Experimental study of damage and mechanical reliability of Acrylonitrile Butadiene Styrene subjected to uniaxial loading

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Abstract. This paper investigate the mechanical behavior of Acrylonitrile Butadiene Styrene (ABS) subjected to uniaxial loading, with particular interest in the effect of damage on its mechanical properties. This investigation was conducted in two phases: an experimental characterization of the standard mechanical behavior of ABS, followed by an analysis of the influence of notches of different lengths (1 to 14 mm) on specimens drilled with a 3 mm diameter hole. The obtained results show a progressive decrease in the ultimate residual stress proportional to the increase in the notch length, following a characteristic three-phase process. This study proposes a quantification of the damage and establishes a correlation between this parameter and the reliability of the material as a function of the fraction of life, thus making it possible to identify three distinct stages in the evolution of the damage. This approach constitutes a predictive tool for the evaluation of the residual life of ABS components subjected to mechanical stress.

Keywords: ABS – Student's t-distribution – Weibull distribution.

1 Introduction

Several theoretical and experimental works have been carried out to study the mechanical properties of polymers [1-23]. For instance, the researchers in [1] investigated the mechanical responses of the amorphous thermoplastic materials. Note that type of materials have the important industrial applications. They have found that their behavior is complex and present a lot of .difficulties due to the structure of these polymers [2].

Note that, deformation and damage at the microscopic scale and the resulting models are generally complex to understand because of the disordered of the macromolecular chains of this material. However, Moreover, as shown in [3], Acrylonitrile Butadiene Styrene (ABS) has the the good properties in terme of resistance, rigidity, dimensional stability and its suitability for decoration. Consequently, it has a significant industrial development, due to all of its properties. Bucknall et al. have showed in [2] that all these physical and chemecal properties allow to obtain a kind of material with good performances .

In this present paper, this investigation consists to study the mechanical behavior of ABS subjected to uniaxial loading. In the one hand, we carried out an experimental study to characterize the mechanical behavior. in the other hand, we took into account the damage, creating a notch in drilled specimens with a diameter of 3mm and notch lengths ranging from 1 to 14mm.

2 Experimental method

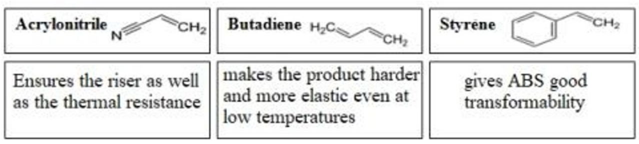
In this section, we present the polymer used in our study, the geometric configuration of the specimens as well as the experimental protocol used for the acquisition of stress-strain data during the application of mechanical loads.

II.1 Material studied

Acrylonitrile Butadiene Styrene (ABS) is the subject of this investigation. This amorphous polymer is obtained by an emulsion or mass polymerization process of acrylonitrile and styrene in the presence of polybutadiene.

II.2 Operating mode

The experimental protocol consists of carrying out static tests on ABS specimens with a hole of diameter Ø=3mm and comprising simple notches of variable lengths ranging from 1 to 14mm.



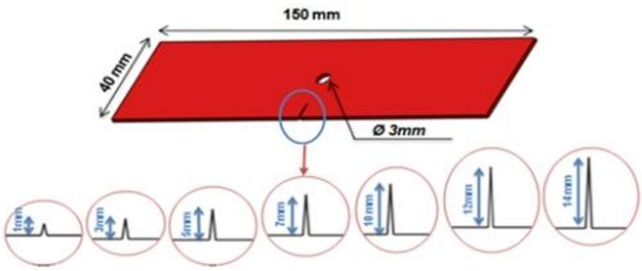


Fig. 1 ABS test piece drilled Ø3mm and prepared according to ASTM D5766M standard [4]

3 Results and Discussion

In this section, we begin our discussion by analyzing the mechanical behavior of virgin ABS specimens in figure 2. Cut according to ASTM D882-02 [5]

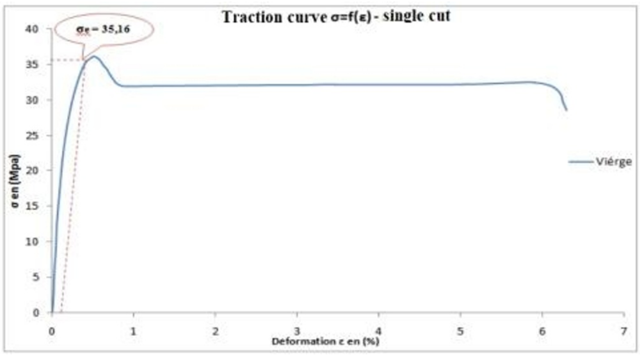


Fig. 2 Stress-Strain Tensile Curve of Virgin Specimens

From the obtained results, we observe a significant variation in the values as the constraints increase. The curve in Figure 2 can be divided into three distinct areas or zones:

- Zone 1: Corresponds to the elastic zone where the material retains the ability to return to its initial shape after stress. This zone allows the extraction of the intrinsic parameters of ABS, including Young's modulus, 0.2% elastic limit, ultimate stress and breaking stress, the values of which are compiled in Table 1.
- Zone 2: This region is characterized by reaching the maximum stress value (36.14 MPa), followed by a slight decrease to a stabilization value.

- Zone 3: In this phase, the stress remains constant while the strain continues to increase, illustrating the viscoelastic behavior of the material. This zone corresponds to the formation of a necking, a precursor phenomenon to the complete rupture of the specimen.

Table 1: Mechanical characterization of ABS specimens.

Young's modulus (GPa)	Elastic limit $\sigma e_{0,2}$ (Mpa)	Ultimate constraint σ_u (Mpa)
2,8	35,16	36,14

3.1 Notch effect on the material

The curves presented in Figure 3 illustrate the evolution of stresses as a function of deformations for Acrylonitrile Butadiene Styrene (ABS) specimens comprising a hole with a diameter of Ø=3mm, associated with notches of variable lengths between 1 and 14 mm. This graphical representation makes it possible to observe the parametric influence of the notch length on the mechanical behavior of the polymer material studied during uniaxial tensile tests.

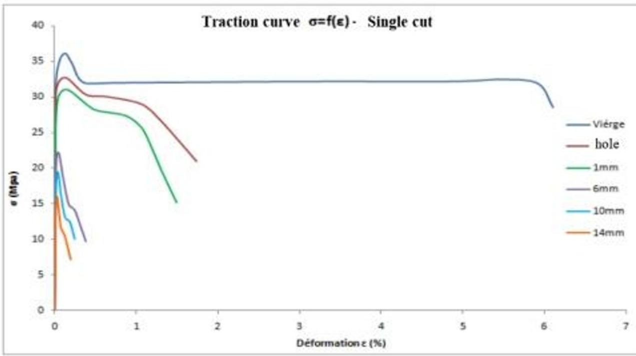


Fig 3 Stress-Strain tensile curve of notched specimens.

The variation in the curve is characterized by an initial phase of increase followed by a decrease, with a significant shift between the different sample configurations depending on the notch length. We observe a progressive reduction in the viscoelastic behavior and an increase in the notch length for the specimens with various notch lengths compared by the virgin specimen.

These results can be interpreted as the manifestation of a stress concentration in the vicinity of the notch. Consequently, a transition in mechanical behavior is observed and characterized by a decrease in viscoelasticity and a tendency towards embrittlement of the polymer material as the notch length increases.

3.2 Loss of ultimate residual stress in static tension for damaged specimens.

The analysis of the mechanical behavior of ABS specimens reveals a significant evolution of the residual ultimate stress as a function of the level of damage. By analogy with the behavior of the polymer material subjected to static stress, the virgin specimens present a characteristic ultimate stress "σ_u" which undergoes a progressive decrease correlated with the increase in the notch length, until the complete rupture of the specimen.

Figure 4 provides a graphical representation of this degradation of mechanical properties, illustrating the evolution of the ultimate residual stress as a function of the life fraction β=a/w, where "a" represents the sum of the notch length and the hole diameter (3mm), and "w" corresponds to the total width of the specimen.

The examination of this curve highlights a monotonic decrease in the residual ultimate stress with increasing life fraction β. This decrease occurs according to a characteristic three-phase process: an initiation phase, followed by a slow propagation phase, then a sudden propagation phase. This behavior is indicative of the progressive damage mechanisms that affect the residual mechanical properties of the polymer material studied.

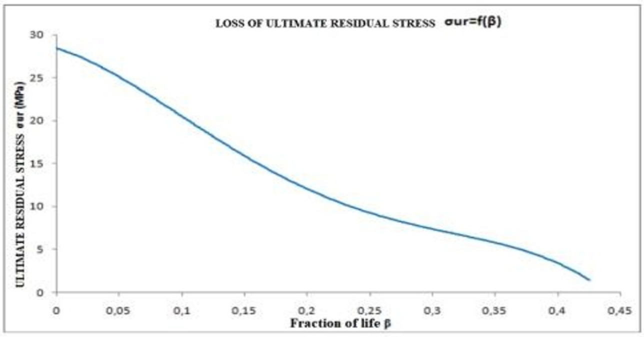


Fig 4 Reduction of the ultimate residual stress as a function of the life fraction, for drilled and simply notched specimens.

3.3 Loss of dimensionless stress in static tension for damaged specimens.

In order to normalize the residual stress, we analyzed the ratio (σ_{ur}/σ_u), representing the dimensionless residual ultimate stress, as a function of the life fraction (β). This relationship is illustrated in Figure 4, for all specimens with a hole in addition to a simple notches whose lengths vary from 1 to 14 mm.

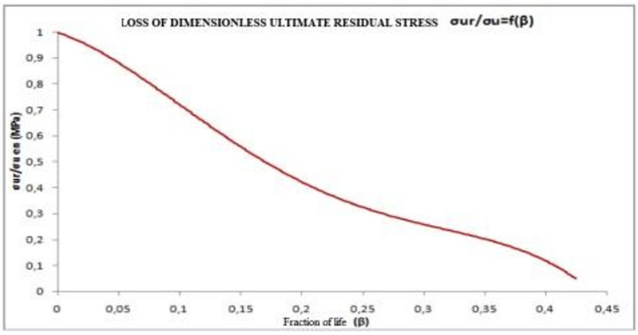


Fig. 5 The loss of non-dimensional stress in static tension for drilled and simply notched specimens of (1 to 14 mm)

The examination of this curve reveals that the ultimate residual stress decreases proportionally and progressively as a function of the life fraction.

This graphical representation highlights that the rate of loss of residual stress increases for high life fractions. Indeed, a systematic decrease in residual stress is observed with increasing life fraction.

3.4 reliability and Determination of damage

The determination of the ultimate residual stress volutions, which are due to damage, allows to know a static damage model. This approach led to establish a correlation between the microstructural modifications of the material and its macroscopic mechanical properties [6].

In the case of absence of external forces [7], residual stresse, result from deformation incompatibilities, are defined as the internal forces that remain in mechanical parts. This can have an impact on the mechanical behavior of the material. Also, it can affect their lifetime.

During the test, we monitored the damage phenomenon between the virgin state and the complete rupture of the specimen, by measuring the residual ultimate stresses. This experimental methodology allows us to quantify the progressive evolution of the degradation of the mechanical properties as a function of the progress of the damage. This phenomenon is quantified by the damage parameter according to the following equation. This quantification constitutes a reliable indicator of the residual structural integrity and can serve as a basis for establishing predictive criteria for rupture [8].
With

$$D = \frac{1 - \frac{\sigma_{ur}}{\sigma_u}}{1 - \frac{\sigma a}{\sigma u}} \quad (1)$$

σ_u: is the ultimate stress value in the initial undamaged state; σ_{ur}: is the ultimate residual stress value for different notch lengths and σ_a: is the stress value just before failure. We have then:

$$\frac{ai}{w} = 0 \longrightarrow \sigma ur = \sigma u \longrightarrow D = 0$$
$$\frac{ai}{w} = 0 \longrightarrow \sigma u = \sigma a \longrightarrow D = 1 \quad (2)$$

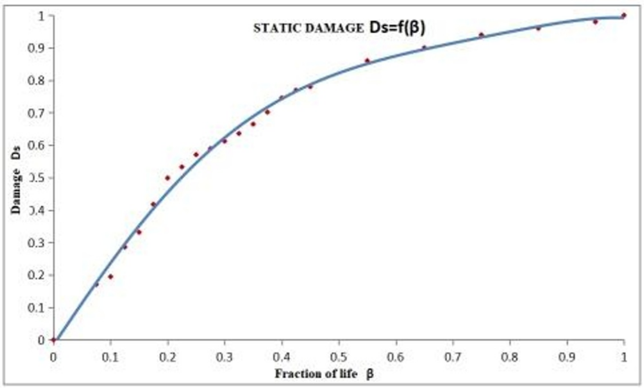


Fig. 6 Evolution of damage as a function of notch length

The curve shown in the figure illustrates the evolution of static damage (Ds) as a function of life fraction (β) for the tested ABS specimens. Analysis of this curve reveals a non-linear relationship between damage and life fraction. The following characteristics can be observed:

- Damage progression starting at the origin (0.0), indicating the absence of initial damage in the pristine sample.
- Rapid damage progression in the initial phase ($\beta < 0.3$), characterized by a relatively steep slope. This region likely corresponds to the damage initiation phase where defects begin to develop [9].
- A gradual decrease in the slope for intermediate values of β ($0.3 < \beta < 0.7$), suggesting a slowdown in the damage growth rate. This phase may be associated with stable defect propagation.
- A flattening of the curve for high values of β (> 0.7), tending asymptotically towards the value Ds = 1, which represents complete damage leading to failure.

The curve represents a mathematical model fitted to the experimental data, demonstrating a good correlation between the experimental results and the proposed model. This representation of damage as a function of the fraction of life constitutes a valuable tool for predicting the residual life of ABS components with notches.

3.5 The reliability approach in the assessment of material degradation

In the context of the analysis of the behavior of materials subjected to mechanical stresses, it is appropriate to consider an additional parameter of a static nature which makes it possible to characterize the evolution of the deterioration of the material [10].

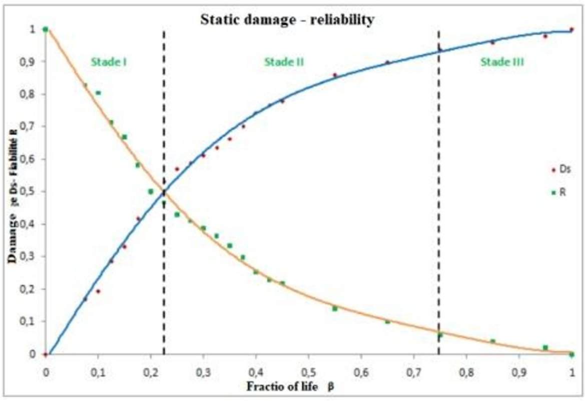


Fig 7: Evolution of damage versus reliability as a function of life fraction

Note that "R" is the reliability parameter (which quantifies the probability of survival of the material). This parameter is used to represent mathematically the ability of a material to maintain its mechanical proprietiesunder specified conditions, we use this parameter. The integration of this concept into the analysis of polymer materials allows for the establishment of a correlation between microstructural damage mechanisms and the macroscopic performance of the material, thus facilitating the development of robust predictive criteria for the evaluation of the residual life of structures. R(ai) + D(ai) = 1.

The figure 7 illustrates the relationship between static damage (Ds), reliability (R), and fraction of life (β) for the ABS specimens studied. This graphical representation highlights several fundamental aspects of the material's mechanical behavior.The graph reveals an inverse relationship between static damage and reliability. As damage increases with fraction of life, reliability decreases proportionally. The stages of this curve are:

- The first stage, $0 \leq \beta < 0.25$, Initial phase characterized by relatively rapid damage accumulation and a linear decrease in reliability. This phase corresponds to the initiation of microcracks.

- The second stage, $0.25 \leq \beta < 0.75$, in this phase the damage growth rate decreases gradually and the reliability decrease at a moderate rate. This phase represents stable crack propagation.

- The third Stage, $0.75 \leq \beta \leq 1$, corresponds to a final phase where the static damage is marked (≈1). the reliability tends toward zero in this case. This stage corresponds to rapid crack propagation leading to imminent failure.

- Intersection point at $\beta \approx 0.25$: the critical point , where the material transitions from a reliable state to a damaged state, is indicated by the curves intersect. In this case it correspind to the value of 0.5.

This representation constitutes the evaluation of the residual life of ABS components subjected to a mechanical stress, making it possible to optimize maintenance strategies.

4 CONCLUSION

The study of the mechanical behavior of ABS under uniaxial loading has highlighted the significant influence of damage on the mechanical properties of this amorphous polymer. Tensile tests carried out on drilled specimens with notches of varying lengths revealed a progressive decrease in viscoelasticity and a tendency towards embrittlement of the material with increasing notch length. The analysis of the evolution of the ultimate residual stress as a function of the life fraction showed a monotonic decrease following a three-phase process: initiation, slow propagation, and then abrupt propagation. This observation made it possible to establish a static damage model correlating the microstructural modifications of the material to its macroscopic mechanical properties.

The inverse relationship between static damage and reliability has been clearly identified, allowing three characteristic stages in damage evolution to be distinguished: an initial phase of rapid accumulation, an intermediate phase of stable propagation, and a final phase of rapid propagation leading to failure. The critical point where the material transitions from a predominantly reliable state to a predominantly damaged state has been identified at a life fraction of approximately 0.25.

This approach combining damage and reliability analysis provides a valuable predictive tool for assessing the residual life of ABS components, enabling the anticipation of potential failures and the optimization of maintenance strategies in industrial applications. These results also provide a better understanding of damage mechanisms in amorphous polymers, thus helping to overcome the challenges encountered during the sizing and optimization stages of thermoplastic products.

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