested in the case of simple tension conditions by assuming large strain. In the next step of this study, a finite element analysis (FEA) will be applied under the same conditions of this part in order to obtain the agreement between experimental and FEA results.
Originality/value: This study propses a threshold criterion for the damage just at the beginning of the tearing for thin sheet rubber composites and gives a detail discussion for explaining the damage mechanisms by SEM results. This type of study gives many facilities for the sake of simplicity in industrial application.
Keywords: Mechanical properties; Rubber composites; Static solicitation; Plane stress; Tearing energy

1. Introduction

Currently, the study of the deformation and the failure of rubber specimens are of considerable practical interest. It is generally accepted that under static loading conditions, rubbers is considered as an isotropic hyperelastic incompressible material. Because a rubber material element cannot be extended to infinite stretch ratio, a damage mechanism at large strain is considered. Today, many of the rubber studies are carried out by real fracture surface to well understand the damage and/or tearing mechanisms underlying the failure process by means of Scanning Electron Microscopy (SEM).

The resistance to failure is measured by the tearing strength for the rubber composites subjected to continued streching. It means that higher tearing resistance gives better toughness. For industrial applications, many of the damage of the rubber composites are due to the growth of the microcracks coming from the manufacturing processes or can be generated by static or cyclic stress prior to failure under the service conditions.

The tearing energy (strain energy release rate, used interchangeable), G, has been found to be the most useful damage criterion for a diversity of fracture phenomena in rubber [1-3, 5]. In its usual description, the strain energy release rate for a crack in a deformed elastic body is given by the following equation;

$$G = -\frac{\partial U}{\partial A} \tag{1}$$

where U is the total elastic strain energy stored in the body, A is the area of one crack surface (measured in the no deformed state), and the partial derivative is taken under conditions of constant boundary displacement so that external forces do no work [1-3].

Evidently this criterion for the tearing of rubber is based on the Griffith's failure theory. The starting point of Griffith's studies was the then current knowledge based on ample observations in glass and metal wires, rods, and plates that there is an approximately two orders of magnitude difference between theoretical strength and bulk strength of solids, and his conclusion, based again on observations, that various forms of imperfections, defects and scratches are primarily responsible for this discrepancy. The obvious approach would then be to calculate the correct values of the maximum stresses around these defects and compare them with the theoretical strength of the material. For certain simple test specimens and loading conditions, it is possible to derive analytical solutions for G and these have been used to verify its validity as a failure criterion. It describes the slow propagation of a crack as a result of conversion of elastic energy stored in the bulk into surface free energy. This energy is independent of the shape of the test piece. After that, the tearing theory was validated in the case of a crack edge present in the specimen and shown by following equation [3, 5].

$$T = -\frac{l}{t}\left(\frac{\partial U}{\partial a}\right) \tag{2}$$

where T=tearing energy, t=thickness of the specimen, l=deformed length, a=crack length (edge length/notch), ε=density of elastic stored energy.

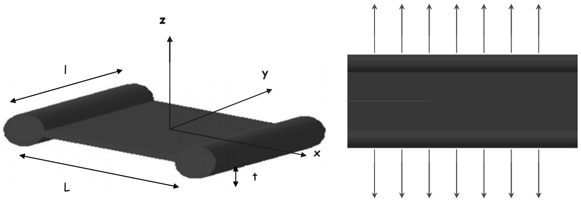
For more complex specimens and loading conditions, it is often necessary to turn to experimental or computational methods to evaluate G. Finite element analysis (FEA) became now most popular method in this domain [4-15]. Even our literature review is limited, it expose a number of divergence in this area. These should motivate the present work to discuss the damage mechanisms above all instantly at the beginning of tearing in thin rubber sheets. The cause which is the origin of the first damage has not been studied. This is main objective of the present paper.

2. Experimental conditions

2.1. Materials, tests and SEM analysis

Pure shear specimen geometry was used for both of two types of rubber in this study; Natural rubber, NR vulcanised and reinforced by carbon black and Synthetic rubber (styrene-butadiene-rubber, SBR). The geometry and nominal dimension of the specimen is shown in the Figure 1.

Testing was run on a uniaxial, servo hydraulic test machine (10 kN) with a nominal laboratory air temperature of 20°C. A software program was used for all of the test data acquisition system with a 1ms period. A constant speed of extension was used (1 mm/s) for all the tests.



(L=157 mm, l=34 mm and thickness, t=2 mm)

Fig. 1. Pure-shear sample geometry used for NR and SBR

In order to measure the effect of the crack size on the tearing energy, all the samples were razor nicked to different length for creating edge crack (hereafter called a_1…. a_5) on the specimens as shown in Table 1. This type of specimen geometry favourite the pure shear and plane stress conditions.

Table 1.
Length of edge cracks for NR and SBR

a_1	17 mm	a_4	52.33 mm
a_2	26.16 mm	a_4	78.5 mm
a_3	40 mm	a	no edge crack

The lengths of a_2, a_4 and a_5 represent 1/3 of L/2, 2/3 of L/2 and L/2 with the total length of the specimen.

The SEM photomicrographs were carried out in a 435 VP – LEO-2003 model scanning electron microscopy (SEM). Failure analysis of the specimens were analysed just at the beginning of the crack initiation at the end of the notch. The cause which is the origin of the first damage was evaluated, in other words, above all instantly at the beginning of tearing in thin rubber sheets were examined.

3. Results and discussion

Tensile test results were given in the Figure 2a and b for the smooth and notched specimens of NR and SBR with different edge cracks. Generally, the same evolutions are observed in all of the stress strain curves in the case of tension. For each geometry (without edge crack and with edge crack), All the tests were repeated 5 times. During the test, the characteristic effect of the crystallisation on the NR specimens was observed at the level of the elongation of ~5 mm just after an incubation time. But, in major of the NR specimens with different length of the edge crack, the effect of the recrystallisation results in the decrease of the tearing energy. In every condition, the SBR specimens have shown higher mechanical properties. Evolution of the crack at the end of the notch is the same for NR and SBR. It begins to open with the solicitation and takes an elliptical shape. During the test, the crack does not propagate up to instable propagation. It means that there is no progressive and smooth crack propagation but failure occurs suddenly. Additionally, a typical phenomenon of bifurcation was observed on the NR and SBR notched specimens. This takes shape at the beginning of the failure but after a short time, the crack goes back over the initial direction due to decrease of the strain energy.

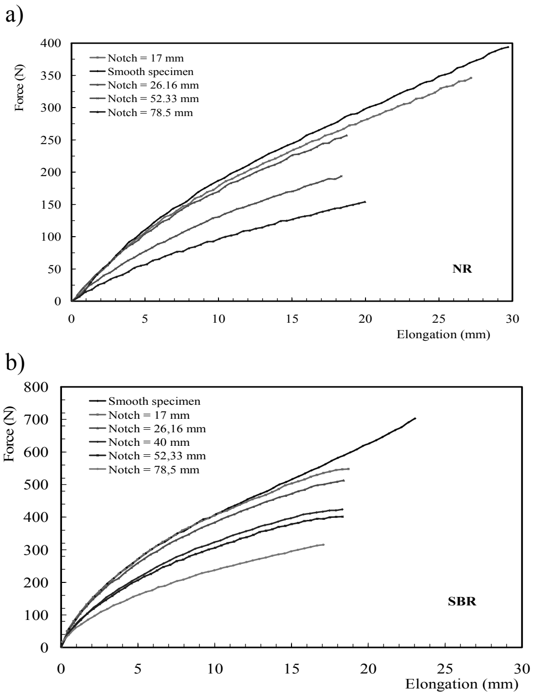


Fig. 2. Tension test results of the smooth and notched specimens of NR a) and SBR b) with different edge cracks

Figures 3 shows the calculation of the tearing energy for NR obtained directly starting from its principal definition given in the equation of 2. The same way were realised also for SBR. For the sake of simplicity, a method known as of "tensile testing of multi-samples" is employed. All the samples smooth and with edge cracks in various lengths were stretched until the rupture and then, the partial derivation of the elastic stored energy was calculated in the specimens depending of the length of the edge crack. For this research, more than 200 case studies were carried out on the NR and SBR (smooth and notch) specimens. The values of lengthening for each length of edge-crack during the rupture were variable between1 and 18 mm.

After that, the results of the Figure 3 were used for determining the tearing energy, T, of the tested specimens as a function of the displacement. All our experimental results showed that the tearing energy, T, is independent of the length of the edge crack. In other words, tearing energy increases as a function of the displacement, i.e. resistance to the tearing increases (Figure 4a).

Here, for practical usage, critical tearing energy, T, in final failure should be defined. In order to calculate these values, total displacement values up to the final failure have been recorded for each length of the edge crack and then calculated the elastic stored energy were found for each condition. Finally, critical tearing energy, T, was compared for NR and SBR specimens depending on the length of the edge crack.

The mean values for critical tearing energy of the NR and SBR are found around the 10, 47 and 19.15 kN/mm respectively (Figure 4b). These experimental results are very useful in industrial applications and they are in conformity with the theoretical approaches signifying that the tearing energy is independent of the length of the crack [1-5, 15].

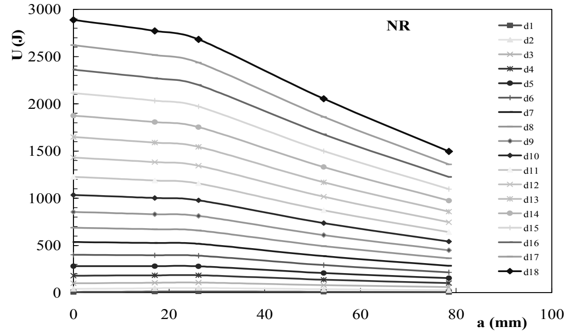


Fig. 3. Elastic stored energy depending on the length of the edge crack for a given displacement

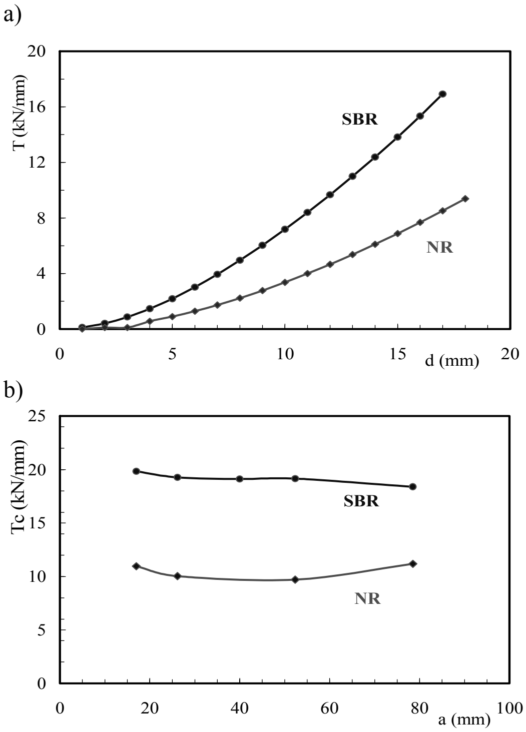


Fig. 4. Evolution of the tearing energy depending on the displacement a) and evolution of the critical tearing energy as a function of the length of the edge crack b)

Damages in the specimens for NR and SBR evaluated by SEM just at the beginning of the tearing, are shown in the Figures 5 and 6 respectively. For this analysis, tensile samples were drawn only up to the beginning of the crack propagation and then stopped the machine.

The SEM photomicrographs show the same damage mechanism and/or the evolution of early propagation for both of the NR and SBR in a state of plane stresses. A convex form is observed at the bottom of crack of the samples. It is noted that the presence of holes of round form and originally defects begin around the small metallic particles used as fillers during the fabrication of the materials mainly in the SBR specimens (Figures 5 and 6). These holes indicate well the formation of micro cavitations just at the early beginning of the crack propagation (at the bottom of the edge crack) that these cavitations play an important role in final damage of the rubber composites. It means that the development of the cavities occur just at the early beginning of the deformation at the bottom of the edge notch of the specimen and final rupture take shape from one of the well developed cavities.

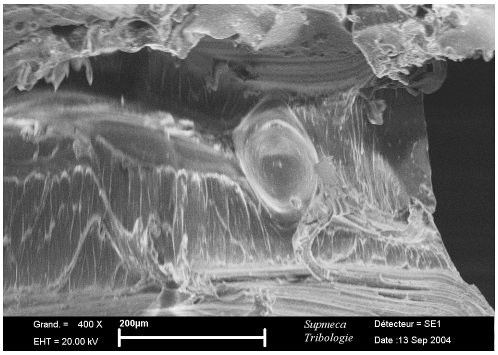


Fig. 5. SEM photomicrographs of early propagation of NR

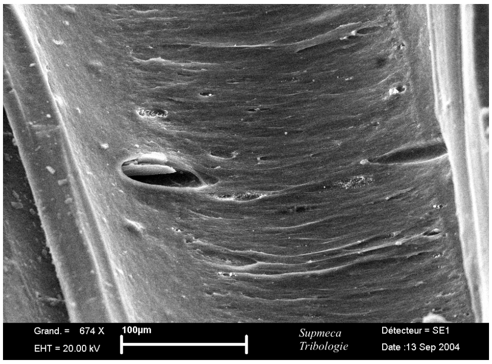


Fig. 6. SEM photomicrographs of early propagation of SBR

4. Conclusions

This work gives a clear idea on threshold criterion for the damage just at the early beginning of the damage for thin sheet rubber composites. The edge crack opens and does not propagate during the deformation by taking an elliptical shape up to failure. Recrystallisation decreases the tearing energy of Natural Rubber samples. Cavitation formed at early beginning of the deformation is the major effect on the damage mechanisms of NR and SBR materials even the type and nature of the form of the cavitation is different in both of the materials.

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