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## NUMERICAL INVESTIGATIONS ON THE PLASTIC MEMORY EFFECT OF PTFE COMPOUNDS

*To describe the nonlinear material behaviour of thermoplastic materials via the example of Polytetrafluorethylene (PTFE), a viscoplastic material model of overstress type is proposed. The approach is motivated by a rheological model, consisting of a rate-independent elastoplastic element with an endochronic flow rule and a nonlinear elastic element in parallel connection with a nonlinear Maxwell model. For the generalization to three dimensions, the theory of finite viscoplasticity based on material isomorphisms is applied. To describe the non-isothermal plastic memory effect, thermally induced plastic strains and a scalar back stress (inside the equilibrium branch) are taken into account.*

### 1. Experimental investigations

Due to their tribological characteristics, chemical inertness and temperature stability, PTFE compounds are increasingly used in many engineering applications. It was observed that the hysteresis effect is not only caused by the viscoplastic deformation, but also by the plastic memory effect (PME), see [1]. The PME is of special interest, because it is possible to increase the inelastic deformation of a mechanically strained specimen by a temperature treatment. These additional inelastic deformations can be recovered by another temperature treatment in the unloaded state.

Figures 1 b) to d) illustrate the characteristics of the PME in uniaxial tension tests using a typical PTFE compound (90% PTFE, 5% MoS<sub>2</sub>, 5% short cylindrical glass fibers). Small specimens (58mm x 5mm x 2mm) were produced for the experiments. First the specimens were strained up to 5% and 15% at 23°C at a constant strain rate ( $\dot{\epsilon} = 10\%/min$ ), see Figure 1 b). The state of strain was kept constant afterwards. During this strain controlled part of the experiment, a first temperature cycle - up to 100°C and down - was performed. Figure 1 c) and d) show the corresponding stress development.

The next step is to switch from a strain to a force controlled test by unloading the specimens at a rate of 0.5 N/s. The result of this unloading process is an inelastic deformation. Some parts of the viscous deformation, which are not affected by the PME, are responsible for the small retardation process, which can be identified in Figure 1 b). To activate the PME, another temperature cycle was performed. The recovered inelastic strain is larger than the thermal expansion of the specimen. This is the reason why the measured strain decreased during the heating part of the second temperature cycle. The reduction of the strain that was measured during the cooling phase of this temperature cycle, is only due to the thermal contraction.

### 2. Material model and numerical simulations

The isothermal viscoplastic material model of the analyzed PTFE compound, see [3], is motivated by a rheological model consisting of a Maxwell element and an endochronic elastoplastic element in parallel (Figure 1 a)). The associated approach to finite plasticity starts with the definition of the independent and the dependent variables of a deformation process. If  $\mathbf{F}$  is the deformation gradient and  $\mathbf{T}$  Cauchy's stress tensor, then  $\mathbf{C} = \mathbf{F}^T \mathbf{F}$  defines the right Cauchy-Green tensor, and  $\mathbf{S} = \mathbf{F}^{-1} \mathbf{T} \mathbf{F}^{-T}$  the material stress tensor.  $\mathbf{S}_\infty$  is the material equilibrium stress of the endochronic element. The plastic deformation is characterized by an internal variable  $\mathbf{P}_P$  (called plastic transformation).

For the description of the non-isothermal PME, thermal strains and thermally induced plastic strains (inside the equilibrium branch) are taken into account. Hence, the associated flow rule for the evolution of the plastic transformation  $\mathbf{P}_P$ , depends on the equivalent equilibrium stress  $\sigma_{Vp}$ , the equivalent plastic strain rate  $\dot{\epsilon}_{ip}$ , the equivalent memory strain rate  $\dot{\epsilon}_{PME}$  and the direction of the plastic flow  $(\mathbf{S}_\infty \mathbf{C})^{dev} := \mathbf{S}_\infty \mathbf{C} - (1/3) tr(\mathbf{S}_\infty \mathbf{C})$ .

In contrast to other models and due to the continuous evolution of the plastic deformation during the tests, the endochronic theory of plasticity is applied. An elastic range limited by a yield stress is not needed in the present model. Hence, it is not necessary to evaluate a flow limit and a consistency condition during the numerical computations. This simplifies the identification and the simulations in general, see [2]. The equivalent plastic strain rate  $\dot{\epsilon}_{ip}$  is given by an endochronic flow rule.  $Y_P$  is a stress like model parameter. The thermally induced plastic

strains are assumed to be independent of  $\dot{\theta}$ . Hence, the equivalent memory strain rate  $\dot{\epsilon}_{PME}$  is determined by an endochronic flow rule too.  $Y_{PME}$  and  $\kappa_{PME}$  are model parameters. In combination with a constitutive law for the scalar back stress  $\sigma_B$  (including the model parameters  $Y_i$  and  $C_{PME}$ ) the PME of PTFE compounds is described by these additional thermally induced plastic strains. The constitutive equations are summarized in Table 1. Numerical simulations show that the proposed model is capable of describing the nonlinear material behaviour of the analyzed PTFE compound in stress and strain controlled isothermal and non-isothermal simulations. The results are presented in Figure 1 b) to d).

Associated flow rule:	$\dot{\mathbf{P}}_P \mathbf{P}_P^{-1} = - (3/2) ((\dot{\epsilon}_{ip} + \dot{\epsilon}_{PME}) / \sigma_{VP}) (\mathbf{S}_\infty \mathbf{C})^{dev}$
Equivalent plastic strain rates:	$\dot{\epsilon}_{ip} = (1/Y_P) \sigma_{VP} \dot{\epsilon}_V$ and $\dot{\epsilon}_{PME} = (1/Y_{PME}) (\sigma_{VP} - \sigma_B)^{\kappa_{PME}}  \dot{\theta} $
Backstress:	$\sigma_B = (1/Y_i) \tanh \{ (C_{PME}/Y_i) \epsilon_{PME} \}$
Equivalent stress and strain rate:	$\sigma_{VP} := \sqrt{(3/2) \text{tr} \{ (\mathbf{S}_\infty \mathbf{C})^{dev} \}^2}$ and $\dot{\epsilon}_V := \sqrt{(3/2) \text{tr} \{ (\mathbf{D}^{dev})^2 \}}$

Table 1: Plastic memory Effect - Constitutive equations

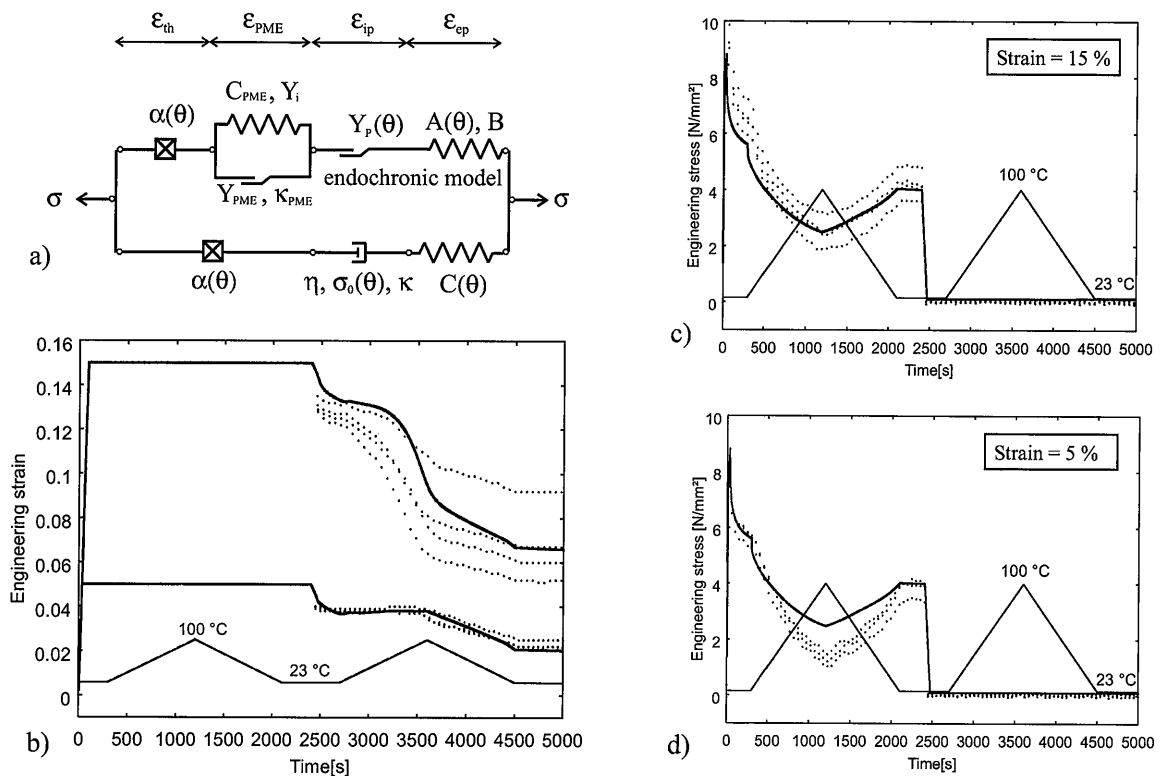


Figure 1: Rheological model a), simulations (solid lines) and experimental data (dotted lines) b)-d)

### 3. References

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