CHARACTERIZATION OF THE CRACK PROPAGATION IN A MICROSTRUCTURALLY RANDOM MATERIAL

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ABSTRACT

In the study of mechanical properties of materials the microstructure of a material is usually subjected to some kind of homogenization; however, there are materials in which the microstructural disorder must be considered. This disorder manifests itself in the fracture resistance of materials. Some empirical experimental studies and various types of models (based on variations in mass per unit area) have been made to relate the effect of the disorder during crack propagation with the macroscopic resistance of the material, but the absolute-density/mass projections have not been a good descriptor to extrapolate the behavior of the material between its microstructure and the macroscale since it is difficult to determine the porosity and the net trajectory of the fibers. The physical phenomenon of the instability of the crack propagation of interest in the present work occurs on a meso-scale, where the microstructure of the materials can be characterized only statistically and has been established as the range in which the bridge can exist between the micro and macro behavior of this kind of materials. By the Digital Image Correlation Technique the crack propagation is followed based on the displacements produced locally by the arrangement of the fibers in front of the crack tip of paper, as a material model. At the beginning of the load process is observed a smooth trace in the peak local deformation corresponding with the elastic part of the stress-curve; after, when the stress-curve starts to deflect, the peak local-deformation trace change in its slope and it becomes intermittent, this behavior is attributed to the local conditions of material. Finally, it observed that the local deformation is a good descriptor for the crack extension.

Keywords: local deformation, crack path, inhomogeneity.

1 INTRODUCTION

Fracture has been one of the phenomena that has attracted the most attention in the scientific and engineering community of materials. As a failure condition, it limits the function for which a material was developed, since it can be understood microscopically, as interatomic separation, while at the macro level, as rupture in two or more parts of the material.

Even though the study of the effect of fracture on the strength of materials dates from the pioneering works of DaVinci, it is only from the 19th century, when it has been based on two principles based on the microstructural formation of materials: from the Classical *Theory of Continuous Media* and recently the *Size Effect*. In the first case, homogeneity and continuity are assumed and, the microstructural effect of the material is lost; while in the second, when the size effect is taken into account, a microstructural dependence of the material must be considered. This limitation has once again drawn attention in its application to heterogeneous materials. That is, in heterogeneous materials of complex structure such as paper, it is known that structural inhomogeneity (called formation) has an influence on the mechanical properties of strength and fracture. The structural disorder manifests itself in the variation of the mass density, the elastic coefficient and the local stresses of the material. These variations are presented in a short range order, but they could not be correlated on larger scales (long range).

Due to the heterogeneity caused by the complex fiber arrangement which make up the paper, this material has been a good descriptor of the effect of disorder and it has been found

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in many applications as a model material in studies of disordered phenomena such as fracture [1]–[3]. In order to relate the fibers disorder during the crack propagation with the macroscopical strength of the material have been carried out some experimental studies and generated several kind of empirical models to predict the fracture mainly based on the variations *mass/unit area*, but the *absolute density/mass* projections have not been a good descriptor to extrapolate the behavior of the material between its microstructure and the macroscale since it is difficult determining the porosity and the net trajectory of the fibers.

During the fracture of the paper, the load causes an initial sliding between fibers and interfiber bonding (considered as two different phases due to the absence of a matrix) until the catastrophic failure of the material is finally reached with the breakdown of both phases [4]. These mechanisms are factor of energy consume during the crack propagation and related with the area of the microscopic damage and of the local deformation [5]–[8].

In this work the crack propagation in paper is studied. In the present work is considered that during the initiation of crack growth, the inhomogeneity, as a precursor to the imminent propagation of cracks, can be determined from local displacements on a meso-scale (scale between millimeters and centimeters) around the crack tip and within which the local variations in the field of displacements correlate with the overall strength properties of the sample.

2 EXPERIMENT

In order to relate the micro and macro behavior of fracture, a synchronization between a universal tensile testing machine and a high resolution/rate camera was done, as shown in Fig. 1.

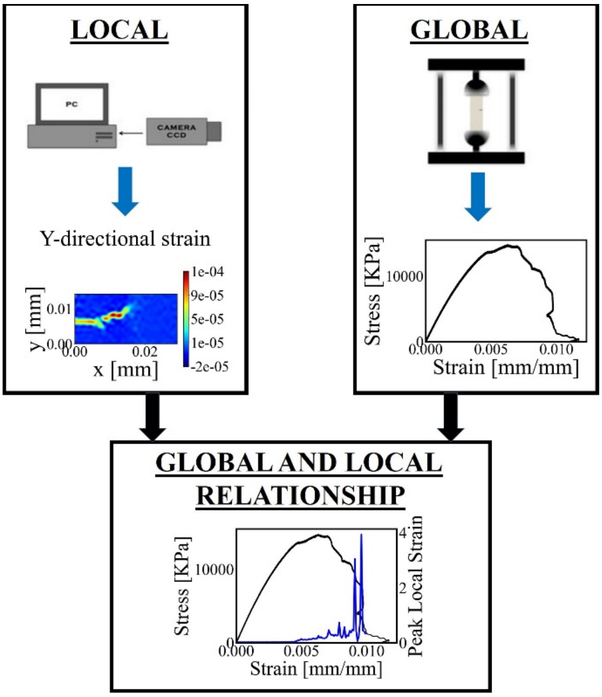
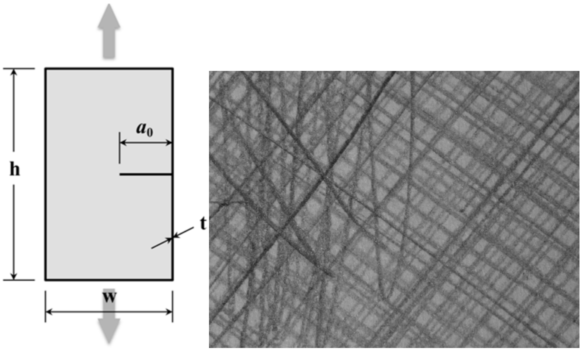


Figure 1: Experimental procedure.



(a) (b)

Figure 2: Specimen configuration. (a) Single edge notch testing; and (b) Scratched sample for the images acquiring.

Here, the time is considered as the common term for the tests. By the universal tensile testing machine which run at a constant displacement rate, the stress–strain curve is obtained and from which the global fracture behavior of the material is studied: while whit the high resolution camera *n*-images are obtained and from which the local deformation maps are calculated with correlation numerical techniques.

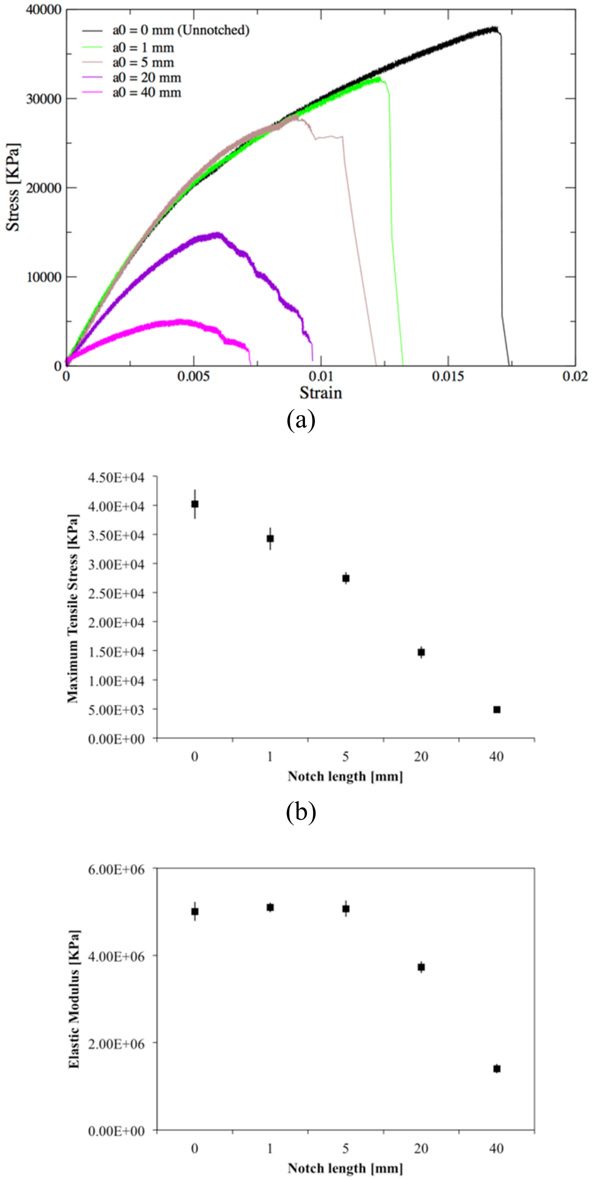
Single Edge Notch Tension (SENT) specimens of commercial paper, with constant width of w = 50 mm, total height h = 100 mm, and thickness t = 10.07 μm with a variable initial notch (a_0 = 1, 5, 20 and 40 mm) were considered, as shown in Fig. 2. In order to get the randomness in the grey colour for the images the specimens were prepared by scratching. The testing were done by an axial load until to reach the total rupture of the specimens in an electrodynamical universal tensile testing machine of 1 kN at a 0.01 mm/s under similar conditions of Room Temperature of 22.5 ± 0.11°C and Relative Humidity of 27.94 ± 0.2%. The images, with a resulting size of 1027 × 767 pixel (29 mm × 21.7 mm), where 1 pixel = 28.34 μm, were got only during the lapse that each testing lasts and at a 10 images/s rate (the region of study final was 5.7 × 7.1 mm). Therefore, with the considered experimental set up results that 10 images = 0.01 mm of constant displacement between clamps. The image correlations were based on the elastic image registration procedure [9] by the sequential comparison between a reference image and the deformed image.

3 RESULTS

3.1 Macroscale behavior

By the stress–strain diagrams the macroscopic behavior is observed for different sizes of initial crack in Fig. 3, paper develops an elastoplastic constitutive model (Fig. 3(a)). The tensile strength is dependent of the length of the initial notch (Fig. 3(b)); that is, in an increase of the initial notch there are a reduction in the ligament area which increasing the stress intensity to reach the strength of the material. That is why this parameter is in inconvenient to use as a design parameter in heterogeneous materials.

The stiffness is the capacity which have a system to withstand loads without excessive deformations. Based on the stress–strain curves it is observed two behaviors: the stiffness is constant and independent for the relation $a_0/\mathrm{w} \leq 0.1$, while for $a_0/\mathrm{w} > 0.1$ a linear dependence of the elastic modulus E with the initial notch is observed; that is, $E = E(a_0/\mathrm{w})$ as shown in Fig. 3(c).



(a)

(b)

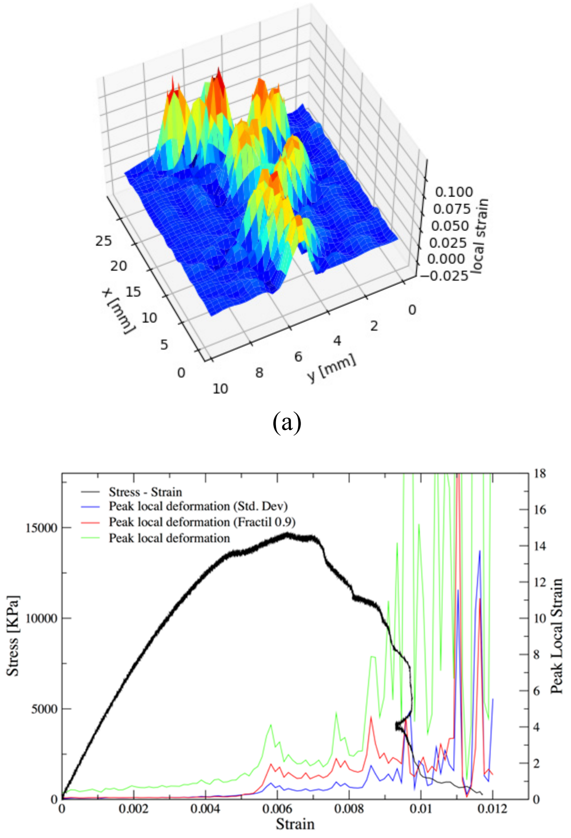
(c)

Figure 3: Macroscopic fracture behavior of the material for several initial notch size. (a) Typical stress–strain curves; (b) Tensile strength; and (c) Elastic modulus.

3.2 Fracture process in paper

The microstructural disorder makes the study of the fracture in the paper complex, for example one of the main difficulties in the characterization of cracks is the specification of the instant in which the localized crack get started to grow [4]; also, it causes that the path of the propagation be random which difficult to follow.

The fracture micromechanisms in this type of materials makes an intensification in the local strain in front of the crack [6]–[8] and it can be measured and followed each instant for all fracture process through the Digital Image Correlation Method (DIC). In this work, the *Peak Local Deformation* (PLD) was defined as the parameter to characterize the crack behavior and its propagation at a meso-scale (Fig. 4(a)). However, due to the existence of small intrinsic deformations distributed over all the specimen and produce noise in the measurements it was considered only the fractile 0.9 of deformation in order to only ensure the use of the localized deformations in front of the crack tip. Fig. 4(b) shows that the PLD is inversely related with the macroscopic behavior of the material; that is in an increasing of the intensity of PLD the stress–strain curve deflects.



(a)

(b)

Figure 4: Behavior of a crack at meso-scale. (a) Local strain of a developed crack; and (b) Relationship between the Peal Local Deformation (PLD) and the stress–strain curve.

In the resulting deformation maps is observed that once the crack initiate to grow there is a sudden increase in the maximum strain and a random behavior in the path of the crack advancing due to microstructural disorder of the material (Fig. 5).

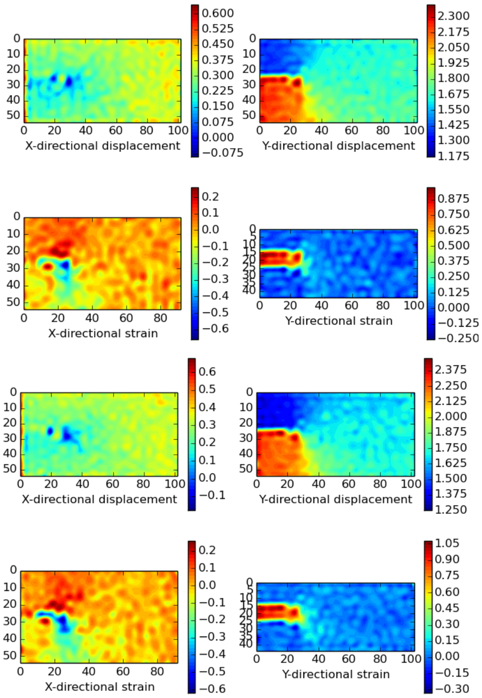


Figure 5: Displacement and strain fields at the instant in the initiation of the crack to grow.

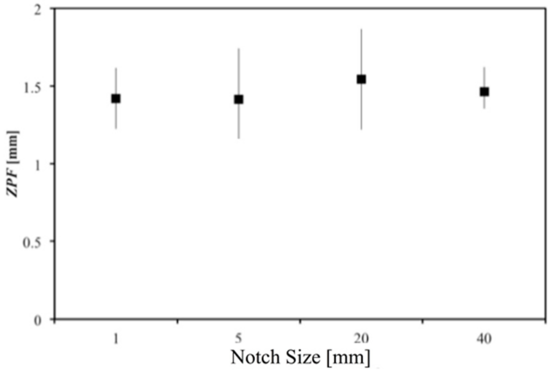


Figure 6: Fracture process zone behavior for several initial sizes of notch a_0.

The fracture in materials with complex microstructure is basically defined by a localized crack and a *Fracture Process Zone* (FPZ). This is a diffuse area which is characterized by its width, length and depends on the load, and microstructural disorder of the material [10], [11]. With the experimental process used here the FPZ was measured. The formation of the FPZ is when the stress–strain curve lost its first linear slope and developed until the beginning of stable crack propagation. By the local strain intensity this phenomenon is shown as a sudden peak (in Fig. 4 the FPZ begins approximately at 0.004). As shown in Fig. 6 there is not dependence of the FPZ on the initial size of the notch a_0, this corroborates the importance of its consideration as a material property.

3.3 Relationship between the meso and macro scales

By setting the peak local deformation around the tip of the crack as a monitoring parameter, both the length and the crack path can be determined, this is carried out by monitoring the specific position of this parameter. It should be mentioned that in order to carry out the measurement, the condition that the specific position must have positive or zero increments on the x axis must be met. Therefore, comparing the resulting crack length with the stress–strain diagram, it is possible to observe such advancing and its effect on the strength of the material during the entire loading process (Fig. 7), an effect that was shown through the intensity of deformation.

The crack onset a_C has been a fracture parameter difficult to get, it has been done under direct observation or with microscopy, however, it has become difficult since the ZPF manifests itself as a diffuse rather than localized zone and the speed with it spreads is rapid. Fig. 8 shows that the instant can be localizable and measurable (based on the peak local deformation, in Fig. 4, this point is approximately at 0.0053 in the strain). In all figures a direct relationship between the stress–strain curve and the crack growth is observed. Once the crack grows, the sudden change in both the slope and the intermittence of the crack length curve is observed, which means that the crack begins to develop and the intermittency is due to disorder of the material.

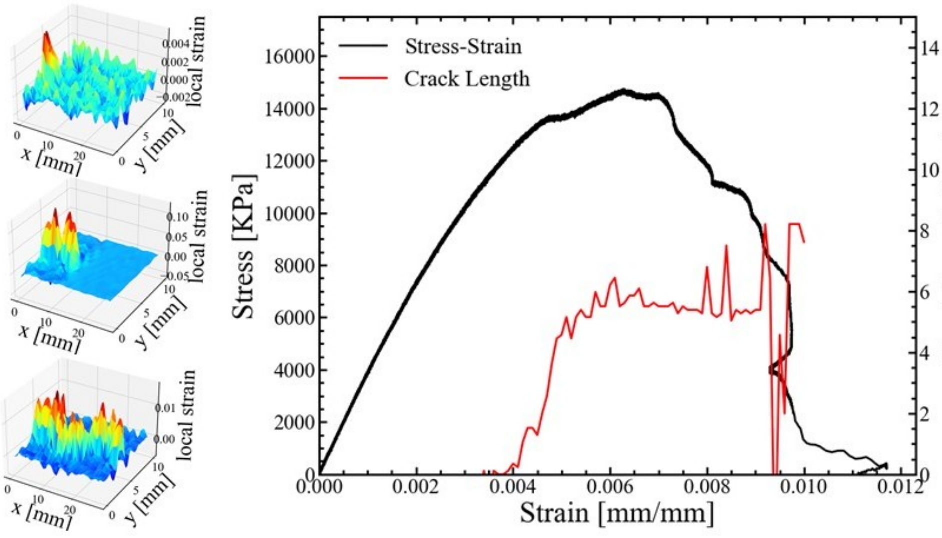


Figure 7: Typical crack length behavior during the fracture process for paper.

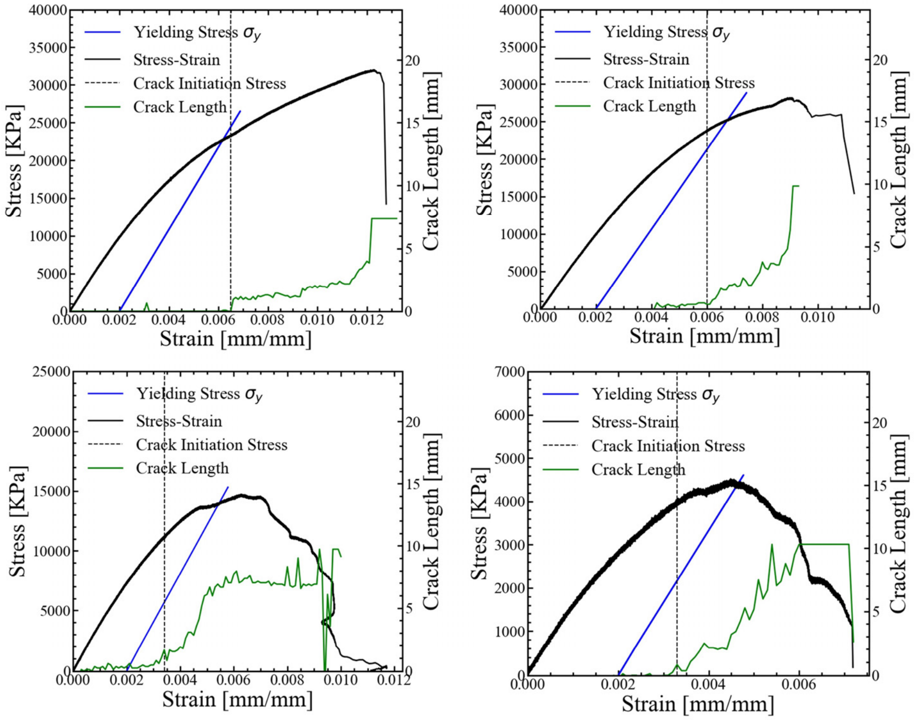


Figure 8: Typical stress–strain/crack length relationships for several initial notch a_0. Vertical line specifies the instant of the crack onset.

For an initial defect of a_0 = 1 mm, the crack length necessary to reach the critical rupture, which is catastrophic, is of 3 to 5 mm and in the stress–strain diagram this is imperceptible since the tensile stress is approximately equal to the rupture stress σ_R; while, for the initial notch a_0 = 40 mm a crack length of 8 to 12 mm approximately is required, in the stress–strain curve it is observed as a deflected curve. This behavior is due to when the initial notch a_0 is longer the effective area of the specimens is reduced such that the microstructural disorder of the material takes more importance.

For the initial notch range considered the crack onset stress is approximately equal or less than the yielding stress (σ_y = 0.2%), this imply that in this kind of materials with crack like defect the yielding stress cannot be used as a design parameter, similar results have been found in other types of paper [4]. When $a_0/w = 0.1$ the crack onset stress is approximately equal to the yielding stress and for a $a_0/w > 0.1$ the crack initiation stress is less than it.

4 CONCLUSIONS

Intrinsic disorder is manifested in the fracture behavior of materials with complex microstructure. When establishing the displacements as descriptors for the characterization of the fracture, it was assumed that the local variations of inhomogeneity are uniform. The DIC technique made it possible to directly evaluate the intensity of the maximum local deformation (PLD) developed around the tip of the crack. Here it was observed that this value is strongly related to the resistance of the material; that is, the increase in PDL is inversely proportional to the resistance of the material and through it, was possible to carry out the monitoring of the crack path until the rupture of material. In all the cases considered here, it was observed that the onset crack stress is equal to or less than the yield stress, depending on the size of the initial defect, which implies that in this type of materials when has a defect, the yield stress cannot be considered as a design parameter. Therefore, based on the above, it is concluded that the displacements are a good descriptor for the characterization of fracture in disordered materials since they do not depend on the mass/unit area relationship.

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