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Damage initiation mechanism in rubber sheet composites during the static loading

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ABSTRACT

Purpose: Mechanical behaviour and damage initiation 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: Damage mechanism; Static solicitation; Rubber composites; Plane stress; Tearing energy

PROPERTIES

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.

Damage mechanism of rubber composites, involves a complex interplay between material properties and service conditions. 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. 2]. 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].

An important feature of fracture mechanics is that G is largely independent of test geometry, even though it is rate and temperature dependent. Just as viscosity is a material property characterizing the flow behaviour of a fluid, G is the analogous material property indicative of the strength of a solid. For elastomeric structure, G normally increases as the test rate is increased or temperature decreased. At sufficiently high temperatures and slow test speeds, G achieves a threshold value, *Go,* which is the lower limit of the mechanical strength of an elastomer in the absence of chemical effects.

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 calculated the correct values of the maximum stresses around these defects and compare them with the theoretical strength of the material.

A simple question is introduced here if it is possible to identify a tearing energy by a formula for a particular case of rubber composites. 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. This situation 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].

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

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

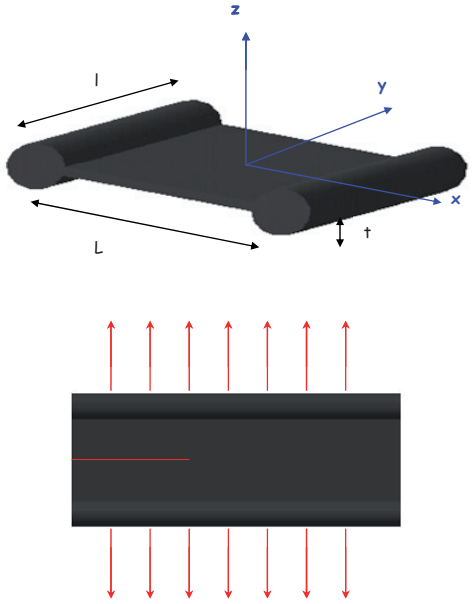
For more complex specimens and loading conditions, it is often necessary to turn to experimental or computational methods to evaluate G. Finite element analysis (FEA) became now most popular method in this domain [3-19]. Even our literature review is limited, it expose a number of divergence in this 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

The 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. It consists of a thin, wide sample, with a small height, h, containing a long crack as shown. Because the sample is clamped along its length, it is prohibited from deforming in this direction when the sample is strained. Typically, a constant rate of displacement of the clamps is imposed to cause the crack to propagate. Away from the crack tip, the state of the deformation is pure shear.



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

Fig. 1. Pure-shear specimen geometry used for NR and SBR rubber composites

Testing was run on a uniaxial, servo hydraulic test machine (10kN) 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.

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

Remark to table 1: 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

3.1. Tensile tests and evolution of the tearing energy depending on the displacement

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. The level of the force-elongation curves decrease regularly depending on the edge crack size.

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. This evolution was shown by Figures 3a and b for NR and SBR specimens respectively. 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. In this case, the energy level (deformation) decrease and after a certain time, the crack evolution takes its initial direction.

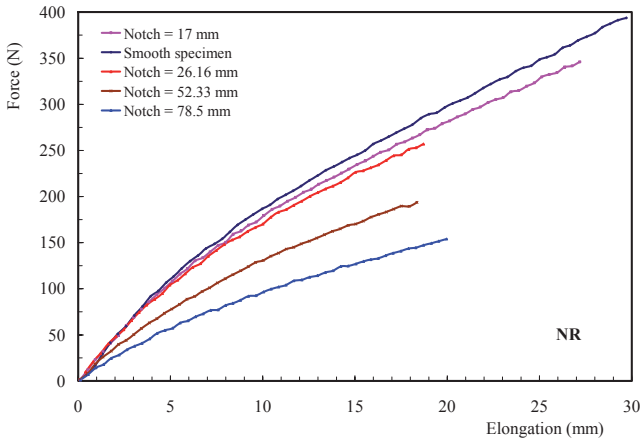


Fig. 2a. Tension test results of the smooth and notched specimens of NR specimens with different edge cracks

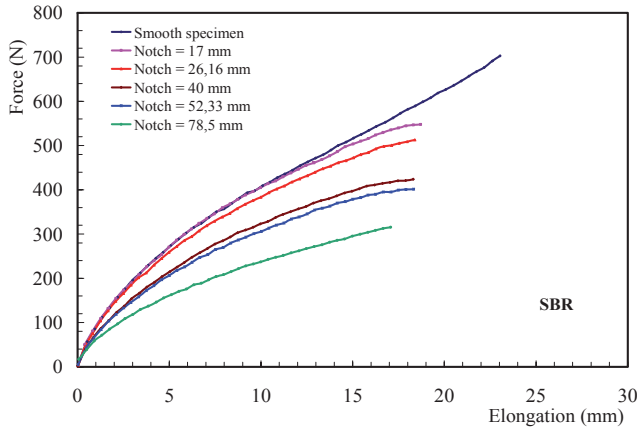


Fig. 2b. Tension test results of the smooth and notched specimens of SBR specimens with different edge cracks

Figures 4a and b show the calculation of the tearing energy obtained directly starting from its principal definition given in the equation of 2. 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 4 were used for determining the tearing energy, T, of the NR and SBR 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 5a).

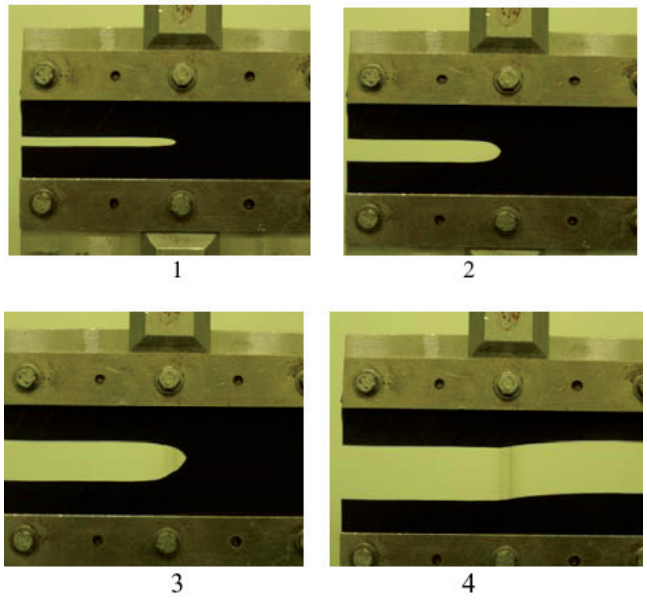


Fig. 3a. Different stages of the crack evolution in the NR specimen during uniaxial tensile test, 1) opening of the crack, 2) elliptical shape of the bottom of the notch, 3) beginning of the crack and 4) final stage, tearing of the specimen

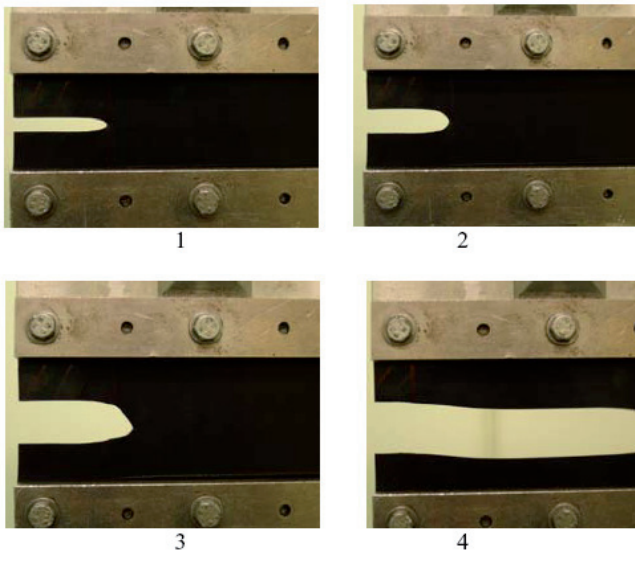


Fig. 3b. Different stages of the crack evolution in the SBR specimen during uniaxial tensile test, 1) opening of the crack, 2) elliptical shape of the bottom of the notch, 3) beginning of the crack and 4) final stage, tearing of the specimen

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.

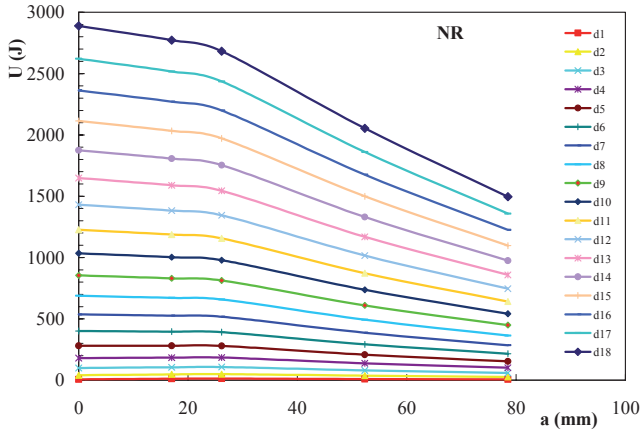


Fig. 4a. Elastic stored energy depending on the length of the edge crack for a given displacement for NR specimens

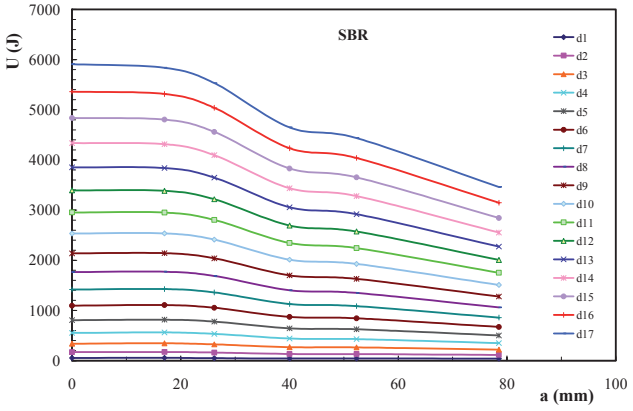


Fig. 4b. Elastic stored energy depending on the length of the edge crack for a given displacement for SBR specimens

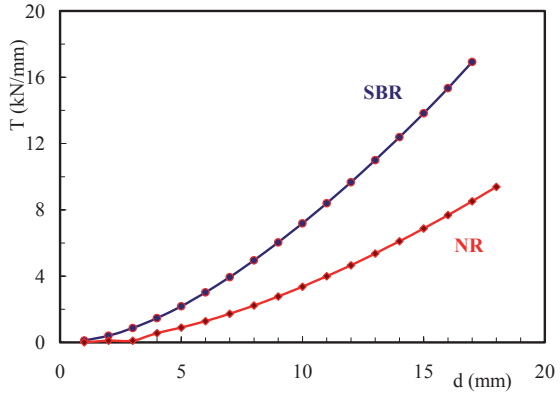


Fig. 5a. Evolution of the tearing energy depending on the displacement for NR and SBR specimens

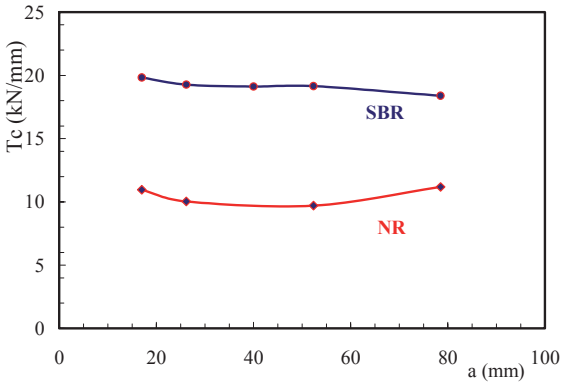


Fig. 5b. Evolution of the critical tearing energy as a function of the length of the edge crack for NR and SBR specimens

Finally, critical tearing energy, T, was compared for NR and SBR specimens depending on the length of the edge crack. Additionally, strain crystallizing rubber such as NR show virtually no time dependent crack growth under static solicitation.

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 5b). 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, 2-5].

In fact, it is very easy to understand the damage behaviour of the rubber composites by this simple method. At least, a safety values in a short time can be obtained during the manufacturing.

3.2. Study of the tearing surfaces by means of Scanning Electron Microscopy (SEM)

Damage in the specimens for NR and SBR evaluated by SEM just at the beginning of the tearing, are shown in the Figures 6a-b-c, 7a-b and 8 respectively. For this analysis, tensile samples were drawn only up to the beginning of the crack propagation and then stopped the machine. The samples were kept constant at this position by means of a special device having a quick locking system where special cover has been arranged and then, the entire setting is placed in SEM for the examinations.

The SEM photomicrographs show about the same damage mechanism and/or the evolution of early beginning of the crack 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 (Figure 6b). These holes indicate well the formation of micro cavitations just at 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. These results are news and originals for explaining the damage evolution just at the beginning of the crack initiation.

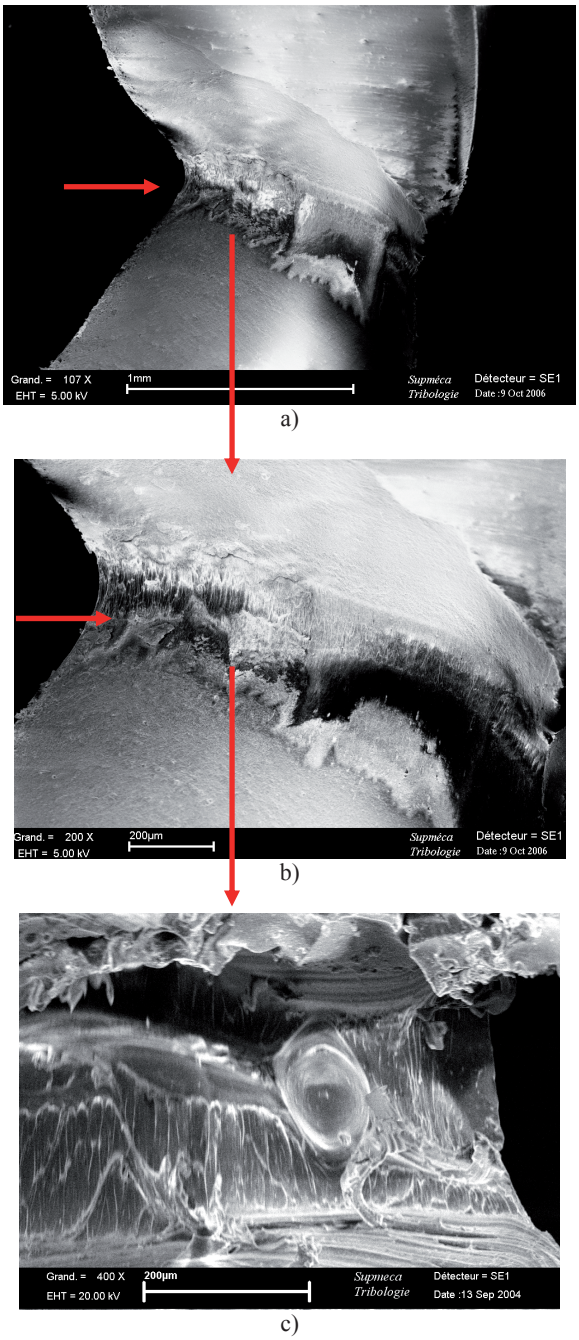
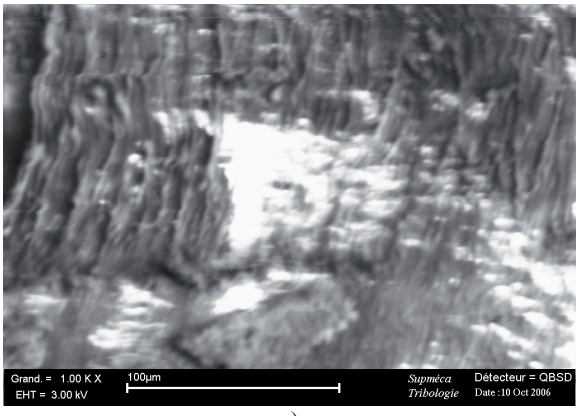


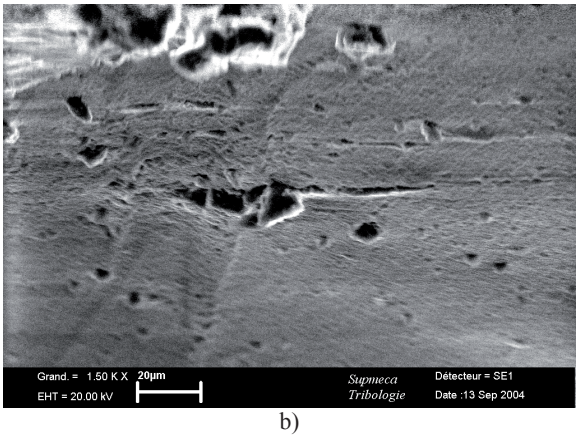
Fig. 6. SEM photomicrographs showing the beginning of the crack propagation at the bottom of NR specimen, a, b and c

If the formation of the micro cavities at the bottom of the notch are compared for both of the NR and SBR specimens, it can be

detected that they occur from the beginning of the crack initiation. However, the formation of the micro cavities, in other words, the causes of the form for both of the materials are different. In the case of the SBR specimens, mainly metallic particles are observed at the origin of the formation of the micro cavities.



a)

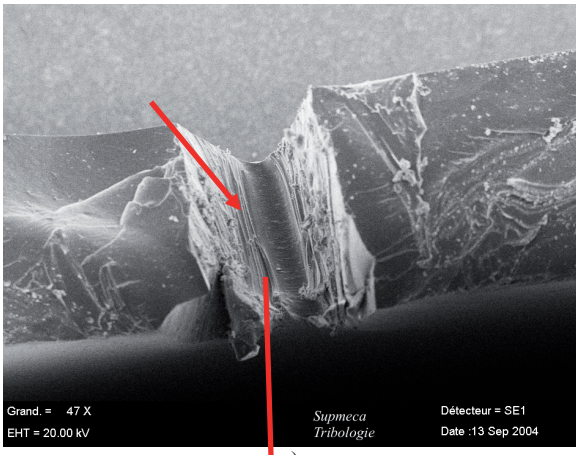


b)

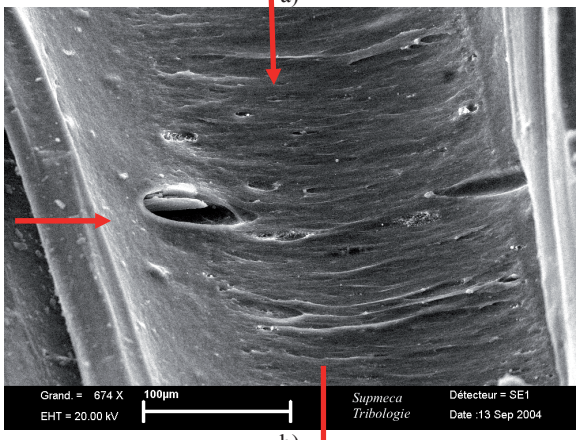
Fig. 7. SEM photomicrographs showing the damage too early at the beginning of the crack propagation of NR specimen a) and the hole formation at the bottom of the notch b)

In reality, this discrepancy comes from the crystallisation phenomenon of the NR specimens. In any case, the cavities take place in a helicoidally form from a simple defect, which should be the origin of the different natures such as metallic or non metallic particles or local heterogeneity or even the nature of the structure such as the natural defect of the matrix, which are not the coherent with the matrix.

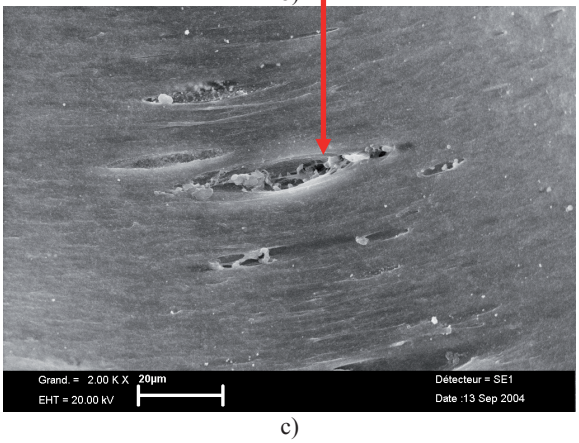
More detail pictures of the micro cavities formed at the beginning of the crack initiation are shown in the Figure 8c and 8d that can be observed metallic particles inside of these micro cavities very clearly. Figures 6c and 7a indicate the alignment of chains just at the edge cracks, only the initiation stage of the failure of chains. Mainly this observation were on the NR specimens



a)



b)



c)

Fig. 8. SEM photomicrographs showing the beginning of the crack propagation at the bottom of the SBR specimen, a, b and c

As well known, high-molecular-weight elastomers contain a distribution of chain lengths between crosslink points. When deformed, chains align, and the load is irregularly carried by the structure (set-up) filaments like fibre. The structure make every effort to distribute the stress among the chains, thereby reducing

local stress concentration, but it is limited from completely doing so because of the complex topology.

At sufficiently low elongation levels, no chains are broken, but as deformation progresses, chain rupture occur well before crack initiation. In fact, chain rupture is a dissipative process, in which the energy store elastically in the chain is lost (converted to heat), and the force that the chain was carrying prior to breakage is quickly distributed among neighbouring chains. This results in the overloading of other chains. Chain breakage is not random, but rather is more extensive at the tips of inherent or intentional flaws.

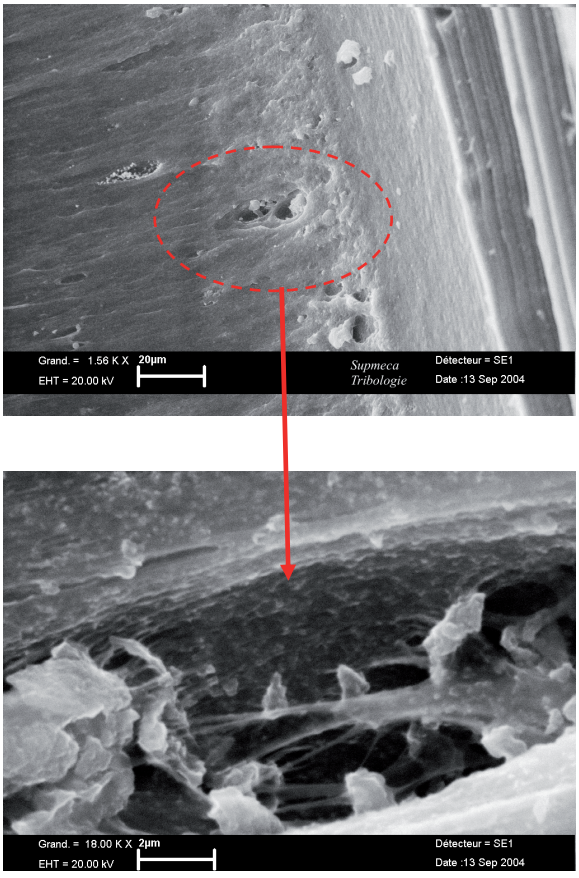


Fig. 8d. SEM photomicrographs of micro cavity formed at the just beginning of the crack propagation in the SBR specimen

3.3. Discussion on the role of the energy dissipation on the NR and SBR samples

Generally, if, upon deformation, stress concentrations within a complex structure were somehow eliminated, all load bearing chains would carry the same force. Fracture would then occur by a rapid dissociation of spinal column bonds at a very high critical stress causing complete collapse of the sample. Naturally, some molecular mechanisms might result in this phenomenon and somehow they can play on the failure mechanism on the rubber composites. When an overloaded chain in a structure breaks irreversibly and transmits the load it was carrying to neighbouring chains, the elastic energy of the broken chain is dissipated into heat. This is termed "catastrophic energy dissipation"-the structure is permanently damaged and the chain after rupture bears no load [8-19].

If highly stressed chains could reduce the local stress, but maintain load-carrying capability, the over all effect would be to increase the chain load uniformity, and hence macroscopic strength. This type of mechanism can roughly be cited to explain the higher strength of sulphur cured elastomeric structures but also for the vulcanized elastomeric structures.

The linkages are thought to have the ability to break and reform when over loaded, thereby reducing the load borne by highly stressed chains, and thus resulting in a more uniformly loaded structure. A chain that has experienced this type of energy dissipative process still maintains load-carrying capability. This can be nominated "no catastrophic energy dissipation." Similar arguments can also be made to give an explanation for the rubber composites used for this study.

Considering a rubber composite, vulcanised and reinforced by carbon black used in this study, it seems unlikely that the addition of carbon black to elastomers change the natural strength of the spinal column bonds in the structure of chains. This addition results in considerably improved fracture energies. It would seem that the addition of carbon black must somehow reduce, compared to the unfilled case, the degree of stress magnification at the tips of edge crack. [18]. In fact, this is implicit from the fact that a filled material has a higher resistance to deformation than an unfilled one. In spite of the increased average chain load, at an edge crack in a black-filled material, no catastrophic energy dissipating processes can apparently reduce stress magnification-in effect allowing the stress to be rather even distributed throughout the structure.

In the presence of carbon black, the sagging chain may become adsorbed onto the filler surface. Upon application of stress, these chains could bear load, and perhaps the chain may even accommodate the load by slipping along the filler surface. More generally, no catastrophic dissipative processes such as chain slippage along the surface of carbon black seem to be important in reinforcement.

Additives that considerably support bonding of carbon black to rubber have been shown to reduce both hysteretic losses and fracture strength. On the other hand, it is expected that an extremely weak interaction is undesirable, since, even though slippage could readily occur, little energy would be expended in the process. Based on the above arguments, there would seem to be an optimum level of adhesion between rubber and filler for the best reinforcement, although the desired interaction may depend on the particular fracture conditions.

The results obtained on the NR (it crystallises when loaded) and SBR (more elastic) samples under static solicitation, give a clear idea that the structure and additive elements play a major role on the fracture behaviour – failure modes of these materials.

Some interesting interactions between the structure, chains and additive elements occurred in the rubber composites can answer why the evolution of the tearing and or critical tearing energies are different for both of the NR and SBR structures.

4. Conclusions

In this paper, a detail experimental study was carried out on the damage mechanisms of the rubber composites. Some major trends from this comparative study can be underlined from this study:

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. The stresses are the basic reasons at the edge crack just before the crack propagation both in forcing the materials to relocate and in orientation effects, in other words, crack deviation mechanism always occur both of NR and SBR rubber composites.

Crystallisation phenomenon give an additional effect to decreases the tearing energy of NR samples.

Cavitation formed at early beginning of the deformation have also a major effect on the damage mechanisms for NR and SBR materials even the form of cavities is different.

Additional information

The presentation connected with the subject matter of the paper was presented by the authors during the 12th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAM3S'2006 in Gliwice-Zakopane, Poland on 27th-30th November 2006.

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