



# Thermomechanical analysis of the onset of strain concentration zones in wet polyamide 6.6 subjected to cyclic loading



Adil Benaarbia<sup>a,\*</sup>, André Chrysochoos<sup>a</sup>, Gilles Robert<sup>b</sup>

<sup>a</sup> University of Montpellier, Mechanics and Civil Engineering Laboratory, CC 048, Place E. Bataillon, 34095 Montpellier, France

<sup>b</sup> Solvay Engineering Plastics, Centre de Simulation et Validation des Applications, Avenue de Ramboz – BP64 – 69192 Saint Fons, France

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## ABSTRACT

In the present paper, we put forward some experimental results on the local thermomechanical behavior of a wet PA6.6 matrix subjected to cyclic loading. We used photomechanical techniques to assess the creep and cyclic strain rate fields, as well as the associated dissipation and coupling heat source fields. This thermomechanical analysis enabled us, from the very beginning of the cyclic test, to track the onset of strain concentration zones and note their limited development. Moreover, this analysis helped us to highlight the co-existence of glassy, rubber and mixed thermal responses. This revealed that wet PA6.6 was a graded material whose property variations surely promoted the development of strain concentration zones.

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## 1. Introduction

Polyamides (PAs) belong to the wide variety of semi-crystalline thermoplastics that are being increasingly used in various applications such as automotive, aerospace and many others. These engineering materials have received much attention because of their low density, ease of manufacture and deformability as compared to corresponding standard materials. However, PAs exhibit various deformation mechanisms (e.g. rate dependence and strong coupling effects, ratcheting, internal energy storage and release, damage, etc.), which are highly influenced by hygro-thermomechanical boundary and loading conditions (Benaarbia et al., 2014a,b; Arif et al., 2014). Indeed, the mechanical behavior of this type of material is particularly sensitive to its thermal and moisture states. Some of these mechanisms have already been underlined in previous experimental investigations, such as (Horst and Spoormaker, 1996; Bernasconi and Kulin, 2009; Launay et al., 2011; Launay et al., 2013). Further insight is, however, still required on some issues, especially concerning the local analysis of deformation mechanisms boosted by the dissipative effects and competition between standard and entropic thermoelastic couplings, which in turn are highly influenced by the moisture, temperature and strain distribution.

The cyclic behavior of polyamides is becoming a topical issue because of their new industrial application domains. Substantial research is thus currently ongoing to gain further knowledge on

mechanisms affecting the fatigue lifespan, which is often limited by strain concentration and followed more or less quickly by crack inception. Irreversible fatigue mechanisms are associated with dissipation of part of the deformation energy rate, with the complementary part being associated with – at least temporarily – stored energy variations induced by microstructural changes. A promising approach to better monitor and gain insight into these mechanisms is based on the use of quantitative infrared thermography and optical extensometry. Infrared and visible analysis techniques have been successfully used for several years to characterize and understand the behavior of materials (Grediac and Hild, 2012). Dissipation assessment has been the focus of numerous surveys over the last century (Bever et al., 1972). Several experimental approaches based on temperature measurements via quantitative IR techniques have recently been adopted to estimate this crucial energy signature (Chrysochoos and Barton, 2015). Indeed, dissipation can be derived from thermal data fields by estimating the partial differential operators of the heat diffusion equation (Chrysochoos et al., 1989). Several assumptions on thermal fields and dissipation distributions have been formulated to make heat diffusion models operational. A number of simplified formulations are now available for dissipation assessments (Chrysochoos and Louche, 2000).

As already mentioned, PAs are not only sensitive to their thermal state but are also hydrophilic materials inasmuch as their water content strongly influences their mechanical behavior. It is thus essential to detect the existence of so-called water plasticizing effects when using PAs for specific industrial applications where the environmental humidity changes considerably. Calorimetric signatures of these effects can also be provided and, consequently,

\* Corresponding author. Fax: +33467143432.

E-mail address: [adil.benaarbia@umontpellier.fr](mailto:adil.benaarbia@umontpellier.fr) (A. Benaarbia).

contribute to the understanding of the material behavior. Indeed, water plasticizing effects are recognized for their marked influence on the glass transition temperature of some PAs (Brandrup et al. 1999). Glass transition can be defined as a gradual thermally activated process that leads a polymer to change from a glassy to rubbery state (Sperling, 1992; Rodriguez, 1996). The addition of water molecules to the polymer microstructure causes a decrease in the glass transition temperature as, for instance, recently reported for PA6.6 in (Launay et al., 2013). The glass transition temperature markedly decreases as the relative humidity increases, which means that PA6.6 shows rubber effects under standard usage temperatures. Several approaches have been developed in the past to describe the thermomechanical rubber (entropic) effects and so-called thermoelastic inversion. Here we ought to mention the pioneering studies of Joule and Treloar (Joule, 1857; Treloar, 1973; Treloar, 1975). Many other major studies were thereafter conducted, e.g. Flory and Erman (1982), Chadwick and Creasy (1984), Arruda and Boyce (1993), etc. More recently, a simple heuristic description of thermoelastic inversion in rubber materials was proposed in Benaarbia et al. (2014b). This inversion was interpreted as being due to competition between standard and entropic thermoelasticity.

In the present paper, we documented some findings pertaining to the local thermomechanical mechanisms of the polyamide-6.6 matrix. Specifically, we used IR and visible CCD cameras to simultaneously record, during cyclic loadings, fields corresponding to temperature variations and in-plane displacements over the sample gage part. We focused particularly on local estimation of dissipation, coupling sources and strain rate maps throughout the cyclic test in order to correlate thermal, energy and mechanical signatures. This analysis enabled us to characterize the onset and development of dissipative strain concentration zones, which could ultimately be related to the local failure of the studied material.

Prior to that, we first reminded the theoretical framework used to define the energy balance form and interpret the cyclic thermomechanical responses of wet PA6.6. We then presented a very brief overview of overall observations made on PA6.6 specimens, namely material responses averaged over the sample gage part.

## 2. Thermomechanical framework

In the framework of the thermodynamics of irreversible processes with internal state variables, the equilibrium state of each volume material element is characterized by a set of  $n$  state variables (Germain et al., 1983). Generally speaking, for finite transformations, the often chosen state variables are the absolute temperature  $T$ , the Hencky strain tensor  $\varepsilon$ , and the  $n-2$  scalar components  $(\alpha_1, \dots, \alpha_{n-2})$  defining a vector  $\alpha$  of internal variables, introduced to depict the microstructural state of the material. By construction, the thermodynamic potential is the specific Helmholtz free energy  $\psi$ .

The reversible part of the Cauchy stress tensor  $\sigma$  is the conjugated variable associated with the strain with respect to the free energy and is defined by  $\sigma^r = \rho \partial \psi / \partial \varepsilon = \rho \psi_{,\varepsilon}$ , with  $\rho$  denoting the mass density. For finite strain, the volume deformation energy rate can then be written as:

$$w_{def}^* = \sigma : D = \underbrace{\sigma : D - \left( \overbrace{\sigma^r : \dot{\varepsilon} - \rho \psi_{,\alpha} \dot{\alpha}}^{w_e^* + w_s^*} \right)}_{D_1} + w_e^* + w_s^*, \quad (1)$$

where  $D$  is the Eulerian strain rate tensor. According to the material and the loading path, the deformation energy rate  $w_{def}^*$  may involve energy dissipation ( $D_1 = \sigma : D - \sigma^r : \dot{\varepsilon} - \rho \psi_{,\alpha} \dot{\alpha}$ ), elastic  $w_e^*$  and stored/released  $w_s^*$  energies. The intrinsic dissipation is the

heat rate induced by the irreversibility of the material transformation, while the elastic and stored energy rates respectively depict the deformation energy mechanically recoverable during unloading and used in the microstructural changes. Note that the non-standard notation  $w^*$  specifies that the energy rate is path-dependent (i.e.  $w$  is not necessarily a state function).

Combining the local expressions of the first and second principles of thermodynamics leads to the local heat diffusion equation:

$$\rho C \dot{T} - \text{div}(k \text{grad} T) = \mathcal{D}_1 + \underbrace{\rho T \psi_{,T\varepsilon} : \dot{\varepsilon} + \rho T \psi_{,T\alpha} \dot{\alpha}}_{w_{thc}^*} + r_e \quad (2)$$

where  $C$  is the specific heat and  $k$  is the heat conduction tensor. The left-hand side consists of a differential operator applied to the temperature, while the right-hand side pools the various types of heat sources: the so-called intrinsic dissipation  $\mathcal{D}_1$ , the thermomechanical coupling sources  $w_{thc}^*$ , and the possible external heat supply  $r_e$  (e.g. radiation exchanges). The thermomechanical heat sources give effects to the thermosensitivity of the matter, indicating that the mechanical, microstructural and thermal states are closely coupled. In reference to what we previously mentioned in introduction, note that a hygrometric variable should be introduced in the set of the microstructural state variables to take the water plasticizing effects into account.

Let us now consider a load-unload cycle, where  $A = (T_A, \varepsilon_A, \alpha_A)$  and  $B = (T_B, \varepsilon_B, \alpha_B)$  denote the thermodynamic states of the material at the extremities of the process. Both principles of thermodynamics give an alternative expression of the volume deformation energy associated with the load-unload test:

$$w_{def} = \int_{t_A}^{t_B} \mathcal{D}_1 d\tau + \int_{t_A}^{t_B} (\rho \dot{e} - \rho C \dot{T}) d\tau + \int_{t_A}^{t_B} w_{thc}^* d\tau, \quad (3)$$

where  $e$  is the specific internal energy and  $t_B - t_A$  is the cycle duration.

- In the general case ( $A \neq B$ ), the deformation energy balance during a load unload test involves energy dissipation, internal energy variations, variation of heat stored in the material and coupling heat sources.
- If now ( $\varepsilon_A = \varepsilon_B$ ), the stress-strain diagram shows a hysteresis loop. The deformation energy per cycle then corresponds to the “generalized area”  $A_h$  of the different hysteresis loops in the planes  $\sigma_{ij} - \varepsilon_{ij}$ ,  $i, j = 1, 2, 3$ . This hysteresis area depicts a loss of mechanical energy that can, as previously mentioned, be potentially induced by energy dissipation, stored energy variations and/or strong thermomechanical coupling effects.
- Finally if ( $A = B$ ), the mechanical cycle is now a thermodynamic cycle. The hysteresis loop is only due to dissipation and couplings since the heat capacity per unit volume  $\rho C$  is assumed to be constant.

It is worth noting that the existence of an infinite lifespan of materials subjected to cyclic loading is possible when there is no intrinsic dissipation (i.e. no material irreversibility) or, conversely, when the hysteresis area is all intrinsically dissipated. In this very particular latter case – but often mentioned in the literature – with the mechanical cycle being a thermodynamic cycle, the material should periodically pass through the same thermodynamic state  $A$ , thus ensuring an infinite lifespan. For a finite lifespan, intrinsic dissipation and internal energy variations, which depict the gradual evolution of the microstructure, accompany the irreversible fatigue mechanisms.

## 3. Overall analysis

Many experimental results dealing with the thermomechanical cyclic behavior of PA6.6 matrix have been summarized and

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