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A thermo-mechanical large deformation constitutive model for polymers based on material network description: Application to a semi-crystalline polyamide 66

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ABSTRACT

A visco-hyperelastic constitutive model, based on an original approach initially developed by (Billon, 2012) and applied to amorphous rubbery polymers for a one-dimensional formalism, was extended in this study to three-dimensional constitutive equations based on a thermodynamic framework. The model was applied to a semi-crystalline polyamide polymer, PA66. The experiments included tension and shear testing coupled with synchronized digital image correlation and infrared measurements device for capturing the time, temperature, and stress state dependence, as well as the complex thermomechanical coupling exhibited by the material under large deformation. A notion of equivalent strain rate (based on the time–temperature principle superposition) was also introduced to show its capability to build master curves and therefore decrease the number of testing needed to build a material database. The model is based on the Edward Vilgis theory (1986) and accounts for chains network reorganization under external loading through the introduction of an evolution equation for the internal state variable, $\bar{\eta}$, representing the degree of mobility of entanglement points. The model accounting for the equivalent strain rate notion was calibrated using master curves. The thermomechanical model agreed well with the experimental mechanical and temperature measurements under tension and shear conditions. The approach developed in this study may open a different way to model the polymer behavior.

1. Introduction

Thermoplastics and more especially semi-crystalline polymers (SCP) have been increasingly applied in the industry due to their potential to fulfill the mechanical, electrical and/or environmental requirements needed for structural applications ranging from automotive, aeronautic to medical sectors. Unfortunately the design of such structural parts submitted overtime to complex loading is not reliable enough to optimally use these polymers. This is mainly due to their complex

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Nomenclature

e_v	specific internal energy (per unit volume)
r_v	heat source per unit volume
q	heat flux per unit area
C_v	heat capacity per unit volume
λ	heat conductivity
h	thermal convection coefficient (in air)
s_v	specific entropy (per unit volume)
T	temperature
$\bar{\psi}_v$	Helmholtz free energy per unit volume
ϕ_{th}	thermal dissipation
ϕ_{int}	inelastic dissipation
J	determinant of the deformation gradient
$\boldsymbol{J}^e$	determinant of the elastic deformation gradient
$\boldsymbol{J}^v$	determinant of the inelastic deformation gradient
F	deformation gradient
$\boldsymbol{F}^e$	Elastic deformation gradient
$\boldsymbol{F}^v$	inelastic deformation gradient
$\bar{\mathbf{C}}^e$	elastic Cauchy–Green tensor
$\boldsymbol{l}$	velocity gradient
l^e	elastic velocity spatial gradient
$\bar{\mathbf{L}}^v$	inelastic velocity spatial gradient
d	symmetric part of the velocity gradient
$\boldsymbol{d}^e$	symmetric part of the elastic velocity gradient
$\bar{\mathbf{D}}^v$	symmetric part of the inelastic velocity gradient
$\boldsymbol{\sigma}$	Cauchy stress tensor
$\bar{\mathbf{M}}$	Mandel stress tensor
$\bar{\mathbf{S}}$	second Piola–Kirchhoff stress tensor
σ_{num}	numerical stress tensor
σ_{exp}	experimental stress tensor
$\{I_1^e, I_2^e, I_3^e\}$	thee invariants of the elastic Cauchy–Green tensor
k	Boltzmann's constant
T_{ref}	reference temperature
N_C	density per unit volume of permanent nodes
N_S	density per unit volume of slip-link nodes
α	limit of chain extensibility
$\bar{\eta}$	degree of mobility of the slip links (entanglement points)
β	Taylor Quinney's coefficient
w_C	energy stored in permanent nodes
w_S	energy stored in entangled network
$\{z_{p0}, z_{p1}\}$	parameters of the degree of mobility of the slip links
$\dot{\varepsilon}$	experimental strain-rate
C_1	first WLF parameter
C_2	second WLF parameter
$a_{T/T_{ref}}$	WLF shift factor
$a_T\dot{\varepsilon}_{eq}$	equivalent strain-rate at the reference temperature
$\bar{\eta}_0$	initial value of $\bar{\eta}$
χ	tensile and shear correction coefficient

mechanical behavior that is sensitive to external parameters (such as temperature, strain rate, and triaxiality). As a matter of fact, the thermomechanical viscoelastic/viscoplastic behavior of polymers is not always well understood and modeled.

A large number of material models developed to predict the material response of thermoplastic polymers can be found in the literature (see Bouvard et al. (2009) for a review). Previous work proposed constitutive models combining linear and non-linear springs with dashpots enhanced by specific evolution equations to predict the non-linear viscoelastic response of polymers (Chaboche (1997), Moreau et al. (2005), Khan et al. (2006), Ayoub et al. (2010, 2011), Zaïri et al. (2011), among others). Other constitutive models were proposed to capture the elastic–viscoplastic deformation behavior of solid polymers. (e.g., Bardenhagen et al. (1997), Buckley and Jones (1995), Khan and Zhang (2001), Zaïri et al. (2005a, 2005b, 2007, 2008),