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Pierre Charrier, Elisabeth Ostoja-Kuczynski, Erwan Verron, Laurent Gornet, Grégory Chagnon. Influence of the loading conditions on fatigue properties for filled elastomers. International Rubber Conference, 2002, Prague, Czech Republic. hal-01008335

HAL Id: hal-01008335

<https://hal.science/hal-01008335>

Submitted on 5 Jun 2018

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INFLUENCE OF LOADING CONDITIONS ON FATIGUE PROPERTIES FOR FILLED ELASTOMERS

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ABSTRACT

Fatigue characterisation of elastomers is an essential prerequisite of new car project schedules imposed by carmakers. Consequently, durability prediction softwares are needed to reduce the time allowed to design elastomeric parts. Until now, the only theoretical variable used to predict duration life is the tearing energy proposed by Rivlin and Thomas. Classically, fatigue properties are determined using plane stress experiments (trousers or pure shear samples for example) under simple loading conditions.

In the present paper, a brief bibliographical review presents the limitations of this approach and the need of more complex loading conditions is emphasised. Then, a new simple shear sample is proposed to simplify the treatment of experimental results, said the calculation of the tearing energy, under complex loading conditions. The test sample is initially notched and is submitted to controlled displacement loading conditions. The procedure adopted to analyse the results is presented. Assuming that the tearing energy and the crack growth rate remain constant during the test, they can be easily calculated using both the decreasing stiffness of the sample during the test and a FE model. Note that no complex system, such as video recording, is necessary to measure the crack length. Then, experimental results are reported. Both filled crystallising and non-crystallising elastomers are studied in order to highlight the influence of the testing temperature and of the imposed displacement ratio (i.e.: minimum/maximum displacement) on the fatigue crack growth rate law. This fatigue crack growth rate law obtained agrees well with previously published papers. Furthermore, other complex tests are in progress to determine the influence of the Mullins stress-softening on fatigue properties. Finally, in regards with these results, it is demonstrated that the tearing energy is not a sufficient variable to completely characterise the fatigue life of elastomers.

1 INTRODUCTION

Tires manufacturers have studied the durability of elastomers for more than 60 years. Numerous scientific papers induced the definition of a well-adapted criterion for this type of industrial applications: the tearing energy T . Moreover, a large experimental data bank is available, but most experiments are restricted to plane stress test samples under simple loading conditions. Automotive anti-vibration system (AVS) companies have now a great interest in elastomers durability. However, the corresponding industrial components and loading conditions are greatly different than those involved in tires industry. Indeed, the loading conditions are close to the state of plane strain and loading histories are more complex: they include variable pre-loading, non-relaxing conditions... In order to investigate the durability of elastomers in AVS applications, it is necessary to determine the limitations of the tearing energy criterion to ensure that its use for AVS products is well-adapted. Second, new test sample geometries have to be defined to reproduce the local stress state encountered in these applications.

In the first part of the present paper, limitations of the tearing energy T are investigated. More precisely, the assumptions that were made by Rivlin and Thomas to define T , the effect of pre-loadings (maintained or not) and the limitations due to the elastic nature of T are thoroughly examined. In a second part, a new test sample geometry is presented. This new sample provides plane strain conditions and could be used to study the influence of loading history, and especially of non-relaxing conditions. The corresponding experimental methodology, said the determination of T and the measurement of the crack propagation, is described in details. More precisely, although the crack growth measurement is easily performed for thin rubber sheets [GEN64], in the present case of a massive rubber block, it is more difficult to determine the crack length. So, a new method for the crack growth measurement is proposed. It is based on the determination of the global stiffness of the sample. Note that the present experimental approach does not need any video equipment to measure the crack propagation. Finally, first experimental results under different temperatures and pre-loading conditions are presented. Two filled materials are considered: a NR that exhibits strain crystallisation and a PU that does not

2 THEORETICAL FRAMEWORK

2.1 DEFINITION OF THE TEARING ENERGY

In order to study the fracture mechanics of rubber-like materials, the first step consists in defining a failure criterion.

Opposite to metallic materials, present geometric and material non-linearities do not permit the use of simple criteria based on the stresses, because the stress state can not be simply calculated analytically. Rivlin and Thomas [RIV53] proposed an energetic failure criterion: the tearing energy T . This approach can be seen as the extension of Griffith's theory [GRI20] to rubber-like materials. The corresponding crack propagation criterion can be written as:

$$T = \frac{\partial(W_{ext} - W)}{\partial A} \geq T_c,$$

where T_c is the critical value of the tearing energy at the failure point, W is the stored elastic energy, W_{ext} represents the work of external forces and A stands for the crack area. Under constant displacement loading conditions, the work of external forces is equal to zero and the previous equation becomes:

$$T = -\frac{1}{t} \left(\frac{\partial W}{\partial c} \right)_l \geq T_c$$

in which t is the thickness of the sample and c is the crack length. This definition of the tearing energy is widely used in the bibliography. It is to note that the Griffith's criterion, that is the basis of the definition of T , considers that the decrease of the stored elastic energy during the crack growth is only balanced by the energy dissipated in the crack front during propagation. Nevertheless, in the case of elastomeric materials, the decrease of the stored elastic energy is balanced by both the energy dissipated in the new crack area and by other dissipated energies that are due to the material behaviour (e.g. Mullins effect, viscoelasticity, strain-crystallisation).

Consider now the tearing of thin sheets and let us examine the assumptions of Rivlin and Thomas in order to determine if it is possible to consider the previous definition of T relevant in that special case. According to the authors, the energy dissipated in the volume of the sample, far from the crack front, can be neglected in the case of low dissipative materials. This is not the case of dissipation phenomena that occur in the neighbourhood of the crack front. In this area, the strain magnitude is higher and the stress state is more complex (anisotropic, viscoelastic, compressible...) than in the rest of the sample, said far from the crack. Rivlin and Thomas assume that these locally dissipated energies remain proportional to the crack propagation dc and to geometric characteristics of the crack front. They concluded that the energy required to propagate the crack of a length dc does not substantially depend on the sample geometry and on the way loading conditions are applied. Consequently, this energy, classically measured during experiments, only characterises the tearing of thin sheets and includes both the tearing energy T and the energy dissipated in the crack front.

2.2 CLASSICAL TEST SAMPLES

In order to study the crack propagation in elastomeric materials, Rivlin and Thomas proposed three different geometries for the test samples. Every samples are thin sheets in plane stress conditions close to the crack front. These three samples are the tensile test sample, the trouser sample and the pure shear sample; they are presented in Figure 1. They have been widely used in the papers dealing with the durability of elastomers.

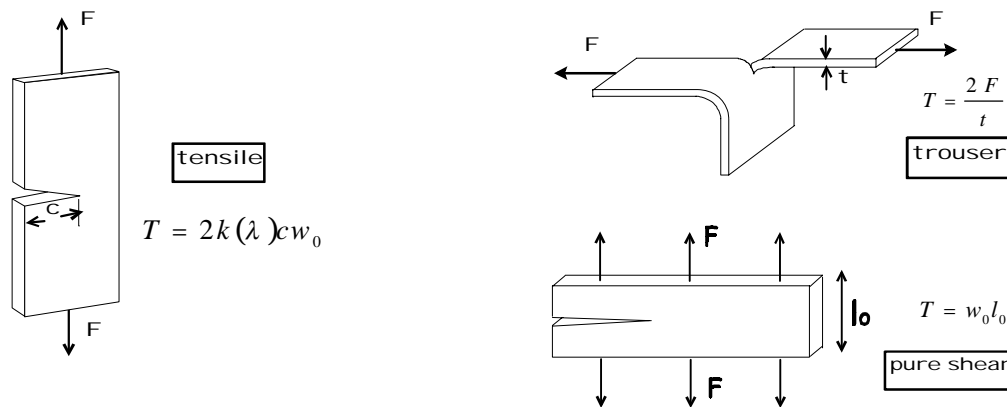


Figure 1: thin sheet test samples

2.3 LIMITS TO THE USE OF T

Before using the tearing energy for samples that are different than thin sheets, we have to review the experimental and theoretical limits of the tearing energy defined above, as already highlighted in literature.

First, strictly regarding to the definition of T , the experimental procedures proposed in literature are not well-adapted to its measurement. Indeed, during experiments, it is not possible to separate the energy used for the propagation of the crack area, said the tearing energy, from other energies that are dissipated both in the volume and in the neighbourhood of the crack front. Only a global value of the dissipated energy can be obtained. Moreover, the tearing energy as defined by Rivlin and Thomas is a purely elastic parameter. It does not take into account the complex behaviour of elastomers that includes strain-softening, viscoelasticity ... Gent and Kim proposed a new experimental definition of T that partially overcomes this difficulty [GEN78]. To take into consideration the hysteresis of the material under cyclic loading, they determine the tearing energy using the elastic energy restored during the unloading part of the cycle and not the elastic energy that is stored during the loading part. Finally, the bibliography exhibits different experimental results which prove that T is not an intrinsic parameter, said it can not be used as a criterion. This is the case of Thomas who demonstrates that the critical tearing energy T_c is modified by cyclic loadings of the test sample [THO58]: the material is strengthened during this cyclic loading. The works of Gent and Kim under static conditions [GEN78] and of Busfield *et al.* under cyclic conditions [BUS96] highlight the effect of pre-loading on the tearing energy. In the case of pure shear test samples, the authors show that a pre-loading parallel to the crack weakens the material, said the corresponding critical tearing energy is divided by 25. These results demonstrate that the tearing energy is not an appropriate parameter to characterise the durability properties of elastomeric materials.

3 DEFINITION OF A NEW TEST SAMPLE

3.1 GEOMETRY OF THE SAMPLE

As mentioned above, classical test samples used to study the crack propagation in elastomeric materials are considered under plane stress conditions. So, they can not be used to study the local stress state encountered in AVS components. In order to reproduce the plane strain conditions, we should consider test samples under plane strain conditions. This consideration has led us to a new design of samples.

Lindley *et al.* ([LIN77,LIN79,LIN82]) provide the methods needed to calculate T for elastomeric blocks in which a crack propagates at the interface between the material and a rigid insert. Using their results, we consider a “2 blocks - simple shear sample” with a pre-cut at the interface elastomer/insert. Figure 2 presents this sample. As proposed in the previous cited papers, both the block width and the crack length are at least twice larger than the block thickness. Moreover, using a well-defined pre-cut length, our new sample can be used for crack propagation experiments in which the tearing energy and the crack growth rate remain constant when the crack propagates.

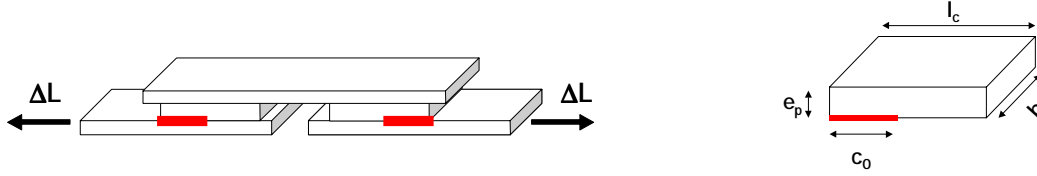


Figure 2 : Design of our new sample

3.2 DETERMINATION OF THE TEARING ENERGY

The determination of the tearing energy that corresponds to an elastomeric block under enforced displacement is directly based on the definition of Rivlin and Thomas:

$$T = -\frac{1}{b} \left(\frac{\partial W_{elas}}{\partial c} \right)_l,$$

where b is the block width and W_{elas} is the elastic energy stored in the sample. This elastic energy is calculated assuming that the material behaviour is linear under simple shear loading. Denoting L_{max} and the maximum enforced displacement and resulting force, respectively, the maximum tearing energy obtained during the test is denoted T_{max} and can be written as:

$$T_{max} = \frac{L_{max}}{2b} \frac{\partial F_{max}}{\partial c}$$

In regards with this equation, the maximum tearing energy only depends on experimental parameters ($L_{max}/2b$) and on the global stiffness of the sample that is a function of the crack length ($\partial F_{max}/\partial c$). In the present work, this global stiffness is determined by a finite element analysis. The rubber block is modelled under plane strain conditions and simple shear experiments are simulated using the software ABAQUS. For a given value of the crack length increment, said dc , the crack propagation effect on the global stiffness is determined by performing computations on samples in which the crack length value is set to c , $c+dc$, $c+2dc$, For the simulations, the material behaviour is modelled by the nearly incompressible hyperelastic Mooney-Rivlin constitutive equation.

The results of these simulations can be summarised by the curve of the resulting force versus the crack length. More precisely, we consider non-dimensional variables, said the non-dimensional resulting force F/F_0 , where F_0 is the resulting force obtained for the block without pre-cut, and the non-dimensional crack length c/l_c where l_c is the sample length. The corresponding curve is presented in Figure 3. As shown in this figure, the curve can be fitted by a linear equation for sufficiently large values of the crack length. The fitting results are shown in Figure 4. The slope of the line is denoted A and given by:

$$A = -\frac{l_c}{F_0} \frac{\partial F_{\max}}{\partial c}$$

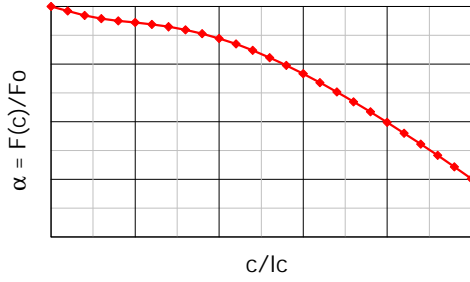


Figure 3 : resulting force versus crack length.

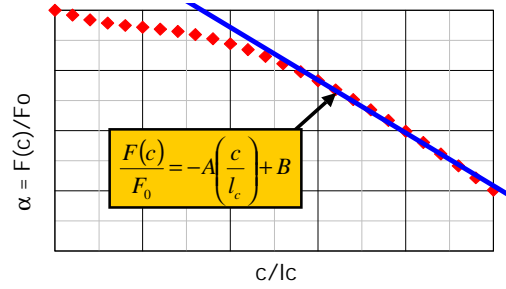


Figure 4 : linear fit.

Using this new parameter, the maximum tearing energy can be written as:

$$T_{\max} = A \cdot \frac{L_{\max} \cdot F_0}{2b \cdot l_c}$$

This equation expresses that T_{\max} is a function of experimental parameters and of the resulting force of a block without pre-cut F_0 . As this force can be related to the resulting force F_{c0} (corresponding to a pre-cut block) by a constant parameter $1/\alpha$ as shown in Figure 3, the maximum tearing energy only depends on experimental parameters:

$$T_{\max} = \frac{A}{\alpha} \cdot \frac{L_{\max} \cdot F_{c0}}{2b \cdot l_c}$$

where b and l_c describe the geometry of the sample, L_{\max} is the enforced displacement and F_{c0} is the resulting force corresponding to the accommodated sample without crack propagation.

The method adopted for the determination of T_{\max} presents a major limitation. The pre-cut length and the crack length considered during the test should be chosen in order to ensure that the parameters A and α remain constant during the cyclic experiments.

3.3 MEASUREMENT OF THE CRACK GROWTH RATE

In the bibliography, the crack growth rate is often measured using a video recording system that gives Δc every Δn cycles. This method is well-adapted to experiments under plane stress conditions, but it is no more suitable for our plane strain samples, because of edge effects. Consider a massive elastomeric block, the crack front shape is not straight because it is deviated by edge effects: the crack growth is not constant along the sample width, as shown in the left-hand side of Figure 5. Consequently, the measure of the crack length close to the edge of the block may be highly different than its measure in the middle of the block, as described in the right hand-side of Figure 5. In order to overcome this difficulty, a new method based on measurement of the resulting force is proposed in order to estimate the crack growth rate.



Figure 5 : shape of the crack front for a sample under plane strain conditions

Figure 6 presents the evolution of the maximum and minimum forces obtained during a fatigue test under controlled displacement conditions.

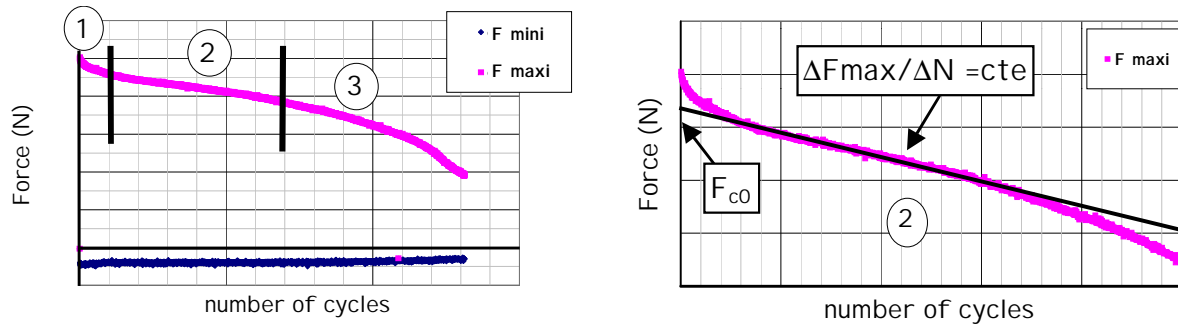


Figure 6 : evolution of the resulting forces during the fatigue tests

It is to note that the maximum force highly varies during the test, whereas the minimum force that corresponds to zero displacement remain almost constant. This could be simply explained. On one hand, the zero displacement configuration represents the closure of the crack; it can be concluded that the crack length has no effect on F_{mini} . On the other hand, the curve of F_{maxi} can be divided in three different parts, that correspond to three different physical phenomena:

- The beginning of the curve (indexed 1 in Figure 6) shows a high decrease of the resulting force during approximately 1000 cycles. This decrease is a consequence of the dissipative nature of elastomers. It includes the accommodation to the Mullins effect, the viscoelasticity of the material and the stabilisation of the block temperature.
- The main part of the curve (indexed 2) corresponds to the crack propagation. The chosen geometry and the test conditions imposes that the tearing energy remain constant. So, the crack growth rate is also constant and the measured curve can be fitted by a linear equation. Its slope is equal to $\Delta F_{\text{max}} / \Delta N$ and its intersection with the force-axis is F_{c0} (see Figure 6).
- The last part of the curve (indexed 3) corresponds to the catastrophic crack propagation that takes place before the breakage of the sample.

Considering the previous remarks, the determination of the crack growth rate is quite easy. Indeed, the crack growth rate only depends on the slope of the experimental curve and on some parameters previously obtained by FE calculations:

$$\frac{dc}{dn} = \frac{\Delta c}{\Delta F_{\text{max}}} \frac{\Delta F_{\text{max}}}{\Delta n} = \frac{l_c}{AF_0} \frac{\Delta F_{\text{max}}}{\Delta n}$$

4 EXPERIMENTAL RESULTS

4.1 CRACK CLOSURE EFFECT

Experiments under constant enforced maximal displacement were conducted to determine the influence of the minimal strain on the crack growth rate. Two materials were tested: a natural rubber (NR) which exhibits strain crystallisation effects and a polyurethane (PU) which does not. Experimental results are presented in Figure 7 for NR and in Figure 8 for PU.

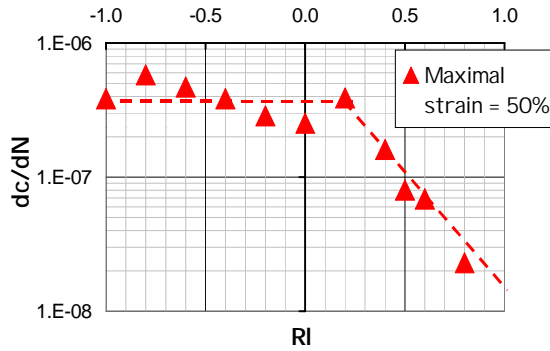


Figure 7 : influence of the minimal strain on the crack growth rate for PU

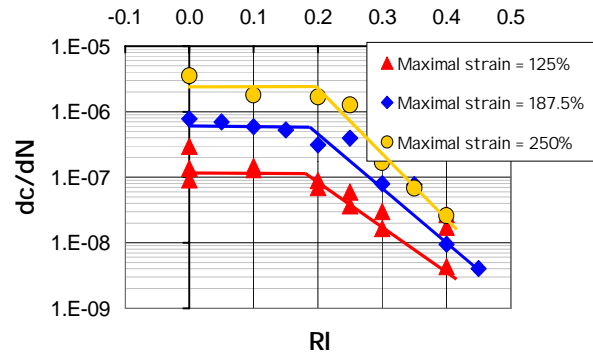


Figure 8 : influence of the minimal strain on the crack growth rate for NR

These figures present the influence of the displacement factor, said the ratio of the minimum on the maximum displacements of the loading cycle, on the crack growth rate. Moreover, as each curve stands for a constant value of the maximum displacement (or strain), the figures highlight the influence of the minimum enforced displacement on the crack growth rate. They demonstrate that the magnitude of the minimal enforced displacement has no influence on the crack growth rate as long as it remains lower than a threshold value. This threshold value corresponds to the special case of a loading cycle without compressive part. Above this threshold value, the crack growth rate significantly decreases as R_i increases. In regards with metallic material state of the art, this effect can be named the “crack closure effect”. In order to account of this effect, experimental results are not analyse considering the maximum tearing energy T_{max} but the maximum amplitude of the tearing energy during the cycle denoted ΔT and defined by:

$$\Delta T = T_{max} - \max(T_{min}, 0)$$

Finally, it is to note that the “crack closure effect” is not sensitive to the strain crystallisation.

4.2 EXPERIMENTS UNDER NON-RELAXING CONDITIONS

Assuming now that the crack closure effect should be considered, we examine more precisely the influence of the pre-load on the crack growth rate law. As mentioned above, this influence is analysed by performing experiments with different values of the displacement ratio $R_f = L_{min}/L_{max}$. Experimental results are presented in Figure 9 for PU and in Figure 10 for NR and lead to the following conclusions:

- If the test sample is compressed during the cycle, said $R_L \leq 0$, then the crack growth rate law is not modified by the magnitude of compression (see Figure 9). Consequently, there is a unique crack growth rate law for the cases $R_L \leq 0$.
- If the displacement ratio is higher than a positive threshold value, the effective stress cycle is tensile / tensile. In that case the crack growth rate law is shifted but the slope

remains constant for all values of R_L (see Figure 9 and Figure 10). It can be said that the material is reinforced whatever it crystallises or not.

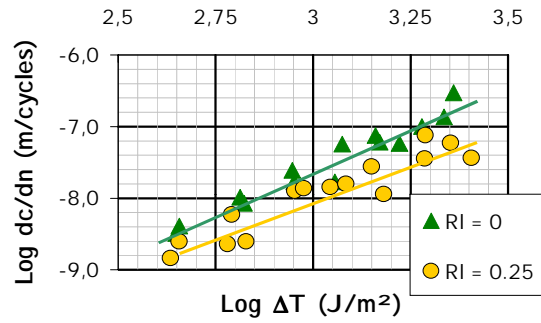
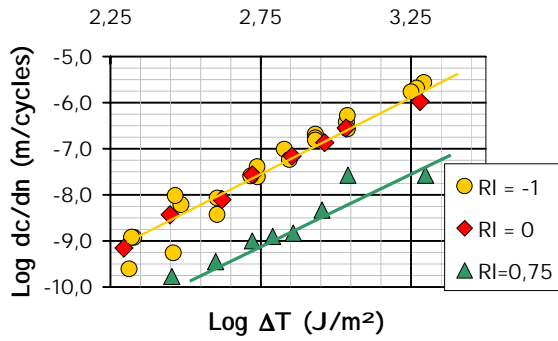


Figure 9 : effect of non-relaxing conditions on the crack growth rate law for PU

Figure 10 : effect of non-relaxing conditions on the crack growth rate law for NR

In conclusion of this study, we propose a first attempt to model the influence of non-relaxing conditions on the crack growth rate law. In order to develop our theory, the curves presented in Figure 8 are redrawn in a different way: for each value of the enforced displacement ratio, the corresponding crack growth rate is non-dimensionalised by the crack growth rate corresponding to $R_L=0$. Here, this method is only applied to NR and the corresponding master curve is presented in Figure 11.

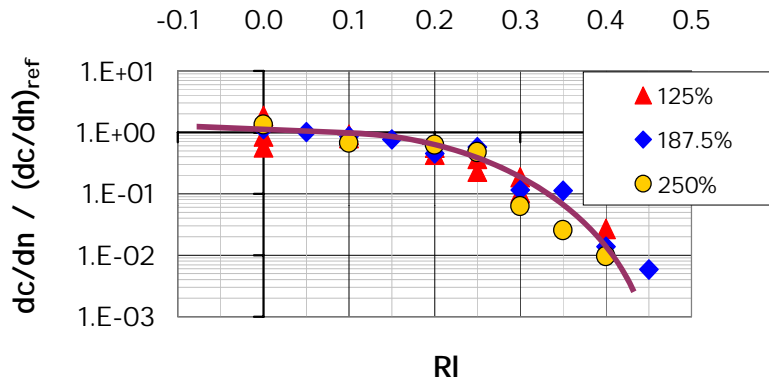


Figure 11 : master curve for the crack growth rate law under non-relaxing conditions. Case of NR
Finally, the crack growth rate law is approached by the following function:

$$\frac{dc}{dn} = f(R_L) \cdot B_0 \cdot T^{\alpha_0}$$

with

$$\begin{cases} f(R_L) = 1 & \text{for } R_L < R_{L_{threshold}} \\ f(R_L) = a \times R_L^2 + b \times R_L + c & \text{for } R_L > R_{L_{threshold}} \end{cases}$$

The corresponding fitted curve is shown in Figure 11.

4.3 INFLUENCE OF THE TEMPERATURE

Automotive AVS components are classically used at different temperatures in service conditions. Indeed, it is important to be able to quantify the temperature effect on the crack growth rate law. That is the reason why cyclic experiments were performed on both materials

at different temperatures. The crack growth rate laws are presented in Figure 12 for PU and in Figure 13 for NR.

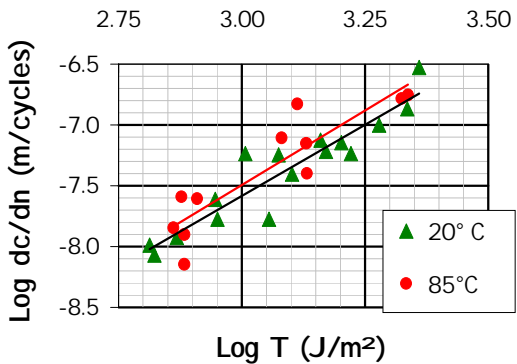
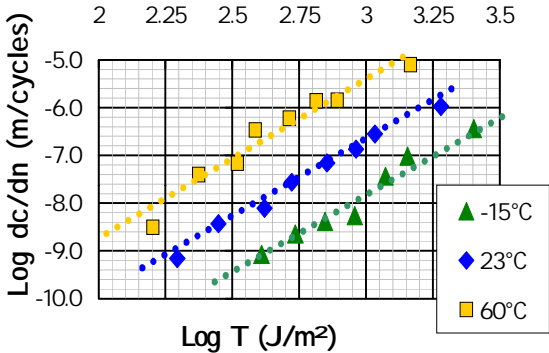


Figure 12 : crack growth rate law at different temperatures for PU

Figure 13 : crack growth rate law at different temperatures for NR

Examining the results and in accordance with previously published results, a major difference between the two materials can be observed:

- PU is very sensitive to the temperature: the crack growth rate law is shifted to higher values of dc/dn as the temperature increases (the material becomes stiffer as the temperature decreases).
- NR results are more scattered but the material seems to be relatively insensitive to the temperature in comparison with PU, whatever the value of the enforced displacement. This observation is confirmed by Figure 14 in which the crack growth rate versus temperature curves are horizontal lines for each values of the enforced strain.

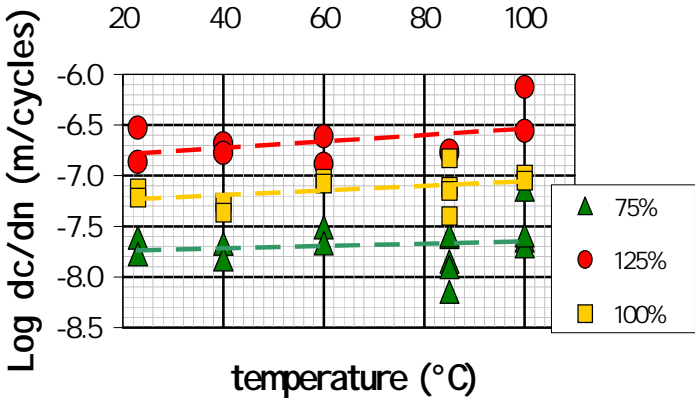


Figure 14 : influence of the temperature on crack growth rate NR

The authors suppose that this sensitivity to the temperature can be explained by the strain crystallisation properties of the material considered. Some works are in progress to prove this proposition.

5 CONCLUSION

The present work is the preliminary step of a wider experimental study on fatigue life of elastomers. The aim of this study consists partly in adapting the classical approach developed previously to investigate the crack propagation under simple loading conditions to the case of anti-vibration system parts.

In this paper, the limitations of the tearing energy as defined by Rivlin and Thomas were highlighted and a new experimental simple shear sample was presented. This sample reproduces plane strain conditions in the neighbourhood of the crack front and can be submitted to complex loading histories. Moreover, the methodology used to determine the crack growth rate was detailed. First experimental results on both PU and NR were thoroughly analysed and the corresponding crack growth rate laws were established. Moreover, the influence of the pre-loading conditions and of the temperature on this law was also considered. All of these results are in good agreement with previously published results and validate our new sample.

Further works are in progress and new experiments are planned in order to investigate the influence of the loading frequency and of ageing conditions on the fatigue life of elastomers. The next step of the study will be concerned with the effect of complex loading conditions (enforced force or enforced displacement, form of the cycle, sample accommodation...) on the crack growth rate law.

ACKNOWLEDGEMENTS

The authors acknowledge the CETIM Nantes for its participation in the study and more especially for the fractographic analysis of the broken samples.

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