



## Damageable Thermal Behavior of Thermoplastic Flat Plate under Uniaxial Stress

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### Research Article

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### Abstract

The behavior of polymers is remarkably related to temperature, its influence on physical characteristics should not be denied in the study of mechanical or physical behavior, especially in the study of forming processes that require an important apport of mechanical and thermal efforts. The behavior of polymers is strongly linked to a known temperature margin noted  $T_g$  and called glass transition temperature, above which the configuration of the macromolecular chains goes largely mobile, and dependence with temperature occurs more dramatically. This dependence is especially remarkable than the dependence with time for viscoelastic materials. Our work is a contribution to the study and characterization of the behavior of thermoplastic polymers with thermal damage, the damage model proposed reflects the state of damage to a structure made of ABS (Acrylonitrile-Butadiene-Styrene) undergoes both mechanical and thermal damage under different temperature spectra.

**Aims:** To introduce the temperature influence on the mechanical behavior of polymers through damage variable, and the evolution of this variable with respect to temperature.

**Study Design:** We study dumbbell shape flat plate specimens made by ABS under a thermo-mechanical effort.

**Place and Duration of Study:** Laboratory of Bioplastics and Nanotechnologie, Department of Applied Sciences, University of Québec in Abitibi-Témiscamingue, between August 2012 and December 2012.

**Methodology:** Two series of test was achieved on ABS specimen, first, thermal characterization was accomplished for determining the characteristicals temperatures, and then thermo-mechanical tests was performed on dumbbell specimen in uniaxial tension and in a range of temperature from 60°C to 180°C by a step of 10°C.

**Results:** For the ABS material, the mechanical characteristics with respect to temperature

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evolution were noted. And the damageable thermal behavior was highlighted.

**Conclusion:** Results show the reliability of the proposed approach, and its ability to present the damageable behavior of the with respect to its intrinsic parameters.

Keywords: Damage, thin flat plate, thermoplastics, ABS, glass transition.

## 1 Introduction

Polymeric parts are subject to mechanical and thermal stresses during production as well as in commissioning. The macromolecular chains tend to move more freely as temperature gradually increases.

The glass transition temperature,  $T_g$ , is probably the most important thermal property and the most influential one on polymers characteristics. It can determine the range of operating temperature of a polymer. The general case of the polymers in the molten state is explained by the interacting particles, in which the molecular mobility is described by the passage of energy gap,  $E$ , also known as activation energy [1]. Exceeding that barrier characterizes generally a phase change.

The phase change is a phenomenon widely discussed in the literature, especially in the study of thermodynamic transformations with the pioneering work of Gibbs that studies the phase change [2] and the work of Kauzmann [3] on the entropy associated to a phase change.

In fact the glass transition is a thermodynamic transition characterized by a progressive variation of the enthalpy of the system and its first derivative [4]. This transition does not have a proper thermodynamic explanation, but rather corresponds to a change in the behaviour of the material. Clearly the degradation of the material's properties (mechanical, electrical, physical, and chemical properties) is more remarkable above the glass transition temperature [5]. Therefore, it is vital to describe the effect of the temperature in the study of the polymers' behaviour.

In this work, a thermal characterization of the studied material was carried out on samples of ABS (Acrylonitrile-Butadiene-Styrene). The goal was to determine the glass transition temperature and the melting temperature using both DSC and TGA methods. Thereafter, uniaxial tensile tests under different temperature margins were carried out in order to characterize the effect of temperature on the mechanical properties of the material. A damage model was also proposed to determine the status of material damage as a result of coupled thermo-mechanical stress.

## 2 Thermal Characterizations

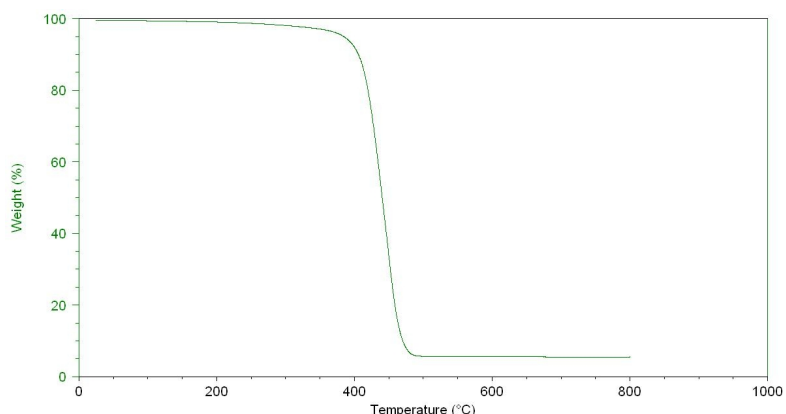
### 2.1 Characterization of the Thermal Stability

To investigate more specifically the thermal behavior of our material, which is a styrene copolymer, Acrylonitrile-Butadiene-Styrene commonly known as ABS, a study of the thermal stability of the polymer was studied using a Thermo-Gravimetric Analysis noted TGA [6].

The TGA analysis measures the change in weight of a sample as a function of time and temperature. These experiments are carried out under defined gas atmosphere (inert or reactive),

or vacuum. TGA is used to study the thermal stability and oxidation resistance of materials. Additionally it is possible to characterize the kinetics of decomposition, decomposition temperatures and thermal aging.

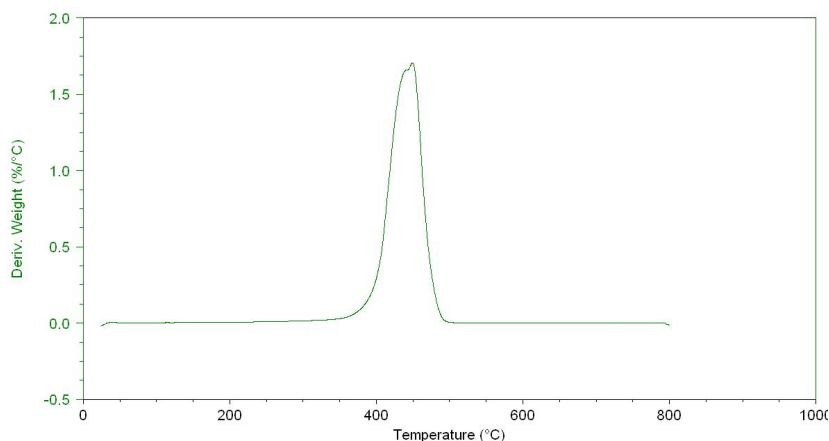
3 mg samples were tested under vacuum, the results are illustrated in Fig. 1 and Fig. 2:



**Fig. 1. Mass percentage variation versus temperature**

Fig. 1 reports the weight loss curve as a function of temperature. It shows three important sections, namely a zone of polymer thermal stability, followed by a continuous decline until the complete degradation. The thermal stability of the polymer remains remarkable till 400°C, where there is a sudden drop in weight percentage, due to the macromolecular chains detachment of the three polymers constituting the copolymer, and to the increased mobility of molecules. Mass degradation of specimens continues its fall in excess of 450°C, and then there is a total thermal degradation of the material at 500°C.

The kinetics of thermal degradation is more shown in Fig. 2 below:

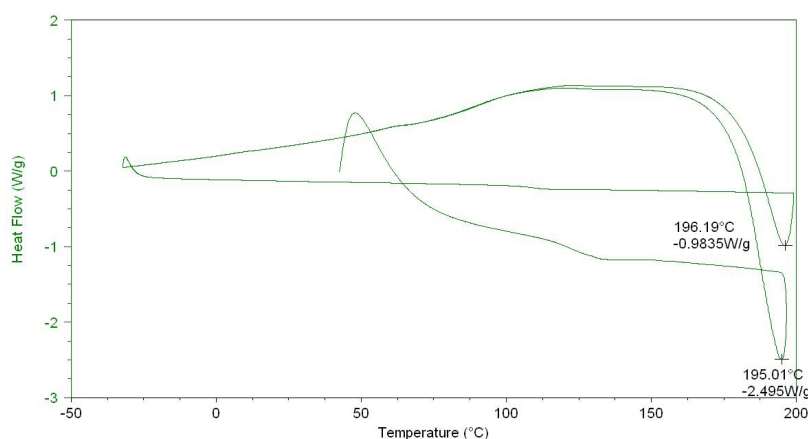


**Fig. 2. First weight derivative versus temperature**

The mass variation rate change according to the temperature is illustrated in the Fig. 2; the curve shows the kinematics of the thermal degradation. Near zero kinematic is observed until 400°C where a point of spades appears, this maximum defines the maximal degradation velocity attained during the test, it also defines the point in which the kinematics of thermal degradation becomes irreversible. The total thermal degradation of the material took place just after this point.

## 2.2 Colorimetric Characterization and Determination of the Glass Transition

Determining the glass transition can be achieved by scanning the material with a heat flux, and recovering the enthalpy of the material [7], the most used method to determine the glass transition temperature is differential scanning calorimetry, DSC, which is a measurement technique wherein the heat flux absorbed or released by a sample is monitored as a function of time and temperature. The DSC method is based on a differential measurement; it involves measuring the differences in properties (physical, chemical...) between the sample and a reference sample installed on two twin compartments [8]. The main advantage of this measurement method is that, as a first approximation, a perturbation, such as temperature change in the surrounding system, affects by the same way the sample and the reference.



**Fig. 3. Procedure to eliminate thermal overlapping and residual stresses in the samples and determining the melting temperature**

Calorimetric properties of ABS were analyzed using Thermal Analysis Instrument DSC Q400 series. The measurement procedure used is shown in Fig. 3. 6mg samples were heated to a temperature of 200°C with a rate of 50°C/min and then cooled at a rate of 50°C/min to a temperature of -40°C, at which were maintained for 5min. The purpose of this step is to eliminate the residual stresses in the material accumulated during the stages of processing and also delete the thermal history of the sample. After this first step, a second heating cycle was performed in order to determine exactly the glass transition temperature and melting temperature.

We note that the melting temperature of the polymer shifted to higher values during the second heating cycle. The melting temperature of the ABS has been estimated equal to  $196.19^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$ .

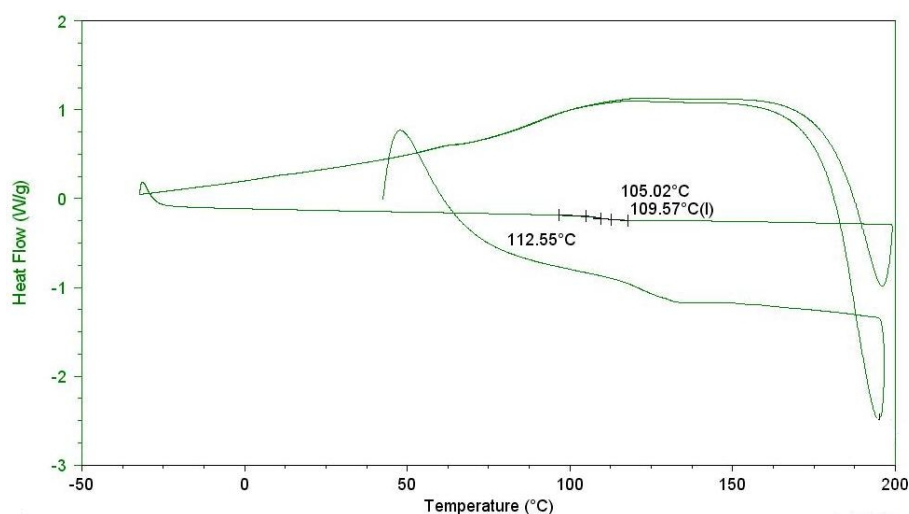


Fig. 4. Glass transition region and the glass transition temperature

The glass transition can be determined based on the same curve, and seeking the first order transitions, in which the phase transition occurs at constant heat capacity, it is the area characterized by the glass transition temperature. Fig. 4 above shows the value of this temperature which  $109.57^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$ .

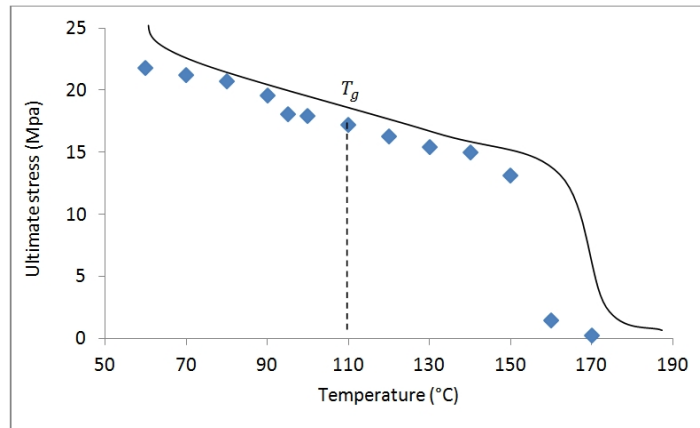
### 3 Thermo-Mechanical Characterizations

#### 3.1 Temperature Effect on the abs Behavior

For characterizing the material behavior according to its temperature, several sets of uniaxial tensile tests were performed in a temperature range from  $60^{\circ}\text{C}$  to  $170^{\circ}\text{C}$ , passing through the glass transition temperature which is in the vicinity of  $110^{\circ}\text{C}$ , for each range of temperature, stress-strain curve is plotted in order to evaluate the measurands that will be needed to analyze the thermo-mechanical behavior of the material.

The ultimate stress reached during the tensile test, the Young's modulus and elongation are recorded, and their evolutions versus the temperature are plotted on figures below.

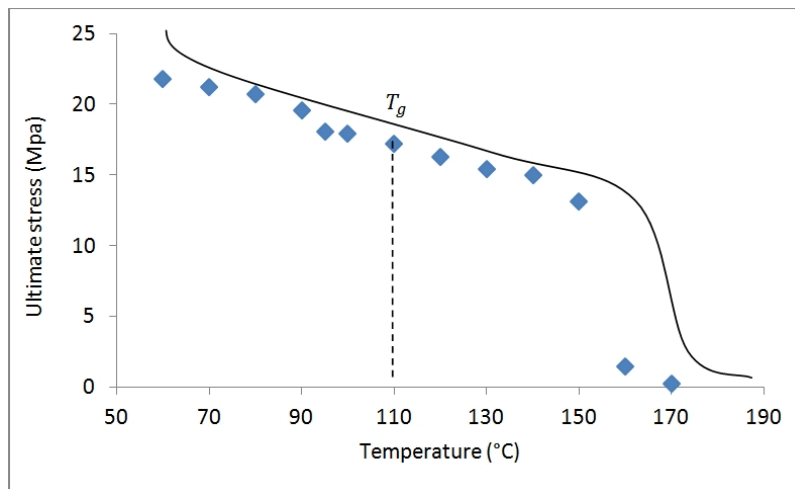
The polymers present for a specific range of temperatures possibilities of movement of radicals or pieces of molecular chains, that is to say that the mechanical behavior of the polymer is affected. Fig. 5 postpones the ultimate stress evolution (maximum stress reached during the uniaxial tensile test) as a function of temperature. A pseudo linear decrease is observed for temperatures below the glass transition temperature  $T_g$ , which is once exceeded, the decay accelerating suddenly drops, approaching the melting temperature.



**Fig. 5. Ultimate stress evolution versus temperature**

The fall of the ultimate versus the temperature is justified by the fact that, below the glass transition temperature  $T_g$ , the macromolecules of the amorphous part of the copolymer are sparsely deformable in a rigid state (vitreous), above  $T_g$ , the chains movements becomes possible in the amorphous areas now, and allow larger and easier deformations, it is generally noted that the properties fall from  $T_g$ .

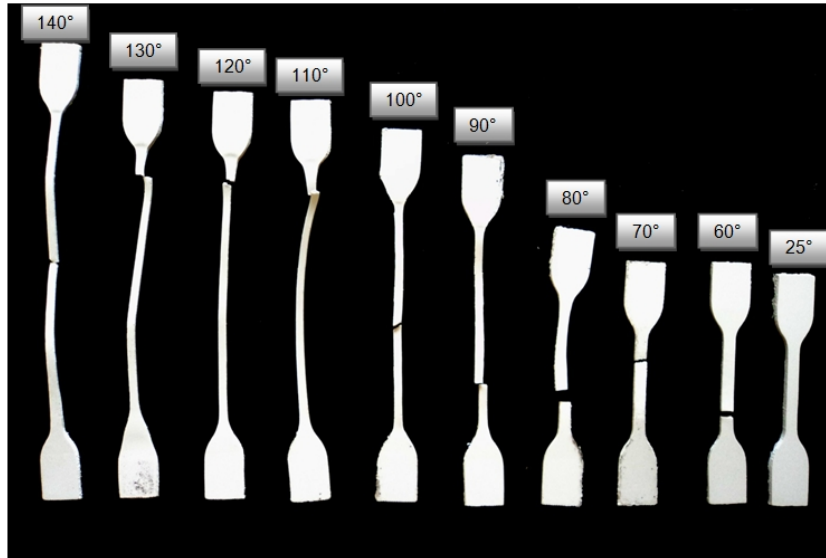
Proportionality between stress-strain is described by the Young's modulus and its evolution as a function of temperature, this evolution is shown in Fig. 6:



**Fig. 6. Young's modulus evolution versus temperature**

The variation of Young's modulus is remarkable, a significant decrease with a temperature raise occurs, this decrease is accelerated once the range of glass transition temperature is exceeded, and continues until the fusion zone where one obtains very low values. This is due to the weakening of intermolecular bonds due to the temperature evolution, and with low effort, we get more important

stretches. Tests carried out in the vicinity of the melting temperature were not constructive, the specimen melts even before test, and flows from the jaws of the machine under its own weight. Fig. 7 below shows specimens undergone tensile tests at different temperatures:

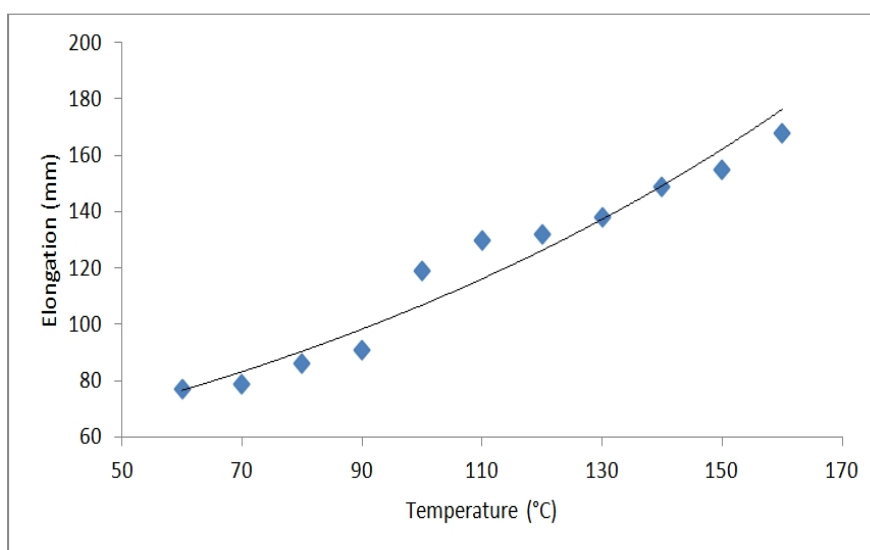


**Fig. 7. Elongation of the specimens after testing in different ranges of temperature**

The elongation evolution versus the temperature being thus remarkable, elongation values increasingly important is achieved with increase in temperature, particularly at temperatures above the glass transition temperature.



**Fig. 8. Elongation of a specimen during testing at 140°C**



**Fig. 9. Evolution of elongation as a function of temperature**

Fig. 9 shows a pseudo linear variation in elongation as a function of the temperature, for temperatures below the glass transition temperature, the evolution retains a slight slope with an elongation which is above 10%. While approaching the T<sub>g</sub>, the elongation values rise more and more significantly to the melting zone, we talk here about a rubbery behavior, which corresponds rather to a flow due to disentanglement of macromolecular chains [9].

## 4 Damage Quantification in the ABS

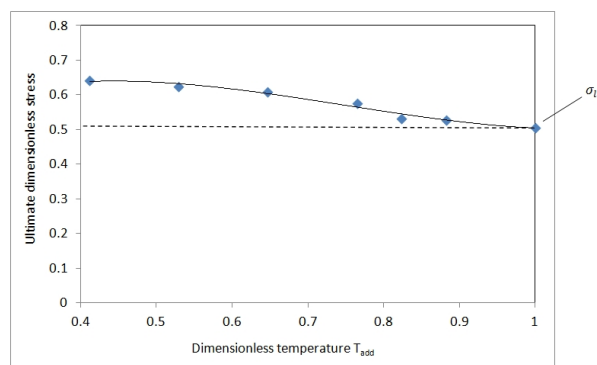
Degradation of mechanical properties due to temperature prove remarkable, thus, it is essential to quantify the degree of degradation of these characteristics, by assigning a variable that will be as a damage indicator of the material.

In addition, above glass transition temperature, the degradation of the mechanical properties becomes more pronounced; from this temperature, there is a drop in the material resistance, this behavior continues until the melting zone [10], and to quantify the material damage, the T<sub>g</sub> is taken as reference parameter for dimensionlessness different material properties.

The variation of the ultimate dimensionless stress (dimensionless with respect to the stress reached in the glass transition region  $\sigma_{add} = \frac{\sigma_u}{\sigma_{Tg}}$ ) versus dimensionless temperature

(dimensionless with respect to the glass transition temperature  $T_{add} = \frac{T-T^0}{T_g-T^0}$ , T<sub>0</sub> is the ambient temperature) is reported in Fig. 10 below:



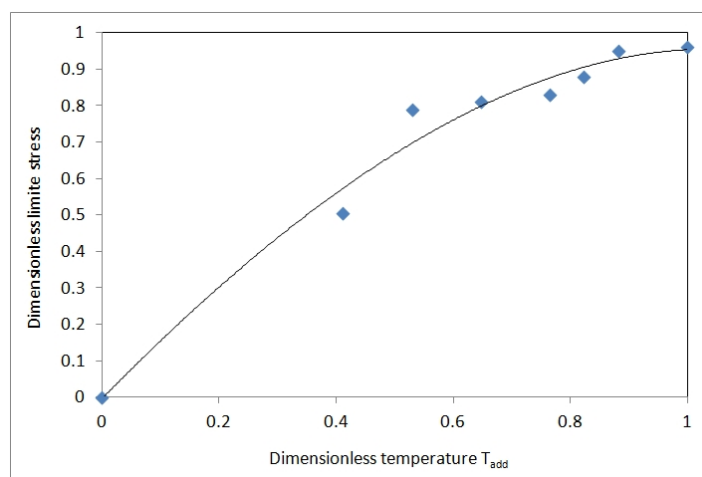


**Fig. 10. Loss of static resistance as a function of temperature**

Fig. 10 shows the degradation of the dimensionless stress as a function of dimensionless temperature, this degradation present the loss of resistance of the material according to the different temperature levels.

This loss resistance increases with temperature and becomes more and more important where approaching the glass transition temperature, its intersection with the boundary of the interval of study allows us to define a stress boundary, which will be estimated as indicator of the state of material damage, this stress takes as value  $\sigma_l = 17.2 MF$  .

This value will be useful later for the study and quantification of material damage. The dimensionless yield stress is plotted against dimensionless temperature:



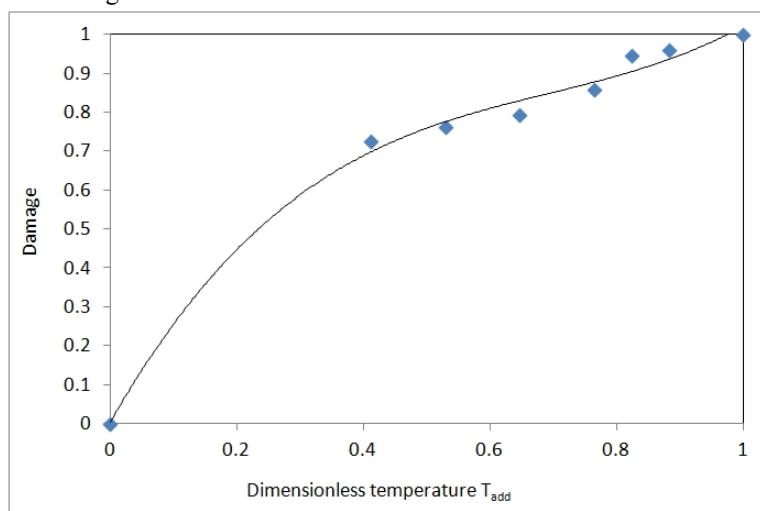
**Fig. 11. Evolution of the dimensionless stress as a function of dimensionless temperature**

Damage theory has as aim to assess the state of damage in a structure with respect to one or more critical stress states [11]. For this purpose, the definition of a quantitative damage variable is paramount.

Measurement and quantification of damage follows a variety of laws and representations depending on the nature of the damage suffered by the material, the simplest presentation of a damage variable model remains Miner's model [12].

Usually a damage variable must reflect the evolution of the deterioration state of the material based on the factors influencing behavior, starting from a zero value for virgin material to one for totally damaged material.

The curve shown in Fig. 11 shows the evolution of the dimensionless stress as a function of dimensionless temperature. First, the curve adopts increasing pace; for temperatures near room temperature, the damage in the material remains negligible, then it accelerates accentually when approaching the glass transition temperature till reaching its maximum value, which is one where the total material damage occurred.



**Fig. 12. Damage evolution versus dimensionless temperature**

The model proposed in this study provides an overview of the state of damage of the material according to its temperature, involving an intrinsic parameter which is its ultimate tensile stress, properties evolution depending on the temperature is considered for this purpose as an indicator of damage.

The proposed damage variable resulting from Bui Quoc damage theory [13], involved damage characterization in materials undergoing fatigue stresses, the determination of the ultimate residual stress is done by coupled dynamic and static tests, and the fraction of life is the number of applied cycles.

After determining the yield stress by the loss resistance curve, and identification with the Bui Quoc model, we can define our damage variable as the following quantity:

$$D = \frac{1 - \frac{\sigma_{ur}}{\sigma_u}}{1 - \frac{\sigma_l}{\sigma_u}}$$

$\sigma_{ur}$  being the ultimate residual stress to which the material is considered blank, the ultimate stress  $\sigma_u$  is the achieved stress at each temperature range.

We report the variation of this variable with respect to the dimensionless temperature in Fig. 12 above.

The curve reflects the impact of increased temperature on the mechanical properties of the material, there is a slow evolution of the damage in the beginning of the cycle, and an accelerated rate of damage with values exceeding 50% by approaching the glass transition temperature, which was taken as the criterion of damage.

## **5 Conclusions**

The objective of this work was to characterize the thermal and mechanical behavior of a thermoplastic plane sheet. It has been estimated that the uniaxial tensile test was the most practical approach and most accurate of the actual state of deformation during loading real, this technique has been used to describe the damage incurred by the material coupled thermal and mechanical stresses.

Unified theory of damages was used in order to give a more complete damage model that can describe more accurately the damage state of the material. The results showed the feasibility of the applied damage approach, the proposed approach involves intrinsic parameters of the material (its ultimate stress, its glass transition temperature), which allows a rigorous description of the damage state of materials.

These preliminary studies are essential steps towards the full realization of our med-term objectives of the implementation and development of tools for modeling and simulating of thermoplastic forming processes.

## **Acknowledgement**

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## **Competing Interests**

Authors have declared that no competing interests exist.

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