Nucleation, Growth and Instability of the Cavitation in Rubber

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Summary
Elastomeric Matrix Composites (EMCs) subjected to static and fluctuating loads basically fail due to the nucleation and growth of defects. In fact, higher hydrostatic pressure influences mechanical behaviour of EMCs. In other words, the change in behaviour of EMCs due to the nucleation of cavitations under the hydrostatic pressure is evaluated for understanding of the mechanics underlying the damage mechanism. Two types of specimens are used in this study; Natural rubber, NR vulcanised and reinforced by carbon black and Synthetic rubber (styrene-butadiene-rubber, SBR).

1. Introduction

Elastomeric Matrix Composites (EMC- rubbers) are considered as isotropic hyper elastic incompressible materials under static loading conditions. Because a rubber material element cannot be extended to infinite stretch ratio, a damage mechanism at large strain is considered. The phenomenon of cavitation influences the toughening mechanism of rubber-modified plastics [1-10]. Indeed, cavitation in elastomers is thought to be initiated from flaws, which grow primarily due to a hydrostatic tensile stress, and ahead of the crack there will be not only a high stress perpendicular to the plane of the crack but also significant stress components in the other direction. [1-3, 5, 7].

In the literature, the cavitation phenomenon is generally related to the existence of the gas bubbles trapped in the material during the production stage and the growing of the cavities would then be the result of the growing the gas bubble. Instable failure mechanism at the end of the cavitation is not well known too. Here, an experimental study was carried out on the cavitation phenomenon of the pancake shaped specimens from NR and SBR (smooth and notch). Initiation and propagation stages of cavity and also the instability conditions of the cavities have been determined by simple static tensile and torsion testing conditions.

In order to complete the exploration of the cavitation in NR and SBR, we have conducted a comparative study on the effect of the hydrostatic pressure and the effect of the stress triaxiality at the tip of the notch. So, tensile and torsion tests conducted on the smooth and notched specimens, of whom the depths varied from 3 to 15 mm, showed that a very strong hydrostatic pressure at the centre of the specimen governs the damage. However, the effect of the stress triaxiality increases at the tip of the notch. So, a real competition between the hydrostatic pressure and the stress triaxiality should be attended just from the beginning of the deformation, which characterises the damage mechanism of the NR and SBR. In-situ observations of uniaxial tensile and torsion testing are also presented by using X-rays computed tomography, CT, (medical scanner) and compared with those of the scanning electron microscopy (SEM).

2. Experimental conditions

Simple tensile and torsional testing were conducted as a very slow constant strain rate in the medical scanner (Exel 2000- X-rays Computed tomography, CT) by means of a mechanical test device (electrical jack + carbon fibre tube equipped with a load cell) for in situ measuring of tomographic density (TD) in the unity of pixel and for observing internal damage-the formation of the cavitation. Pancake shaped specimens from synthetic (SBR) and natural rubber (NR), of which notch lengths varied from 3 to 8 and 15 mm, vulcanised and reinforced by carbon black were used.

Failure surfaces of the specimens were analysed with the scanning electron microscopy (SEM) to evaluate the surface damage and the results are compared with the observations obtained by X-rays CT. Percentage of the cavities depending on the notch size were measured by means of the image analysis (Visilog 4).

3. Results and discussion

3.1. Nucleation and growth of cavitation in static tensile and torsion conditions

Tensile and torsion test results were given in the Figures 1 and 2 for the pancake shaped specimens for NR and SBR (smooth and notched). Generally, the same evolutions are observed in all of the stress strain curves in the case of tension and torsion. However torsion effect applied on the specimens (20°) increases the resistance of the specimens and postpones the formation of cavities. Probably, the effect of torsion gives higher level in the stress strain curves. This evolution explains very well the cavitation phenomenon in three stages. At the first stage, a very high slope, nearly linear, is observed and just after, this stage is preceded by the second stage that gives the nucleation of the first cavity. The slope of the second stage is very low. For the NR and SBR, the nucleation of the cavities during the deformation is identified with the first deviation just after a short

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incubation time due to macromolecular changement of the chains in some local sites. [3-6, 8-10]. So, the first formation of the cavity is essentially due to the change of the slope in the curves (passage from the first stage to the second stage). However, major part of the cavities occurred in the second stage. Evidently, the evolution of these curves changes depending on the size of the notch. Finally, the third stage-final stage the gives a higher slope then the 2nd stage. This is explained mainly by the multiplication and final tearing stage. In other words, the formation rate of the cavities may be important from the beginning of elongation, about at level of 20 %. The curves obtained for the NR specimens stabilise from the elongation level of 75 % and about 100 % of the elongation,

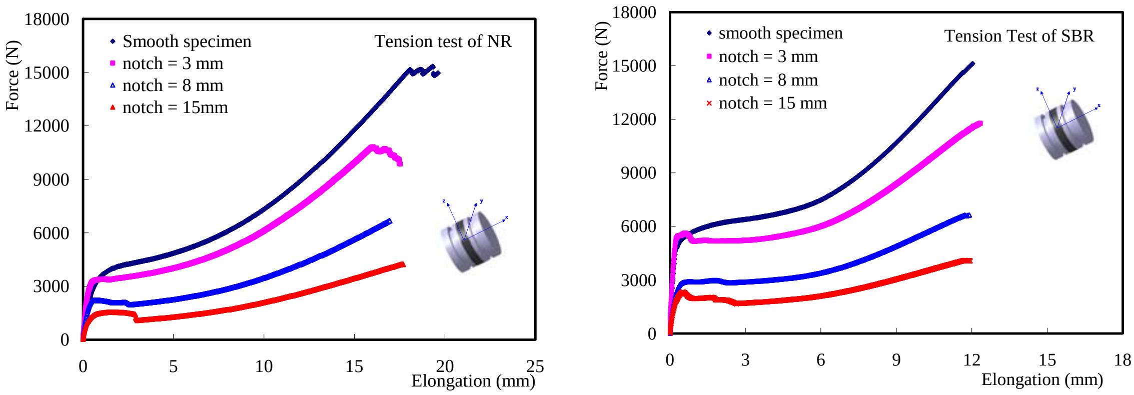


Figure 1 Tension test results of pancake (smooth and notched) specimen of NR and SBR

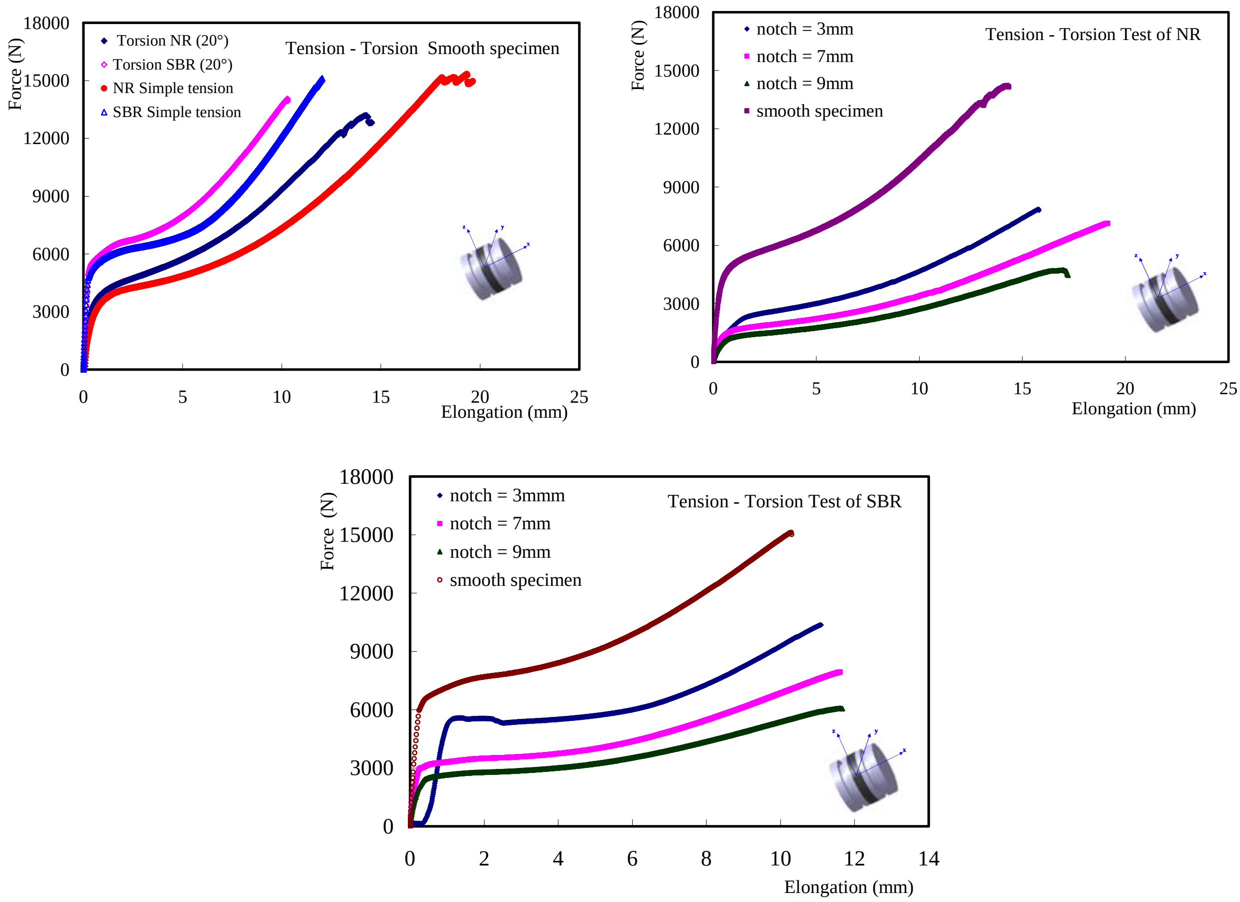


Figure 2 Tension –Torsion test results of pancake (smooth and notched) specimen of NR and SBR

Evidently, these values can be accepted of the beginning of the crystallisation of the NR specimens. However, this stage disappeared in the curves of the notch specimens and these curves show quasi two stages. These results give a good agreement with former studies [4, 7, 9]. This point will be detailed in the following section with SEM and computed tomography results.

3.2. Notch effect and solicitation type on the evolution of the cavitation

A comparative study has been carried out on the effect of the hydrostatic pressure at the centre of the specimen and the effect of the stress triaxiality at the tip of the notch on the damage mechanism in NR and SBR specimens. Because, the notch introduced in the specimen increases the competition between the hydrostatic pressure and the stress triaxiality, which play an important role on the cavitation. All of the tensile and torsion tests conducted on the smooth and notched specimens, of whom the depths varied from 3 to 15 mm, showed that a very strong hydrostatic pressure at the centre of the specimen governs the damage and the notch doesn't propagate and essentially doesn't play on the damage mechanism. The depth of the notch stays the same. However, the effect of the stress triaxiality increases at the tip of the notch. So, a real competition between the hydrostatic pressure and the stress triaxiality should be observed just from the beginning of the deformation, which characterises the damage mechanism of the NR and SBR (Later Figures 5-9).
Additionally, the evolution of the percentage of the cavity surface was illustrated as a function of the notch size for seeing the effect of the notch size on the percentage of the surface cavity zone (Figure 3).

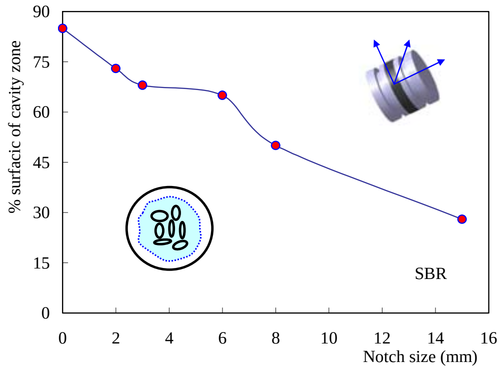


Figure 3. Evolution of percentage of cavity surface depending on the notch size

All of the surface cavities were measured by means of the image analysis-Visilog 4. These values are the mean values obtained on the 3-4 specimens. This curve decreases continuously depending on the notch size. It means that the damage in the specimen becomes a complex mechanism with notch effect and the number of the cavitation. This evaluation has been carried out on the same specimen by X-rays CT. So, evolution of the cavities depending on the notch size was shown in the Figure 4 as 2D and 3D images.

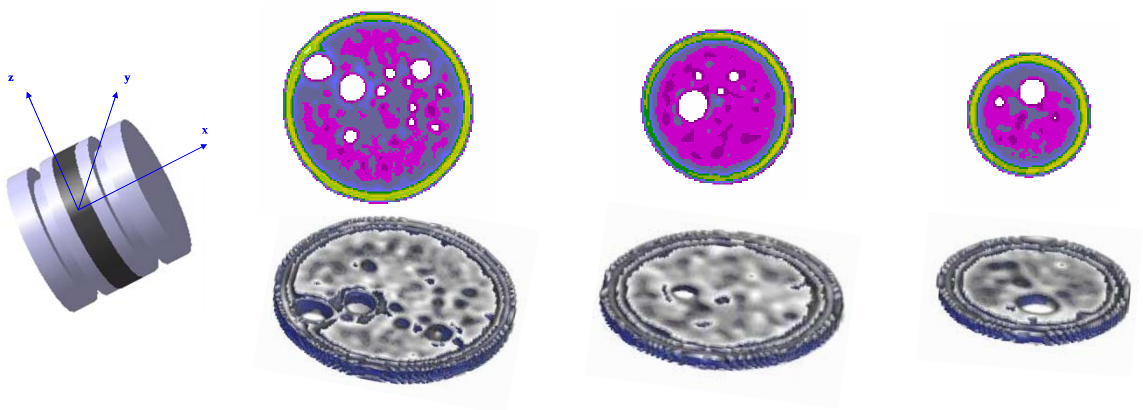
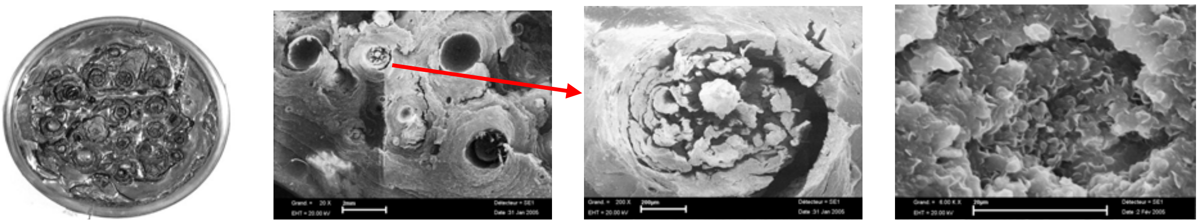


Figure 4 Formation of cavities depending on the notch size; CT cuts in 2D and 3D

As seen very clearly from these images, hydrostatic pressure governs the damage at the centre of the specimen from the beginning up to the final failure and the notch doesn't propagate and essentially doesn't play on the damage mechanism. The depth of the notch stays the same. However, the effect of the stress triaxiality increases at the tip of the notch. So, a real competition between the hydrostatic pressure and the stress triaxiality should be observed just from the beginning of the deformation. In every condition, damage mechanism of the NR and SBR specimens is characterised by the major effect of the hydrostatic pressure. This part will be explained in detail in the following part.

3.3. Study of the failure surfaces by means of Scanning Electron Microscopy (SEM)

Figure 5 presents the failure surfaces of the NR specimen in macro scale a) and failure surfaces showing the development of the cavities and tearing the site of the final rupture and also tongue formation around the cavities due to the uncoiling of the chains of the macromolecules in the materials b). This figure gives more detail about the formation of the cavity due to hydrostatic pressure during the solicitation.



a) Developing of the cavities and tearing the site of the final rupture   b) tongue formation

Figure 5 Failure surfaces of the NR smooth specimen in simple tensile testing and tongue formation around the cavity due to the uncoiling of the chains of the macromolecules in the materials b)

Failure surfaces of the SBR smooth specimen in simple static tensile testing conditions are also shown in the Figure 6. The same evolution of the cavities is observed like NR specimens. It means that development of the cavities occurred inside (mainly centre) of the specimen and final rupture has begun from the well developed cavity.

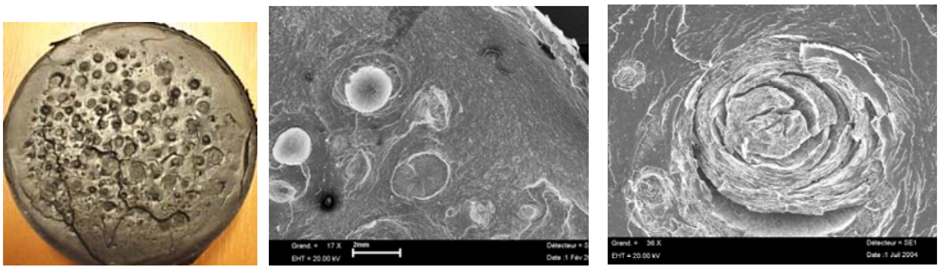


Figure 6 Failure surfaces of the SBR smooth specimen in simple static tensile testing: Developing of the cavities and final rupture from a developed cavity

In comparing the Figures 5 and 6, the nucleation, and growing of the cavities take place in the same forms (helicoidally) both of NR and SBR but their structure and appearance are very different. 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 may 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.

In order to explain more precisely the damage mechanism of the elastomeric matrix composites, the failure surfaces of the pancake shaped specimens in various notch sizes were studied in SEM as illustrated in the Figures 7, 8 and 9 for the NR and SBR specimens.
So, the damage begins firstly with the appearance (nucleation) and the multiplication of the cavities at the centre of the specimen but the number of cavities is always less important then the smooth specimen and then the cleavage zone has absolutely taken place on the border of the notch, which surrounds the cavitated surface due to the triaxiality. Overmatching conditions are always favourable for the hydrostatic pressure during the test and the final tearing has never taken place on the border of the notch by the tearing of one of the cavities, which is the nearby the notch by creating a cleavage zone.

a) NR (notch size =3 mm) b) SBR (notch size =3 mm)

Figure 7 Damaged surfaces of the notched specimens NR a) and SBR b) in simple static tensile testing (developing of the cavities in helicoidally form and the site of the final rupture)

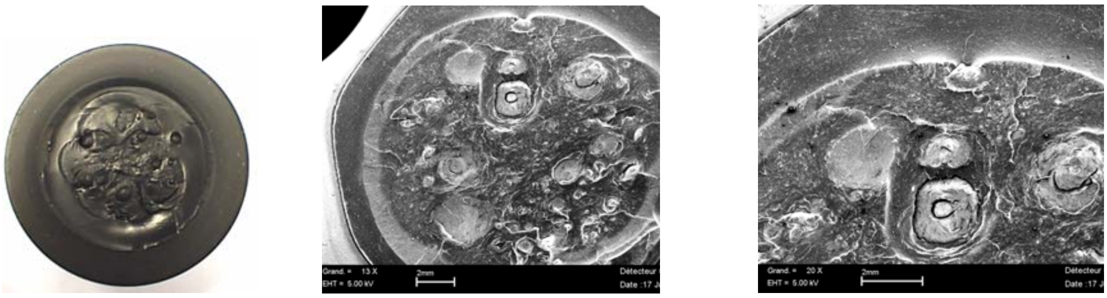


Figure 8 Damaged surfaces of the notched specimen SBR in simple static tensile testing and the site of the final rupture SBR (notch size = 8 mm)

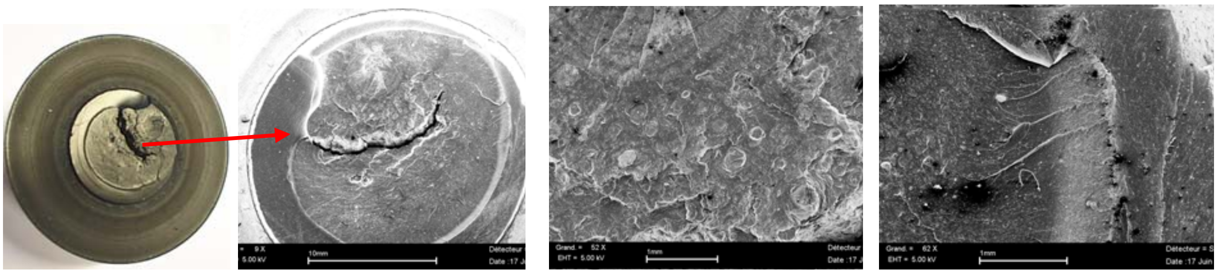


Figure 9 Damaged surfaces of the notched specimen SBR in simple static tensile testing and the site of the final rupture SBR (notch size = 15 mm)

Typical damage surfaces of the notched specimen SBR in static torsion - tensile testing conditions were also shown in the Figure 10. The site of the final rupture SBR was indicated in each specimen, of which notch size varies from 3 to 15 mm.
The first formation of the cavities takes shape internal section of the specimen as in the former conditions (see Figures 7, 8, 9) but after nucleation, the cavities don't develop well due to the torsional effect and only a few developed internal side of the specimen, influenced by the higher hydrostatic pressure. A larger smooth zone (pseudo cleavage) was seen around the cavity zone. In many case, the damage in these specimens has also taken place due to final tearing of the well developed cavity, which is in close proximity to the notch by creating a larger cleavage zone. Many times, at the bottom of the well developed cavities were found metallic and other types particles (Figure 10b) such as ZnO_2, silica and CaCO3, which are composed of carbon black and sometimes sticking of them by creating bigger inclusion.
However, any physical evidence is found for a gas bubble due to the production of the materials submitted to the different solicitation types, which would be evidence or only a cause of the cavitation as claimed by many of the former researchers.
But the notch size can influence the form of the cavitated surface. In both of case, the number of cavities decreases with the depth of the notch increases the formation of a cleavage zone around the cavitated surface. In the case of the NR specimens (smooth and notched), the sizes of the cavities are smaller and the distribution of the cavities is more homogeneous and also the number of the cavities is always higher regarding to the SBR specimens. The results of the X rays tomography and the SEM represent well this comparison.

Finally, Figure 11 explains schematically damage mechanism initiated by the formation of the cavities in a pancake specimen (NR and SBR). This type of presentation gives more detail on the competition between the hydrostatic pressure and the stress triaxiality. In the case of the smooth specimen, the hydrostatic pressure is only responsible from the damage and naturally the total cavitated surface is very high. But, in the case of the notched specimen, the total cavitated surface decreases and the shape and the size of the formed cavities increase with the depth of the notch. In any case, the damage begins firstly with the nucleation and the multiplication of the cavities but always inside of the specimen and less then the smooth specimen. Cleavage zone has also taken place on the border of the notch, which surrounds the cavitated surface due to the triaxiality. The overmatching conditions are always favourable for the hydrostatic pressure during the test

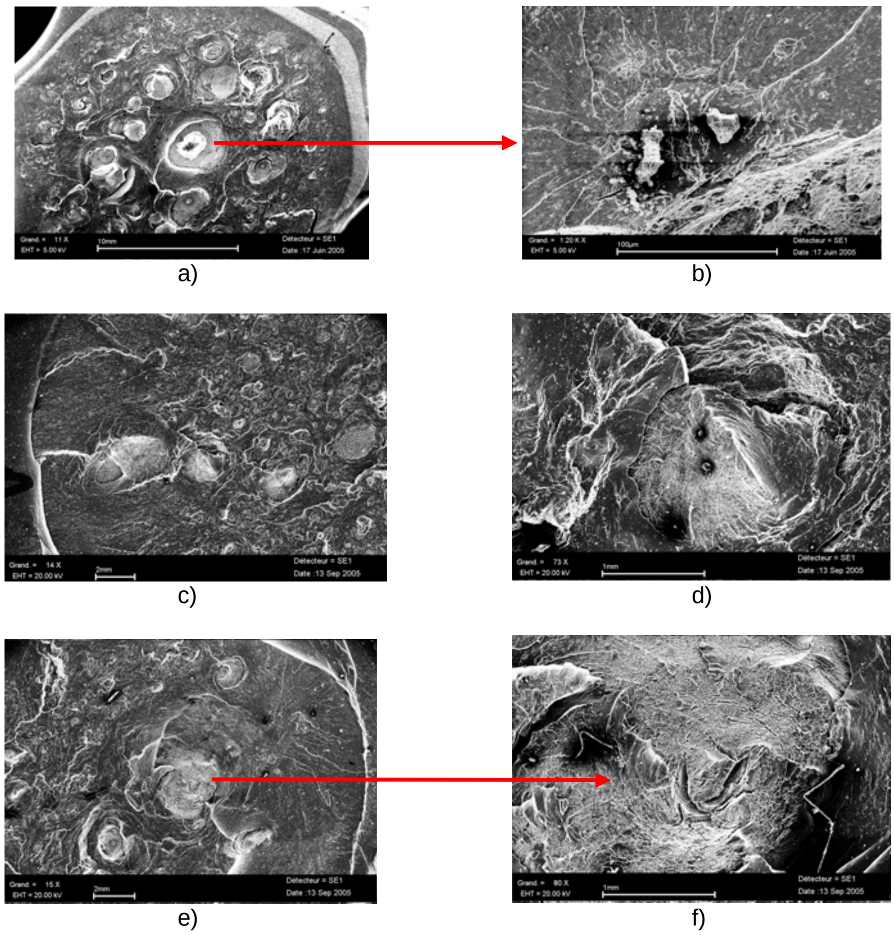


Figure 10 Damaged surfaces of the notched specimen SBR in static torsion - tensile testing and the site of the final rupture SBR, a and b) notch size = 3 mm, c and d) notch size = 8 mm, e and f) notch size = 15 mm

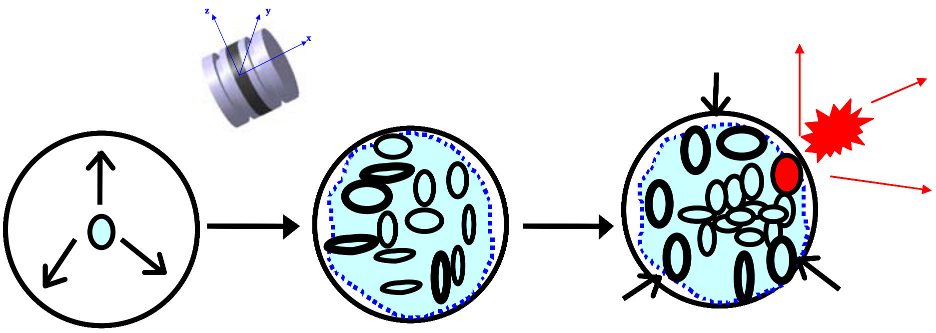


Figure 11 Schematic illustration of damage mechanism initiated by formation of the cavitations in a pancake specimen

4. Conclusion

In this paper, an experimental study on the damage mechanisms of the elastomeric matrix composites is considered. Cavitation phenomenon and essentially the effect of the hydrostatic pressure play a major role on the damage mechanism in the NR and SBR pancake shaped specimens during the tension and torsion testing conditions.

The first formation of the cavities takes place in the internal side of the specimen influenced by the higher hydrostatic pressure. The appearance and the evolution of the cavities takes place in a helicoidally form from a simple defect, which may be the origin of the different natures such as particles or local heterogeneity or even the nature of the structure such as the natural defect of the matrix.

Failure of these materials is not always submitted to shear loading or plane stress state. Sometimes, they are loaded with near plane strain conditions or very high hydrostatic pressure. So, failure mechanism is strongly affected by the triaxiality of the stresses. High hydrostatic pressure induces the cavitation. The notch size influences the form of the cavitated surface and causes to the cleavage zone around the cavitated surface. The number and the geometrical form of the cavities in the NR and SBR specimens are different because of the crystallisation phenomenon occurred in the NR during the deformation.

Acknowledgement

Financial support of this study was given by French Government via MINEFI (Ministère des Finances et de l'industrie) under the project of "CRITEL".

References

[1] Rivlin R. S. and Thomas A. G., Journal of polymer science, 10, Vol. 291-318, 1953.
[2] Chang W. J. and Pan J., J. of Mater. Science, Vol. 36, 1901-1909, 2001.
[3] Lake G. J., Thomas A. G. and Lawrence C. C., Polymer, Vol. 33, (19), 4069-4074, 1992.
[4] Bayraktar E., Antolonovich S. and C. Bathias, Proceedings of ICFC3 on the 3rd International Conference on Fatigue of composites, 13-15 September 2004, Kyoto -Japan
[5] Gdoutos E. E., Schubel P. M. and Daniel I. M., Strain, Vol. 40, 119-125, 2004.
[6] Jancar J., Dianselmo A. and Dibenedetto A. T., Polymer, Vol. 34, (8), 1684-1694, 1993.
[7] Bayraktar E., Montembault F. and Bathias C., Journal of Materials Science and Technology, Vol. 20 (1), 27-31, 2004.
[8] Besri K., Bayraktar E., Montembault F. and Bathias C., Final Research report "Critel", p.86, 12, 2005.
[9] Besri K., Bayraktar E. and Bathias C., Euromech 473, Porto, Portugal, 27-29 October, 2005.
[10] Bayraktar E. and Bathias C., Euromech-473, Porto, Portugal, 27-29 October, 2005.