

# Impact behaviour of an innovative plasticized poly(vinyl chloride) for the automotive industry

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**Abstract.** Plasticized poly(vinyl chloride) (PPVC) is widely used in the automotive industry in the design of structural parts for crashworthiness applications. Thus, it is necessary to study and understand the influence of the mechanical response and mechanical properties of PPVC over a wide range of strain rate, from quasi-static to dynamic loadings. The process is also investigated using different sample thicknesses. In this work, the strain rate effect of a new PPVC is investigated over a wide range of strain rates at three temperatures and for three thicknesses. A modelling of the yield stress is also proposed. The numerical prediction is in good agreement with the experimental results.

## 1. Introduction

Polymeric materials are widely used in automotive industry in order to reduce the mass of vehicles and, by consequence, reduce the fuel consumption. Several polymers are used in the manufacturing of a vehicle. Among the polymers used in the automotive industry, poly(vinyl chloride) (PVC) is largely used for crashworthiness applications. Several authors [1–3] measured the glass transition temperature of PVC around 82 °C. Thus, at room temperature, the PVC exhibits a glassy behaviour.

A large part of the PVC used in automotive industry is modified by plasticizing in order to obtain flexible PVC at room temperature. This new material, so-called plasticized PVC (PPVC), is obtained by mixing powdered resin with stabilizer, plasticizer, lubricant and dioctyl phthalate due to lack of thermal stability of PVC at processing temperatures [4,5]. Then, this compound is melt mixed in a bench kneader at a rotor speed of 100 r.p.m. and at a temperature of 100 °C for 15 min.

The influence of the level of plasticizer on the mechanical response of the PPVC has been of particular interest for academic researchers and industrials because of the interest of PPVC applications in automotive crashworthiness. Kendall and Siviour [6,7] investigated the mechanical response of a PPVC under uniaxial compression, with a high level of plasticizer, from quasi-static to dynamic loadings at room temperature. At high strain rates, the PPVC exhibits a viscoelastic-viscoplastic response. However, no strain softening is observed unlike PVC. At low strain rates, the mechanical behaviour of the PPVC is viscohyperelastic. Thus, a change of behaviour is observed between quasi-static and dynamic loadings.

Kendall and Siviour [6,7] have also investigated the temperature sensitivity of PPVC at  $10^{-2} \text{ s}^{-1}$ . At high temperature, the PPVC has viscohyperelastic behaviour. For temperatures lower than  $-40 \text{ °C}$ , the PPVC exhibits a glassy behaviour with a yield stress clearly identified and followed by a strain softening. They also show that the yield stress of PPVC is bilinearly dependent on the log of strain rate. Mulliken et al. [8] investigated on the mechanical behaviour of a 20% PPVC. They found that the addition of 20% of plasticizers in PVC blends decreased the glass transition temperature. Moreover, contrary to Kendall and Siviour [6,7], they found that the PPVC exhibited a glassy behaviour with the yield point followed by the strain softening at room temperature and high strain rate. Thus, the percentage of plasticizers in the PVC blend is of great importance for the mechanical response of material. Moreover, polymeric materials are well known to be strain rate and temperature dependent [9,10]. Thus, plasticized PVC exhibits a triple dependence on strain rate, temperature and plasticizers content.

At high strain rate, other phenomenon could affect the mechanical response of polymers. Diah et al. [11] investigated on the thickness effects in Split Hopkinson Pressure Bars tests. Using samples with two different thicknesses, they performed quasi-static and dynamic compressive tests, at room temperature, from  $10^{-4} \text{ s}^{-1}$  to  $10^4 \text{ s}^{-1}$ . For several polymers (polycarbonate, high density polyethylene, medium density polyethylene and poly(ether ether ketone)), they observed, for strain rates greater than  $10^3 \text{ s}^{-1}$ , a discrepancy in the yield stress sensitivity to the log of strain rate between the two thickness.

In this study, the strain rate sensitivity of new plasticized PVC, for the automotive industry, is investigated over a wide range of temperatures and strain rates. This material was manufactured by Faurecia. It is well known that the mechanical properties of a polymer are dependent

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of the process, particularly if the final structure can have different thicknesses. A gradient in temperature through the thickness can lead to different microstructure through the thickness, and thus, a gradient of the mechanical properties. In order to verify that the PPVC processing does not affect the mechanical properties of the material, the manufacturer has prepared three different thicknesses.

## 2. Experimental procedures

### 2.1. Material

The plasticized poly(vinyl chloride) (PPVC) is composed of 50% of PVC, 40% of plasticizers and 10% of additives. The PPVC sheets are provided by Faurecia with three different thicknesses: 1, 1.25 and 1.5 in normalized values, respectively called TH1, TH2 and TH3.

A previous investigation has been performed by Bernard et al. [12] on the PPVC used in this study. They investigated the temperature sensitivity of PPVC materials over a wide range of strain rate and temperature for the three thicknesses. They performed thermogravimetry analysis (TGA), differential scanning calorimetry (DSC), quasi-static uniaxial tensile tests, dynamic uniaxial compressive tests and observed the morphology of this material. For each thickness, they measured the glass transition temperature around  $-32^{\circ}\text{C}$  using DSC and two degradation peaks, around  $330^{\circ}\text{C}$  and  $450^{\circ}\text{C}$  using TGA. Thus, Bernard et al. [12] concluded that, for the three thicknesses, thermal properties are similar. Thus, the process used to manufacture the new PPVC does not affect the thermal properties. However, quasi-static uniaxial tensile tests and dynamic uniaxial compressive tests have shown a non-negligible discrepancy in the mechanical response between the three thicknesses. Moreover, a non-linear relationship has been found between the temperature and the elastic modulus, yield stress and yield strain.

In the present paper, we investigate the strain rate dependence by considering a much larger range of loading rates compared to our previous study [12] and considering three temperatures ( $-30^{\circ}\text{C}$ ,  $23^{\circ}\text{C}$ ,  $85^{\circ}\text{C}$ ). We also use the cooperative model to predict the yield stress and compare predicted results with experimental ones for the considered wide range of temperatures and strain rates.

### 2.2. Mechanical tests

Quasi-static tensile tests and dynamic compressive tests have been conducted in order to investigate on the strain rate sensitivity of the material for each thickness. The mechanical characterization of the three thicknesses of PPVC has been performed at three temperatures:  $-30^{\circ}\text{C}$ , close to the glass transition temperature,  $23^{\circ}\text{C}$  and  $85^{\circ}\text{C}$  in the rubbery region.

The low strain rate tests were carried out using an INSTRON 3384 universal testing machine equipped with a temperature chamber. For each temperature, tests were performed at two constant displacement rates: 50 mm/min and 500 mm/min. At the yield point, these displacement rates lead to true strain rates from  $0.01\text{ s}^{-1}$  and  $0.3\text{ s}^{-1}$ . The tensile test samples are cut in PPVC sheets by Faurecia. The specimen geometry follows the ASTM D412 Standard.

The high strain rate tests were carried out on a homemade Split Hopkinson Pressure Bars (SHPB) for a wide range of strain rate from  $1000\text{ s}^{-1}$  to  $7000\text{ s}^{-1}$ . The test fixture is composed of three 22 mm steel bars. The strikers are 0.5 m and 1 m long and the input and output bars are 3 m long. A description of the experimental setup can be found in [9,10]. In order to perform dynamic compressive tests at low and high temperatures, two devices were adopted on our SHPB. The device for high temperatures consists in positioning the sides of the incident bar and transmitted bar in contact with the specimen in a furnace containing two electrical resistances. For low temperatures, the material sample was sandwiched between the two bars inside a temperature chamber. Then, the specimen and a short part of the compressive bars were cooled.

To reach the thermal equilibrium, the sample were heated or cooled in the appropriate chamber during 15 min before testing. The temperature inside the chamber is measured using four thermocouples. The compressive samples, cut from the PPVC sheets, are cylindrical specimens with a diameter of 10 mm and a thickness depending of the material (TH1, TH2 or TH3).

## 3. Results and discussion

### 3.1. Strain rate sensitivity of the mechanical properties

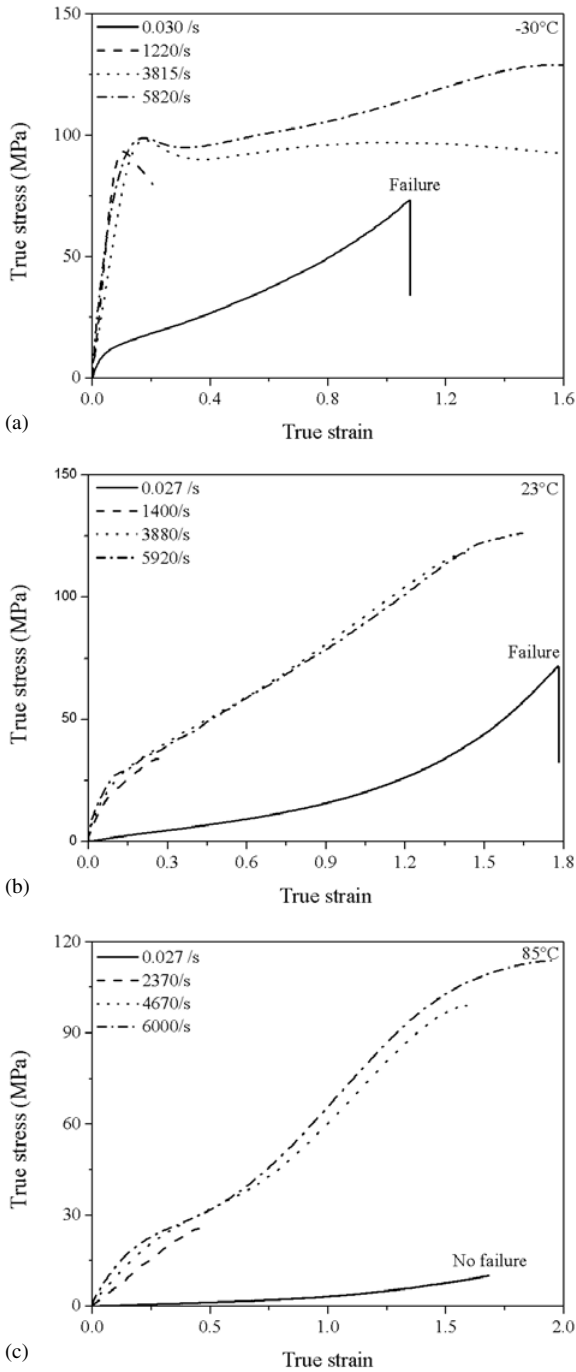
The stress-strain behaviour of PPVC, with thickness TH2, under uniaxial tension at low strain rate and uniaxial compression at high strain rate is presented in Fig. 1 for different temperatures. A change of behaviour could be observed between quasi-static loadings and dynamic loadings for all temperatures. At  $-30^{\circ}\text{C}$  and at low strain rate, in Fig. 1(a), the PPVC exhibits viscoelastic-viscoplastic behaviour. For this temperature and this range of strain rate, the PPVC is tested in its glass transition region. At high strain rate and at  $-30^{\circ}\text{C}$ , PPVC exhibits glassy polymer behaviour with the yield point clearly identified before the strain softening. For strain rates greater than  $3800\text{ s}^{-1}$ , the orientational hardening of the material is also observed.

At  $23^{\circ}\text{C}$  and low strain rate, in Fig. 1(b), PPVC exhibits viscohyperelastic behaviour. At this temperature and this strain rate range, the material is tested at the beginning of its rubbery region. At high strain rates, PPVC exhibits viscoelastic-viscoplastic behaviour similar to the one obtained at  $-30^{\circ}\text{C}$  and at  $0.03-1$ . Thus, at high strain rates and at  $23^{\circ}\text{C}$ , PPVC is tested in its glass transition region. An important strain hardening is noticed in Fig. 1(b).

At  $85^{\circ}\text{C}$ , at low and high strain rates, PPVC exhibits a rubbery behaviour. Moreover, comparing Figs. 1(a), 1(b) and 1(c), we can observed that at low strain rates and at  $85^{\circ}\text{C}$ , due to limitation of the machine, no failure was reached for any specimens.

Comparing Figs. 1(a), 1(b) and 1(c), we can clearly identify the temperature sensitivity of PPVC from glassy to rubbery regions through the glass transition region.

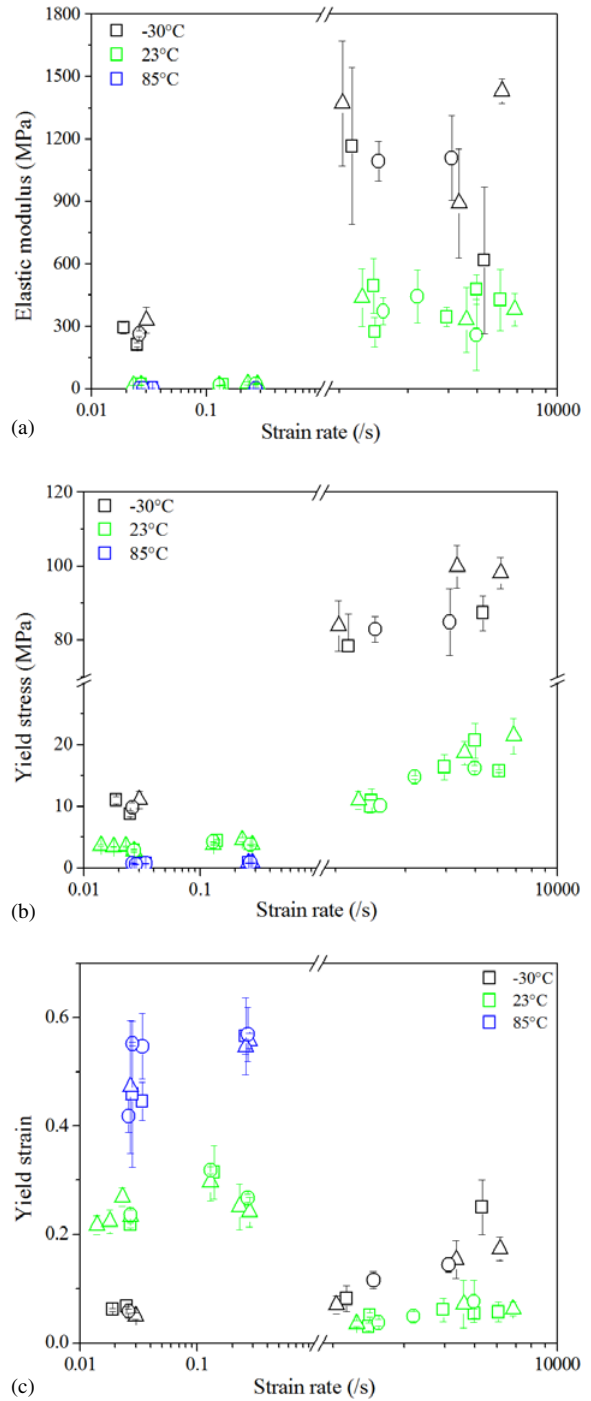
In Fig. 2, the strain rate sensitivity on the elastic modulus, yield stress and yield strain are plotted for the



**Figure 1.** Stress-strain behaviour of the PPVC over a wide range of strain rate at (a)  $-30^{\circ}\text{C}$ , (b)  $23^{\circ}\text{C}$  and (c)  $85^{\circ}\text{C}$  for the thickness TH2.

three thicknesses. For the elastic modulus, in Fig. 2(a), large discrepancy is observed, especially at  $-30^{\circ}\text{C}$  which can be attributed to the proximity of the glass transition region and at non-optimal dynamic equilibrium. However, we can still note an increase of the elastic modulus when the temperature decreases and the strain rate increases. The thickness TH2 presents a higher elastic modulus than the two other thicknesses.

In Fig. 2(b), the discrepancies are less important than for the elastic modulus (Fig. 2(a)). A bilinear dependence



**Figure 2.** Strain rate sensitivity on (a) elastic modulus, (b) yield stress and (c) yield strain of PPVC for the three temperatures and the three thicknesses with  $\square$  TH1,  $\triangle$  TH2,  $\circ$  TH3.

of the yield stress in function of log of strain rate is observed, in Fig. 2(b), particularly at  $23^{\circ}\text{C}$ . At  $-30^{\circ}\text{C}$  and at  $23^{\circ}\text{C}$ , we measured higher yield stress for the thickness TH2. Moreover, we can note that the yield stress increases when the strain rate increases and the temperature decreases.

In Fig. 2(c), the yield strain is plotted as function of log of strain rate from  $0.01\text{ s}^{-1}$  to  $10000\text{ s}^{-1}$ . For quasi-static tests, the yield strain increases with the temperature and the strain rate. However, at high strain rates, a modification

of the mechanical behaviour is observed. The yield strain still increases with the strain rate. However, the yield strain is greater at  $-30^\circ\text{C}$  than at  $23^\circ\text{C}$ . The modification of behaviour could be explained by the transition from quasi-static to dynamic loadings, from rubbery to glass transition region at  $23^\circ\text{C}$  and from glass transition to glassy region at  $-30^\circ\text{C}$ . In order to validate this assumption, experimental tests need to be performed at temperature lower than  $-30^\circ\text{C}$ .

### 3.2. Yield stress modelling

At  $23^\circ\text{C}$ , the bilinear dependence of the yield stress to the log of the strain rate is clearly identified in Fig. 2(b). Numerous theories have been developed in the literature [13–16] in order to model the strain rate and temperature dependence of the yield stress of amorphous polymers over a wide range of strain rate and temperature. However, few models allow reproducing the yield stress of polymers in their glass transition or rubbery regions. The cooperative model, proposed by Richeton et al. [16], is adopted here. In this model, it is proposed to consider individual segment motions as separated events and built a model based on  $n$  cooperative motions. In their formulation of the cooperative model, Richeton et al. [16] considered the time/temperature superposition principle in order to build a master curve at a chosen temperature. The cooperative model assumes the existence of an internal stress  $\sigma_i$  such that the effective stress  $\sigma^{eff}$  is given by (Fotheringham and Cherry [17], Richeton et al. [16]):

$$\sigma^{eff} = \sigma_y - \sigma_i \quad (1)$$

with  $\sigma_y$  the yield stress. The internal stress is a structural parameter which depicts the arrangement of defects inherited from past thermal history. The expression of the cooperative model below and above the glass transition temperature is given by (Richeton et al. [16]):

$$\frac{\sigma_y}{T} = \sigma_i(0) + \frac{2k}{V} \sinh^{-1} \left( \frac{\dot{\epsilon}}{\dot{\epsilon}^*(T)} \right) \quad (2)$$

where

$$\sigma_i(T) = \begin{cases} \sigma_i(0) - mT & \text{if } T < T_g \\ 0 & \text{if } T \geq T_g \end{cases} \quad (3)$$

and

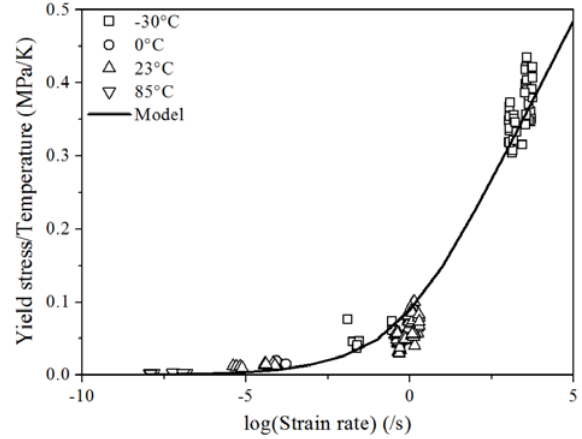
$$\dot{\epsilon}^*(T) = \begin{cases} \dot{\epsilon}_0 \exp \left( -\frac{\Delta H_\beta}{RT} \right) & \text{if } T < T_g \\ \dot{\epsilon}_0 \exp \left( -\frac{\Delta H_\beta}{RT_g} \right) \exp \left( \frac{\ln 10 c_1^g (T - T_g)}{c_2^g + T - T_g} \right) & \text{if } T \geq T_g \end{cases} \quad (4)$$

with  $\sigma_i(0)$  the internal stress at 0 K,  $m$  a material parameter,  $T$  the absolute temperature,  $T_g$  the glass transition temperature,  $\Delta H_\beta$  the glass transition enthalpy,  $k$  the Boltzmann constant  $c_1^g$  and  $c_2^g$  the WLF parameters and  $\dot{\epsilon}_0$  a constant pre-exponential strain rate.

In order to build the master curve of PPVC, we first chose a reference temperature and we performed the time/temperature superposition principle. The material

**Table 1.** Parameters for the cooperative model. The WLF parameters are from Richeton et al. [16] for PVC.

Parameters	PPVC
$\Delta H_\beta$ (kJmol $^{-1}$ )	92
$\sigma_i(0)$ (Mpa)	0
$m$ (MPaK $^{-1}$ )	0
$V$ (m $^3$ )	$2 \times 10^{-28}$
$\dot{\epsilon}_0$ (s $^{-1}$ )	$2.3 \times 10^{20}$
$n$	3.6
$T_g$ (K)	242
$c_1^g$	17.44
$c_2^g$ ( $^\circ\text{C}$ )	51.6



**Figure 3.** Master curve built at  $-30^\circ\text{C}$  for the PPVC tested in uniaxial compression at high strain rate and uniaxial tension at low strain rate. All thicknesses are fused.

parameters are presented in Table 1. Due to a lack of data in the glassy region the internal stress and the parameter  $m$  are assumed null.

In Fig. 3, the master curve is built for the PPVC at  $-30^\circ\text{C}$ . All thicknesses are fused to obtain more data. A good agreement is found between the experimental data and the numerical model in spite of some discrepancies observed at intermediate and high strain rates.

## 4. Conclusion

Strain rate investigation has been performed on a new PPVC dedicated to the automotive industry. The experimental results show that the mechanical properties especially at high strain rates are different for the different thicknesses. For all the investigations, it seems that the elastic properties (elastic modulus and yield stress) are greater for the thickness TH2. The temperature gradient through the thickness reached during the process for TH2 leads to a microstructure which improves the elastic properties. The yield stress of PPVC exhibits a bilinear dependence to the log of strain rate and a master curve at  $-30^\circ\text{C}$  has been built and modelled using the cooperative model. A good correlation is obtained between the experimental data and the numerical prediction. For the yield strain, a change of the behaviour, in the strain rate dependence, is observed between low and high strain rate. This phenomenon could be explained by the change of behaviour of the material at the considered strain rates

from rubbery to glass transition regions and from glass transition to glassy regions.

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