

DEFORMATION MECHANISMS AND THERMAL VARIATION IN YIELD REGIME ON POLYPROPYLENE

Alexandre de Souza Rios^{1,2}

Luiz Carlos Gonçalves Pennafort Junior²

Abner Guilherme Teixeira Lima²

Santino Loruan Silvestre de Melo²

Marcos Daniel Gouveia Filho²

Enio Pontes de Deus²

¹LMT (ENS Cachan, CNRS, Université Paris Saclay, Université Paris 6). 61, av. du Président Wilson. 94235 Cachan, France

²LAMEFF (Department of Materials Engineering, Federal University of Ceara). Campus do Pici. Fortaleza, 60440-554. Brazil

Abstract. *The comprehension of strain mechanics on semi-crystalline polymers are required to explain their rupture behavior and initiation of plasticity. This study presents the 2D displacements and temperature variation during a tensile test on polypropylene. The analysis of digital image correlation were used to determine Poisson's ratio, identify the strain fields and yielding formation mechanisms. The infrared thermography indicates that the adiabatic process onset during the plastic deformation was formed during the alignment of polymer chains in a fibrillar shape and there was no change in temperature before the alignment. The heating zones were governed by post-yield regime and presented parabolic shapes with peak temperature in the center of this polymer.*

Keywords: *polypropylene, yielding, digital image correlation, infrared thermography.*

1. INTRODUCTION

A sequence of deformation events leads to different forms of plastic deformation in polypropylene, which are not only of scientific interest, but also of engineering relevance [1-5]. The initial stages of tensile deformation are governed by the straining of molecular chains of the interlamellar amorphous phase, interlamellar shear, rotation of lamellae stacks and lamellae separation [2]. Above T_g , the initial deformation is located in the amorphous regions because of their low modulus. The tensile deformation of a spherulite is inhomogeneous because the amorphous regions and the radially oriented lamellae have different angles to the direction of the tensile force. The main mode of plastic deformation of the amorphous components is believed to be interlamellar sliding, or lamellae separation in the equatorial regions, where the lamellae are oriented perpendicularly to the drawing direction. The mobility of amorphous chains may vary locally [6]. The constraints imposed by the lamellae imply that only a limited amount of deformation can be accommodated by the interlamellar amorphous phase [7]. When this limit is reached, further deformation can proceed either by cavitation of the amorphous phase or by plastic deformation of crystals. Polypropylene shows a transition in the temperature region around 80°C, which is associated with mobility in the crystalline phase. When drawing is performed at elevated temperatures approaching this transition region, a change of the dominating deformation from cavitation towards shear yielding can be expected.

These irreversible deformations begin at strains below the yield strain. Knowledge of the irreversible deformation modes and load limits for reversible behavior is therefore essential for proper modeling of mechanical behavior and for optimizing polymer component designs. However, appropriate techniques for determining mechanical strains polymers are required [8].

Optical techniques such as digital image correlation (DIC) are particularly suitable for soft polymeric materials, as local stress concentrations arising from the indentation of the specimen and the weight of an attached mechanical extensometer are entirely avoided [9]. In general, DIC is based on the principle of comparing speckle pattern structures on the surface of the deformed and the undeformed sample or between any two deformation states. For this purpose, a virtual grid of subsets of a selected size and shape, consisting of certain pixel gray value distributions, is superimposed on the preexisting or artificially sprayed on surface pattern and followed during deformation by an optical camera system. In this manner, information on the in-plane local strain distribution is gained without assuming the constitutive behavior of the material a priori. Furthermore, this method is independent of specimen geometry and can also be applied to complex parts and geometries [10-14] to gain information on the deformation behavior of components in real service. Moreover, out-of-plane movements of the specimen affect the apparent size of the specimen and, thus, may also alter the strain result in 2D measurements. Finally, the range of the depth of sharpness is limited and determines the operating distance to the measured object if significant out-of-plane movements occur. Knowledge of the intrinsic material behavior of polymeric materials from the small strain range up to ultimate failure is of crucial importance for developing adequate material laws for numerical modeling and for a deeper understanding of the microscopic deformation mechanisms [15].

The use of infrared thermography for in situ detection of fatigue damage in materials has recently been established as a valid non-destructive evaluation (NDE) technique [16,17]. The application of this method has also shown to be useful for the determination of the high cycle fatigue strength (HCFS) of some composite materials [18–20].

This paper aims to understanding the initiation and propagation of the microscopic deformation mechanisms on polypropylene and their temperature variation effects during the pre-yield, yield and post-yield regimes.

2. MATERIALS AND METHODS

Tensile tests on virgin polypropylenes at speeds of 10, 15, 20, 25, 30 and 35 mm/min were performed according to ASTM D638-10 and followed by an infrared camera (model JADE 570 M) for Digital Infrared Thermography (DIT) and a digital camera (model manta IT CCD Sony ICX 285 ExViewHAD and 0.125x of lens objective) for Digital Image Correlation (DIC). These tests were performed in servo-hydraulic machine MTS (model 810 with 10 kN load cell) at room temperature. Each camera was distanced frontally in the opposite side at 25 cm (Figure 1a) and captured 500 and 2 images per second by infrared and digital cameras, respectively. The two surfaces of the specimen were sprayed by JELT Jeltouch RAL 9005 and RAL 9010, one side sprayed of black color for DIT and the other side sprayed of white with non-uniform black points for DIC (Figure 1b), according to procedures that contribute to the acquisition of images with good texture and gray level recommended for DIC analysis in the Correli^{Q4} software [8,15,21].

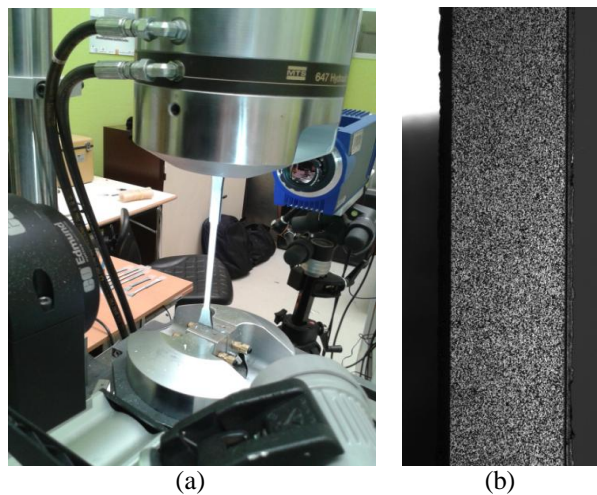
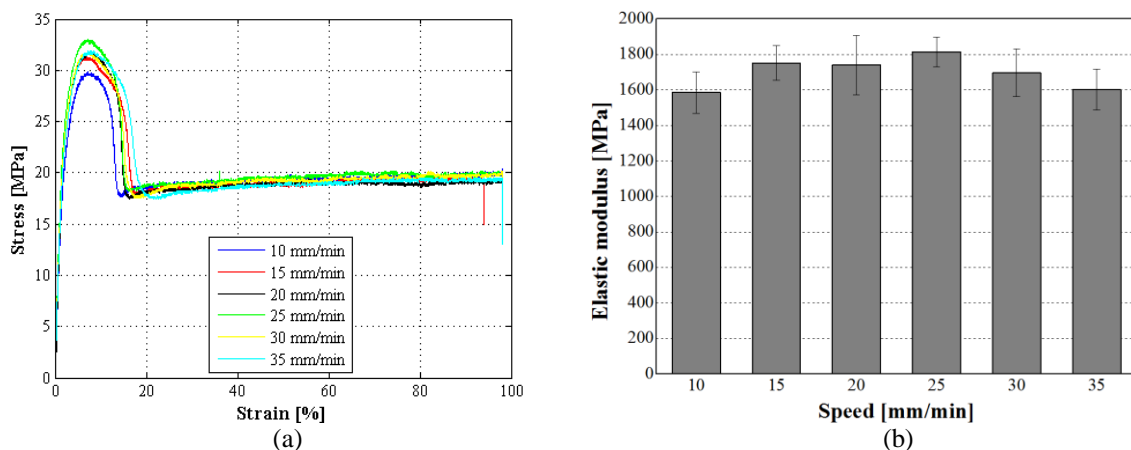


Figure 1. (a) Apparatus for tensile test in virgin polypropylene and (b) surface prepared for DIC analysis. 1 pixel represents 52 μm .

3. RESULTS

The Figures 2a-d show the influence of the test speed (10, 15, 20, 25, 30 and 35 mm/min) on the mechanical behavior of virgin polypropylene according to the stress-strain curve, elastic modulus, tensile strength and strain at tensile strength.



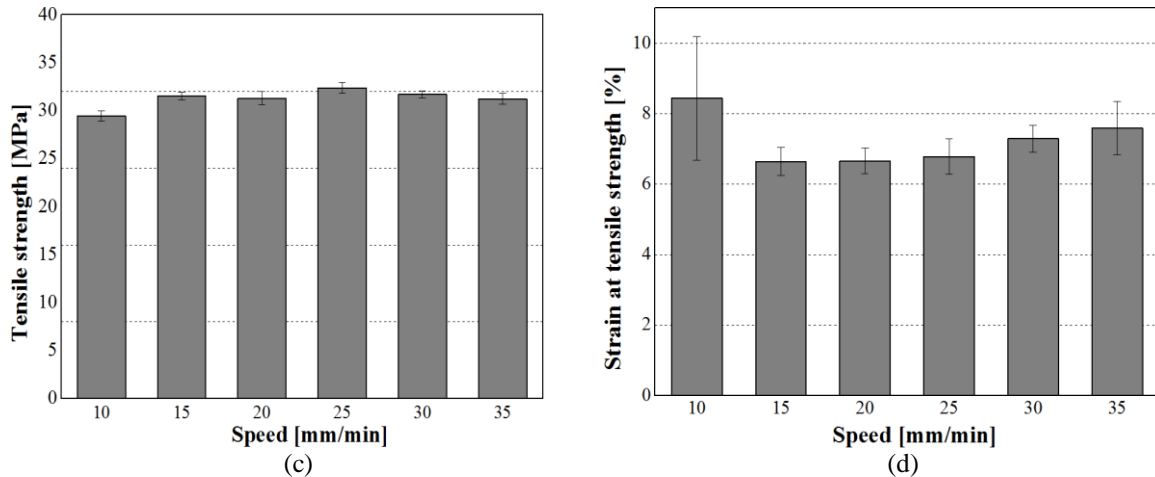


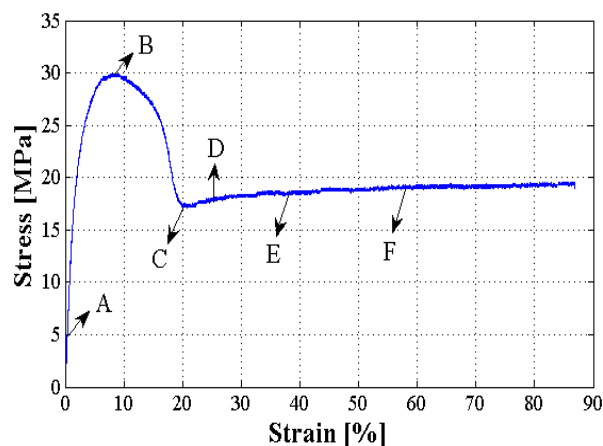
Figure 2. The influence of the test speed (10, 15, 20, 25, 30 and 35 mm/min) on virgin polypropylene in the: (a) stress-strain curve, (b) elastic modulus, (c) tensile strength and (d) strain at tensile strength.

Semi-crystalline polymers such as polypropylene, exhibit high ductility as mechanical behavior also found in this study. According to the Figure 2a, there was a peak stress, which formed a permanently necking extended along the polypropylene specimen. The morphology of the polymer becomes a spherulitic structure into a fibrillar structure oriented in the direction of stretching of the test, resulting in reduced mechanical strength and cross-sectional area [22]. Then, after alignment of the polymer chains during the tensile test, there was a small increase in strength after 20% deformation.

According to the Figure 3, the test speed showed no significant changes in the mechanical behavior of virgin polypropylene. The elastic region of the strain-stress curves was similar and therefore at a slower speed, 10 mm/min, was assumed in the following tests because it contained a greater number of images captured in this region, thus facilitating the identification of its elastic properties by DIC. The Figure 3 show a stress-strain curve at 10 mm/min and some images captured in Correli^{Q4} during the test program and its associated longitudinal and transverse strains.

The points of longitudinal and transverse strains distributed throughout the specimen in the elastic region were presented in Figure 3 (instant A). The relationship between these mean deformations or Poisson's ratio at instant A is 0.375. In the region of tensile strength (instant B) there was a higher concentration of longitudinal strain in the upper region of the specimen. The mean longitudinal strain increased from 0.0032 (instant A) to 0.1010 (instant B). On the other hand, the mean transverse strain is distributed throughout in the sample measurement region. At the instants C and D both located in the plastic region of the stress-strain curve are shown larger mean field strains in the upper region of the same area with larger displacement in the yielding area (purple area). In these instants, is possible to see that the yielding region progresses at its extremity and smaller area than the deformed region, showing that the yielding will progress to large strains, but without reaching the partial or total rupture of the sample. The five stress-strain curves (Figure 2a) demonstrate this event.

Up to the yield point, polypropylene deforms relatively homogeneously, however at large strains, in the yield and post-yield regimes, inhomogeneous deformations are observed in this polymer. The necking formation presented occurs due to alignment of the molecular chains which was allowed by the test. This alignment causes the increase of resistance and yield strength.



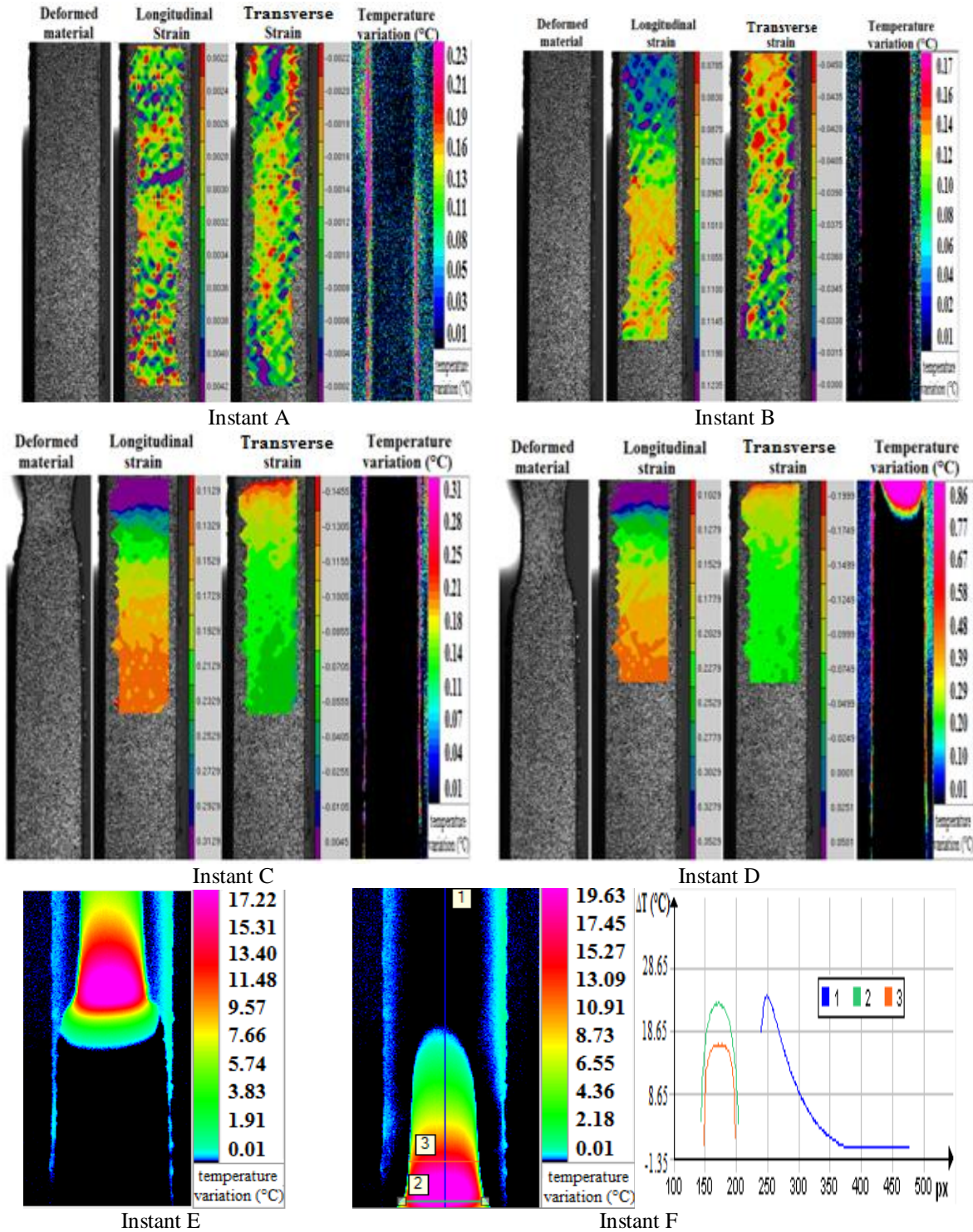


Figure 3. Stress-strain curve followed by DIC and DIT. Instant A (5.09MPa; 0.37%; 2.3s), instant B (29.94MPa; 8.58%; 8.7s), instant C (17.43MPa; 19.99%; 20.4s), instant D (17.93MPa; 24.66%; 25.15s), instant E (18.43MPa; 38.68%; 236.8s) and (f) instant F (19.01MPa; 58.26%; 356.7s). For DIC, 1 pixel represents 52 μm .

The mean longitudinal strains measured in the elastic region and conducted by the tensile machine were compared with the mean longitudinal strains measured by Correli^{Q4} software and both showed similarity (Figure 4a). The mean measurement error reported by the image correlation software was 0.01. The mean longitudinal strain showed magnitude greater than the mean transverse strain, and the progression of both was regular (Figure 4b), allowing the determination of the Poisson's ratio with low dispersion values (mean 0.377 and standard deviation 0.007) (Figure 4c). These results demonstrate the isotropy of polypropylene (Poisson's ratio between -1 and 0.5). The literature, in which this mechanical property was determined by the traction equipment with strain gauges found values between 0.35 and 0.486 [8,23,24]. Therefore good agreement between results of mechanical extensometers and DIC systems were found.

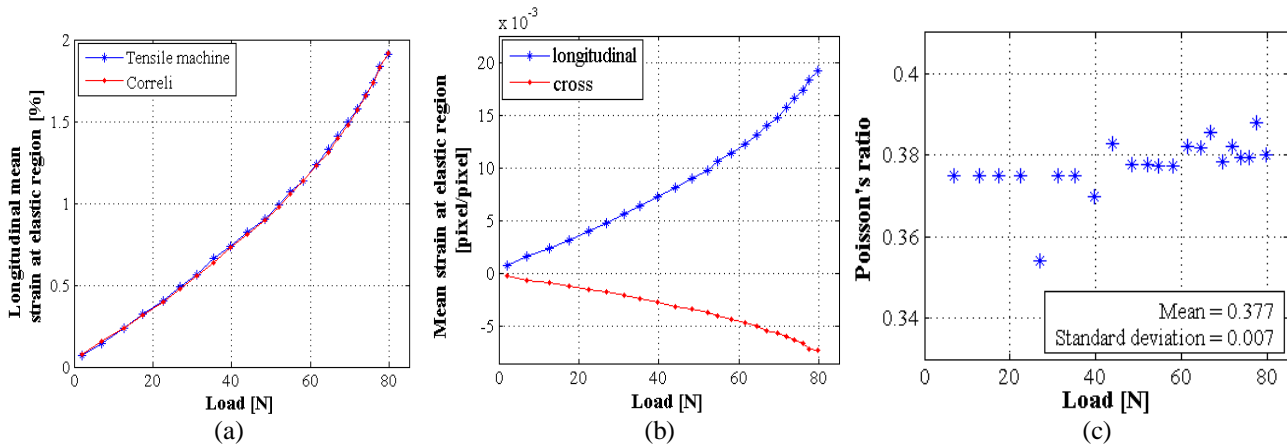


Figure 4. Elastic region and pre-yield regime: (a) mean longitudinal strains measured by tensile machine and by Correli^{Q4}, (b) mean strains by Correli^{Q4} and (c) Poisson's ratio.

From the moment D is possible to visualize larger temperature variations through of an adiabatic process. The alignment of polymer chains in the fibrillar form toward tensile test generated heat during test, while the deformation of the polymer chains in a spherulitic shape (instants A and B) showed no temperature variations.

The polypropylene liberates energy in the form of heat during the tensile test in the moments in D, E and F, all located in the plastic region of the stress-strain curve. The instant C showed little temperature variation in tested specimen, although it locating in the plastic region and presenting yielding zone, demonstrating that the heat released during the test depends on the time for a bad thermal conductor material, such as polypropylene, presents temperature gradients.

These gradients followed polymer yielding during this test and evidenced the deformed material zone of localized manner, in agreement with the results obtained by DIC. The heating zones present direction inside out of the polypropylene.

The instant F has the highest temperature variation found in this test, 19.63°C (after almost 6 minutes of test), and shows a graph with peak temperature variation and their parabolic zones of heating (onset by necking formation).

4. CONCLUSIONS

Using a test speed of 10 mm/min was possible to determine the 2D displacements and temperature variation during a tensile test on the polypropylene. The yielding and necking formation mechanisms were followed by an analysis of longitudinal and transverse strains by digital image correlation. During the plastic deformation process the polypropylene was presented an adiabatic process with an increase of approximately 20°C during the alignment of polymer chains in a fibrillar shape and there was no change in temperature before the alignment by digital infrared thermography. The heating zones was originated by the necking formation and presented parabolic shapes and peak temperature in the center of this polymer.

5. ACKNOWLEDGEMENT

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