



An Endochronic Viscoplastic Approach for Materials with Different Behavior in Tension and Compression

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Abstract. To describe viscoplastic materials with different behavior in tension and compression via the example of filled PTFE (Polytetrafluorethylen), an endochronic viscoplastic material model is proposed. The approach is based on a rheological model without an elastic range, using a rate-independent elastoplastic element with an endochronic flow rule and a nonlinear elastic law in parallel connection with a nonlinear Maxwell model. The SDE (strength differential effect) due to different experimental results in tension and compression tests is described by two internal variables and their evolution equations. Numerical simulations show that the model can describe the short and long time material behavior of filled PTFE under isothermal loading in both, tension and compression.

Key words: endochronic theory of viscoplasticity, PTFE compound, strain rate dependence, strength differential effect, stress relaxation

Abbreviations: SDE – strength differential effect; PTFE – Polytetrafluorethylen; MoS₂ – Molybdenum disulphide

1. Introduction

Semi-crystalline polymers are important for a wide range of technical applications. One typical example are rotary shaft seals made of semi-crystalline PTFE compounds. These materials are increasingly used for rotary shaft seals because of their tribological characteristics, chemical inertness, and temperature stability. Typical fillers in PTFE compounds are short cylindrical glass fibers and MoS₂. The fillers are used to improve the mechanical characteristics. The glass fibers are introduced to reduce wear of the material under friction. MoS₂ is used to reduce the friction.

The behavior of pure PTFE is nearly identical in tension and compression, but the stress-strain characteristic of PTFE compounds filled with short cylindrical glass fibers shows considerable differences between the material behavior in ten-

sion and compression. The SDE of these compounds results in a stress level that is up to 78% higher for loading in compression than in tension.

In the past engineers used different constitutive laws for different processes like the mounting (short time process) and the fitted stage (long time process) of the material on the shaft. In order to include the SDE in numerical simulations of long time processes, stress relaxation in compressed parts of the material was suppressed (Pohl, 1999). This engineering approach neglects the effect of stress relaxation that can be clearly discovered during tests in compression.

In order to prepare numerical simulations of PTFE materials in a unified approach, this paper presents a viscoplastic material model for filled PTFE based on the results of uniaxial experiments at ambient temperature in both tension and compression. Such material behavior can be described by a rheological model consisting of a Maxwell element and an endochronic elastoplastic element in parallel. The present model fits into the concept of general viscoplasticity (GVP), see Haupt (2000). In contrast to models of this framework (Reese, 1998), or to viscoplastic material models based on overstress (Krempf, 1996), the endochronic theory of plasticity is applied to describe the rate-independent material properties and the continuous evolution of the plastic deformation.

Two internal variables of the damage type are used to model the SDE. Their evolution is described by ordinary differential equations. This technique allows to include the SDE in the model by changing just two model parameters of the endochronic model. In the present paper a rheological model is proposed and the three-dimensional generalization of the SDE-concept is motivated. Finally numerical simulations show the capability of the model to describe the nonlinear material behavior of a typical PTFE compound in both, tension and compression.

2. Experimental Results

In this section the results of uniaxial experiments at ambient temperature in tension and compression are summarized, to characterize the material behavior of the analyzed PTFE compound. Engineering stress and engineering strain are used as measurable quantities. This typical PTFE compound consists of 90% pure semi-crystalline PTFE, 5% MoS₂ and 5% short cylindrical glass fibers.

Figure 1a illustrates the strain-rate dependence of the material in strain controlled tension tests using different strain rates. These tests were carried out by Pohl (1999) on a material testing system. The measurement of the quasi-static loading curves obtained during the investigations on the plastic memory effect of PTFE compounds, is shown in Kletschkowski et al. (2000). It has been used to test the repeatability of Pohl's experiments. The stress response in these isothermal uniaxial experiments shows a nonlinear stress-strain behavior and depends clearly on the strain rate. An increase in the strain rate of one decade results in a stress increase of nearly 14% at the end of the test in both experimental studies. The maximum difference between the stress-strain-curves of these different test series

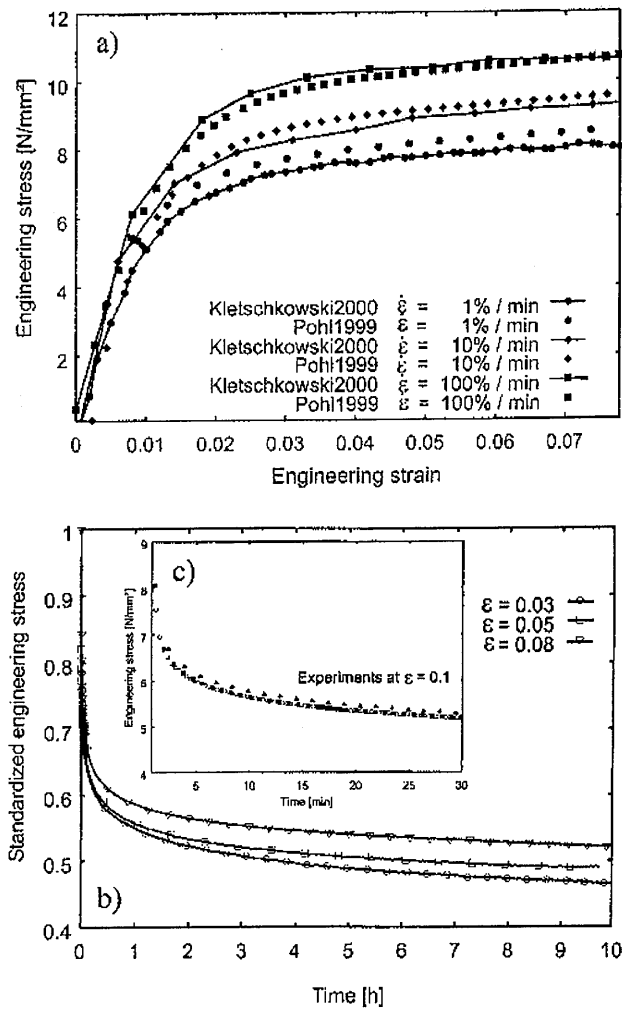


Figure 1. Loading and stress relaxation experiments in tension.

performed on the same PTFE compound at identical strain rates is smaller than 4.5%. Hence, the magnitude of dispersion of the measured values is one decade smaller than the strain rate effect on the stress-strain-curves.

Figure 1b illustrates the effect of the succeeding stress relaxation after loading with a strain rate of 10%/min for different strain levels in tension. It can be seen that the relaxation curves, showing the time dependent decrease of the measured stress, are not even congruent when using a normalization based on the respective maximum value of the performed strain level. In addition the results of short time relaxation tests at $\epsilon = 10\%$ are presented in Figure 1c. The reduction of stresses is extremely high in the first hour of the stress relaxation process. Thus, it is the

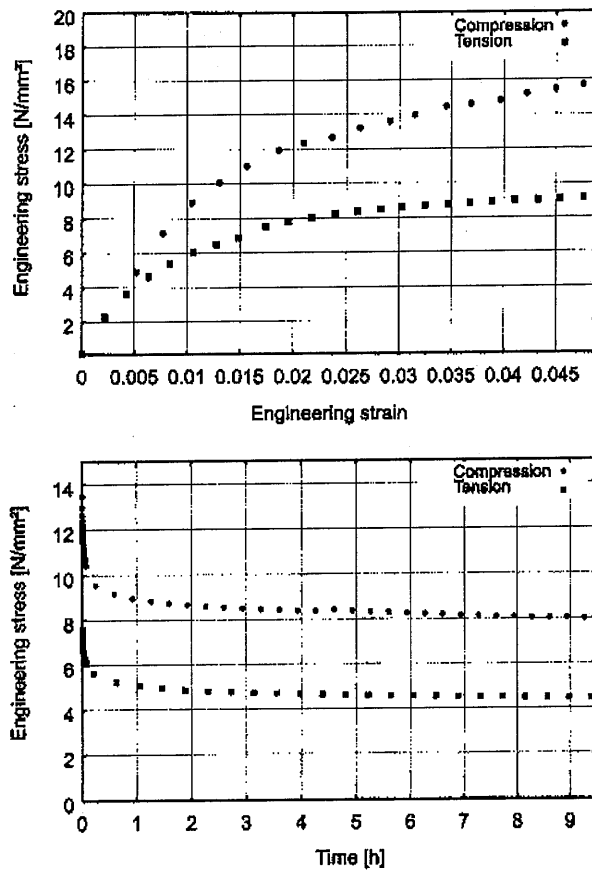


Figure 2. SDE – experiments in tension and compression.

most crucial time period, in which the measured errors during the stress relaxation must be analyzed. Three different curves, indicated by three different symbols, are shown in Figure 1c. They lie together closely. The maximal relative error between these curves is less than 3%.

Figure 2 illustrates the SDE for isothermal loading in tension and compression with a strain rate of 10%/min up to a maximum engineering strain of 5% and further on for the succeeding stress relaxation tests. For simplicity the absolute values of engineering stress are plotted *versus* engineering strain (Figure 2 (top)) and time (Figure 2 (bottom)). The experimental results of these tests show that

- The amount of stress in uniaxial compression is greater than the amount of stress in uniaxial tension, in maximum nearly 78%.
- In both, tension and compression, the stress is reduced to nearly 50% of its initial value after ten hours of stress relaxation, see Figure 2 (bottom). The

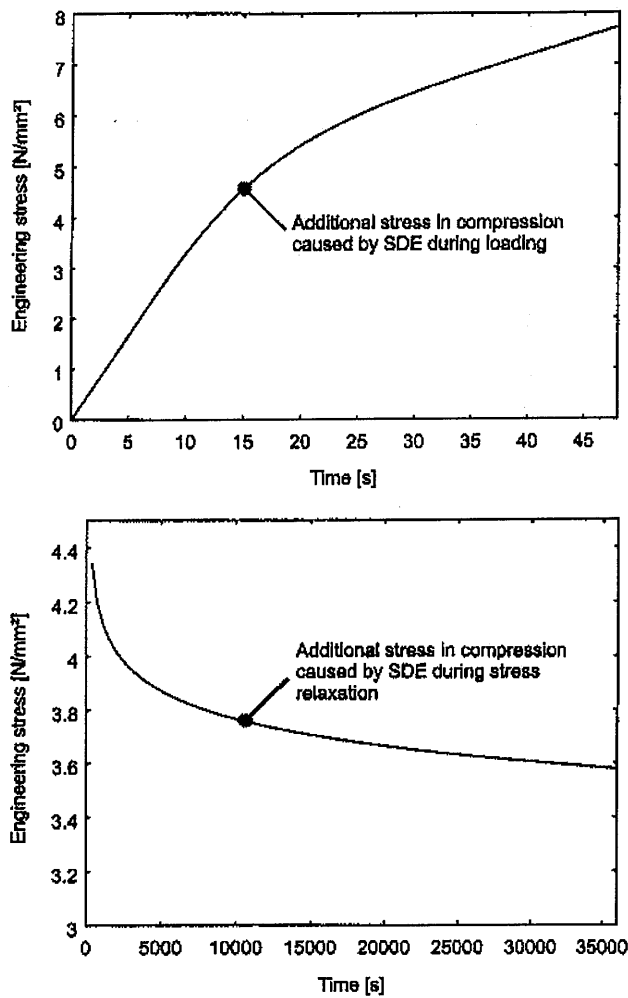


Figure 3. Long and short time characteristic of the SDE from experiments.

stress relaxation effect can be clearly observed in both, tension and compression. From this observation it follows that the engineering approach of neglecting the stress relaxation in compressed regions of structures with the aim to include the SDE in numerical simulations is not adequate to model the material behavior of filled PTFE under compression.

Figure 3 illustrates the short and long time characteristic of the SDE. In Figure 3 (top) the differences between the absolute values of stress response in compression and tension are shown according to the loading curves of Figure 2 (top). In Figure 3 (bottom) the differences between the absolute values of stress response in

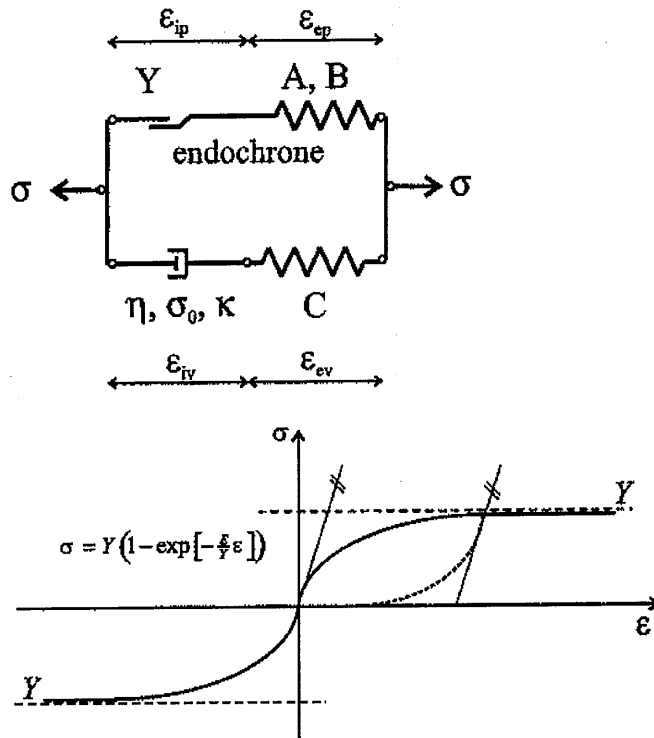


Figure 4. Rheological model and endochronic plasticity (stress-strain characteristic).

compression and tension are shown according to the stress relaxation curves in Figure 2 (bottom). It can be seen that

- the additional stress in compression caused by the SDE during loading is a nonlinear effect;
- the additional stress in compression caused by the SDE shows relaxation in a long time test.

Figure 5 (top) presents various experimental stress-strain curves according to the different compression tests performed on the same PTFE compound. These experimental data clarify that the measured errors have same order of magnitude in both, tension and compression.

Finally, mechanical straining of PTFE at ambient temperature results in a permanent inelastic deformation after unloading and strain recovery, as reported by Kletschkowski et al. (2001). Because of the experimental results, the 10% compound is characterized as a viscoplastic material with nonlinear viscoelastic properties.

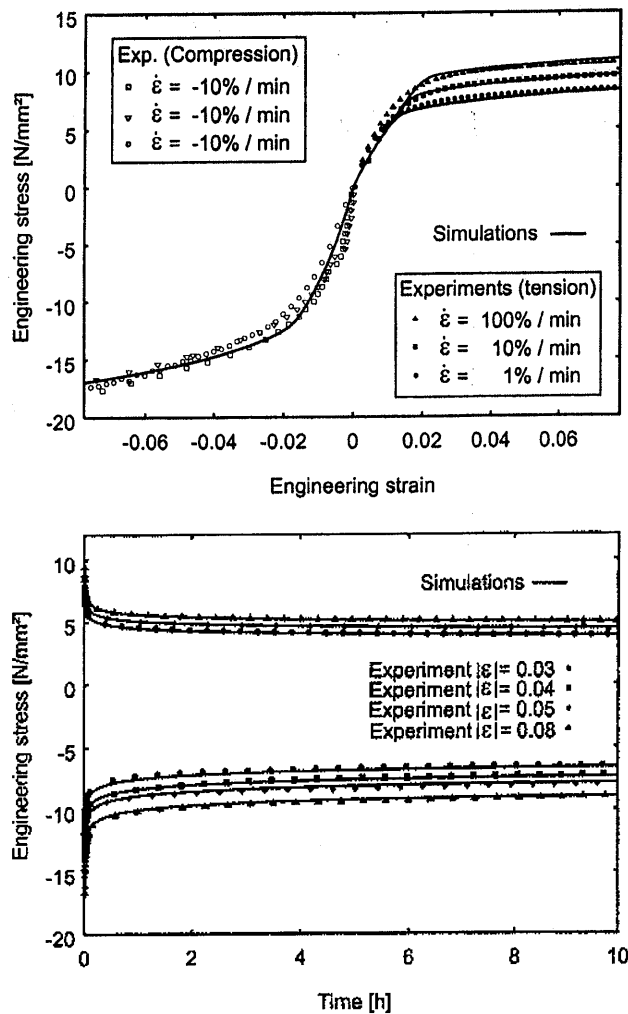


Figure 5. SDE – experimental data and simulations.

3. Constitutive Equations

In order to simulate inelastic material behavior of polymers with different behavior in tension and compression, a small strain viscoplastic theory motivated by the rheological model shown in Figure 4 (top) is used. In contrast to previous models and with respect to the experimental data that indicate a continuous growth of plastic deformations during tension tests without crossing a significant flow limit, the endochronic theory of plasticity is applied. Morphological changes in polymers under load, like the breakup of crystalline structures and their recrystallization, depend on the existence of a non-zero state of stress. But in contrast to metallic materials

the state of stress does not need to reach a critical limit to activate morphological changes.

The endochronic theory of plasticity was developed by Valanis (1971) and is discussed in detail in Haupt (1977). For linear elastic solids and in the absence of hardening effects, such material behavior can be described by a differential equation of the saturation type, Equation (1). The integration of Equation (1) for tension tests with constant strain rates leads to the formula shown in Figure 4 (bottom), which describes the elastoplastic endochronic material behavior during loading. E is Young's modulus, ε the total strain, and Y defines the maximum stress that can be reached during an elastoplastic deformation process.

$$\dot{\sigma} = E \left(\dot{\varepsilon} - \frac{1}{Y} \sigma |\dot{\varepsilon}| \right). \quad (1)$$

The development of the constitutive equations in the present paper starts with the description of the viscoplastic phenomena observed in tension tests. For this purpose, the additive decomposition of the total strain into elastic and inelastic parts is used, Equation (2). The stress response is the sum of the equilibrium stress, Equation (4), and the overstress, Equation (5). The rate of the plastic deformation is given by the endochronic flow rule, Equation (6). The viscous deformation is determined by a nonlinear rate equation of the Garofalo type, Equation (7). For very small deformations Equation (4) reduces to Hooke's law.

$$\varepsilon = \varepsilon_{ep} + \varepsilon_{ip} = \varepsilon_{ev} + \varepsilon_{iv}, \quad (2)$$

$$\sigma = \sigma_{\infty} + \sigma_{ov}, \quad (3)$$

$$\sigma_{\infty} = A \ln(1 + B \langle \varepsilon_{ep} \rangle) - A \ln(1 - B \langle -\varepsilon_{ep} \rangle), \quad \langle x \rangle := \frac{x + |x|}{2}, \quad (4)$$

$$\sigma_{ov} = C \varepsilon_{ev}, \quad (5)$$

$$\dot{\varepsilon}_{ip} = \frac{1}{Y} \sigma_{\infty} |\dot{\varepsilon}|, \quad (6)$$

$$\dot{\varepsilon}_{iv} = \frac{1}{\eta} \left[\sinh \left(\frac{\sigma_{ov}}{\sigma_0} \right) \right]^{\kappa}. \quad (7)$$

Equations (2)–(7) are sufficient to describe the nonlinear stress-strain characteristic, the strain rate dependence, the nonlinear stress relaxation and the nonlinear material behavior during unloading in tension, as reported in Kletschkowski et al. (2002).

The key to include the SDE in this material model is to be found in Equation (4). Due to the mathematical properties of the logarithm, one needs to distinguish between tension and compression in this equation from the beginning. Therefore

the second term of Equation (4) is modified to include the SDE in the rheological model by introducing a new material parameter \hat{A}

$$\hat{A} = A (1 + D_p + D_n). \quad (8)$$

D_p and D_n are internal variables of the damage type. D_p describes the permanent properties of the additional stress caused by the SDE, and D_n describes the non-permanent properties of the additional stress caused by the SDE during the stress relaxation. Using this new material parameter, Equation (4) can be rewritten as

$$\sigma_\infty = A \ln(1 + B \langle \varepsilon_{ep} \rangle) - \hat{A} \ln(1 - B \langle -\varepsilon_{ep} \rangle), \quad \langle x \rangle := \frac{x + |x|}{2}. \quad (9)$$

The evolution of the internal parameters of the damage type is described by ordinary differential equations

$$\dot{D}_p = -K_1 \langle -\sigma_\infty \rangle |\dot{\varepsilon}| (D_p^{\max} - D_p), \quad (10)$$

$$\dot{D}_n = -K_2 \langle -\sigma_\infty \rangle |\dot{\varepsilon}| (D_n^{\max} - D_n) - K_3 (D_n)^{K_4}. \quad (11)$$

The evolution of these additional internal variables occurs only under compression and will end, when the saturation limits, described by the material constants D_p^{\max} and D_n^{\max} , are reached. The second term of Equation (11) is needed to model the relaxation of the additional stress under compression caused by the SDE.

The introduction of the SDE into the rheological model is completed with the assumption that the amount of plastic deformation should be equal in tension and compression. This assumption leads to a modification of the endochronic flow rule

$$\dot{\varepsilon}_{ip} = \frac{1}{Y} \langle \sigma_\infty \rangle |\dot{\varepsilon}| + \frac{1}{\hat{Y}} \langle -\sigma_\infty \rangle |\dot{\varepsilon}|, \quad \hat{Y} = Y(1 + D_p + D_n). \quad (12)$$

Equations (2)–(3), (5), (7) and (9)–(12) are sufficient to describe the nonlinear material behavior of filled PTFE in both, tension and compression, using seven material parameters and four internal variables (ε_{ip} , ε_{iv} , D_p and D_n). These are

- the elastic parameters A and B of the endochronic model;
- the maximum stress Y that can be reached in the endochronic model;
- the elastic parameter C of the Maxwell model;
- the material parameters η , κ and σ_0 of the viscous flow rule.

4. Parameter Identification and Numerical Results

We begin with matching of the stress-strain diagrams in tension to find the constants A , B , C , Y , η , κ and σ_0 . The constitutive equations are integrated numerically by the explicit second-order predictor-corrector method of HEUN with a step size of $\Delta t = 0.01$ s.

Table I. Parameters of the rheological model.

A [N/mm ²]	1.48
B [1]	230.95
Y [N/mm ²]	9.08
C [N/mm ²]	363.33
η [1/s]	$9.5854 \cdot 10^4$
κ [1]	3.51
σ_0 [N/mm ²]	5.62
K_1 [1/s]	235.2
K_2 [1]	4586.9
K_3 [1/s]	0.0044
K_4 [1]	12.874
D_p^{\max} [1]	0.484
D_n^{\max} [1]	1.432

These model parameters are found simultaneously – using a tension test with a strain rate of $\dot{\varepsilon} = 10\%/min$ and a top strain of $\varepsilon = 0.08$ including the succeeding stress relaxation – by the least-squares method from the condition of minimum of the function f , where the sum is calculated over $N = 160$ experimental points, i , σ_{exp} is the measured stress, and σ_{num} is given by Equation (3).

$$f = \sum_{i=1}^N [\sigma_{\text{exp}}(t_i) - \sigma_{\text{num}}(t_i)]^2. \quad (13)$$

Afterwards, the model parameters K_1 , K_2 , K_3 , K_4 , D_p^{\max} and D_n^{\max} are found by minimizing Equation (13) with respect to a compression test ($|\dot{\varepsilon}| = 10\%/min$, top strain $\varepsilon = -0.05$). The set of material constants, identified by this procedure, is summarized in Table I. A reduction of the time step size to $\Delta t = 0.001$ s leads to the same model parameters as in Table I.

In Figure 5 experimental data and numerical results are compared. In Figure 5 (top) the engineering stress is plotted *versus* engineering strain for loading in tension and compression. Figure 5 (bottom) illustrates the measured and calculated curves of the succeeding long time stress relaxation in tension and compression after loading at a strain rate of $\dot{\varepsilon} = 10\%/min$. Figure 5 illustrates that the proposed model is suitable to compute the strain rate dependence during straining at different strain rates in tension. The SDE, observed in compression tests, can be simulated by the presented model, too. The model is very precise in the calculation of the long-time material behavior during the stress relaxation processes for both, tension and compression tests. The numerical results are in fair agreement with the short time relaxation data too, see Figure 6.

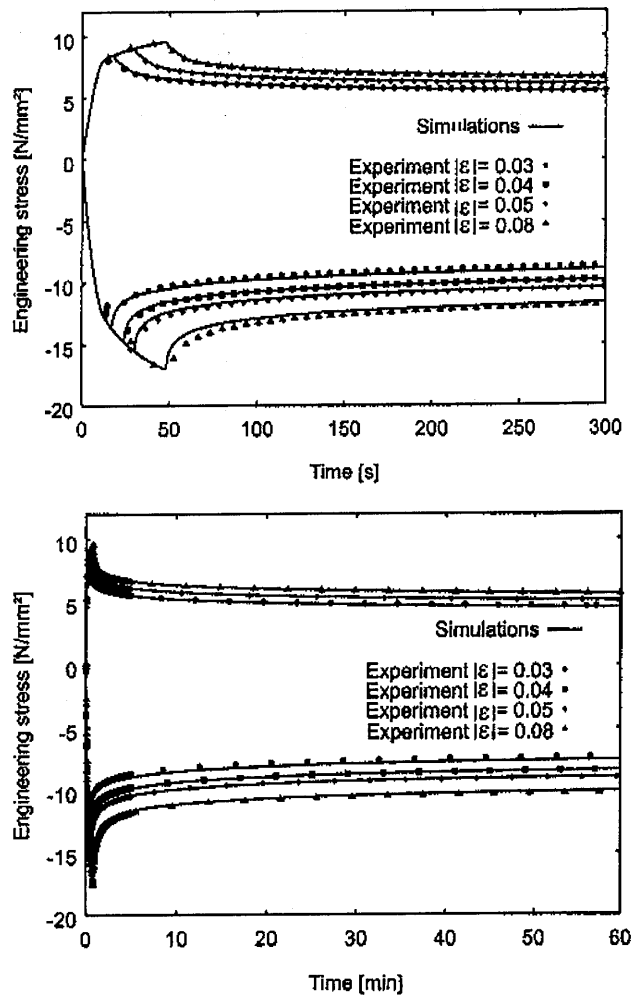


Figure 6. SDE – experimental data and simulations (short time relaxation).

The small discrepancies in tracking the compression response, see Figure 5 (top), is due to measuring errors caused by the more or less statistical distribution of the filler materials.

Finally the question will be discussed, which are the most sensitive model parameters. Therefore in each case one model parameter has been multiplied by 1.1, while the other model parameters have been kept unchanged. Then the sensitivity of the rheological model to these changes has been investigated in numerical simulations. After 13 simulations, which have been performed for the variation of the 13 model parameters, the procedure has been repeated by multiplying one model

parameter by 0.9 at each case, while the other model parameters have been kept unchanged.

The influence of the model parameters A , B , C , Y , η , κ and σ_0 on the stress response of the rheological model has been checked by numerical simulations in tension (straining at $\dot{\epsilon} = 10\%/min$ and succeeding stress relaxation at $\epsilon_{max} = 0.08$).

The influence of the model parameters K_1 , K_2 , K_3 , K_4 , D_p^{max} and D_n^{max} on the stress response of the rheological model has been analyzed by numerical simulations in compression (straining at $\dot{\epsilon} = -10\%/min$ and succeeding stress relaxation at $\epsilon_{max} = -0.05$).

The results of these simulations are shown in Figures 7a–7f and 8a–8f. For simplicity the absolute values of the stress response curves are plotted. Each figure contains numerous results. The solid line in the middle of each array of curves represents the original solution with respect to the unchanged model parameters (Table I).

It can be seen that A , B , κ and σ_0 (in tension) and K_4 , D_p^{max} and D_n^{max} (in compression) are the most sensitive constants. An increase/decrease of A and B corresponds to an increase/decrease of the equilibrium stress and leads to an increase/decrease of the total stress response (Figures 7a and 7b). The loading and stress relaxation curves are sensitive to κ and σ_0 too. The rate dependent properties of the material model are determined by these parameters. While σ_0 affects the short time relaxation behaviour, the long time stress relaxation properties are affected by κ , see Figure 7d.

The most important parameters for the simulations in compression are D_p^{max} and D_n^{max} , because these are the final magnification values for the modified model parameter \hat{A} . D_p^{max} describes the permanent magnification of A with respect to the permanent properties of the SDE. Hence an increase of this model parameter results in an increase of the equilibrium stress and leads to an increase of the permanent total stress response of the rheological model (Figures 8c and 8d).

D_n^{max} describes the non-permanent magnification of A . That is why only the loading curve, see Figure 8e, is affected by a variation of this model parameter. A noticeable influence of the stress response on the other model parameters has not been found in these studies.

5. Some Notes on the Three-Dimensional Generalization

First of all the question must be answered, why a three-dimensional generalization of the SDE-concept should be presented, if the experimental results are focused on uniaxial problems.

Rotary shaft seals are typical engineering applications of PTFE compounds, filled with short cylindrical glass fibers. As it is shown by Sui et al. (1995), the hoop stress and the radial stress are the most important stress components, if a rotary shaft seal is analyzed in an axisymmetric calculation. Hence, a multi-dimensional generalization of the SDE-concept is needed for numerical simulations of complex

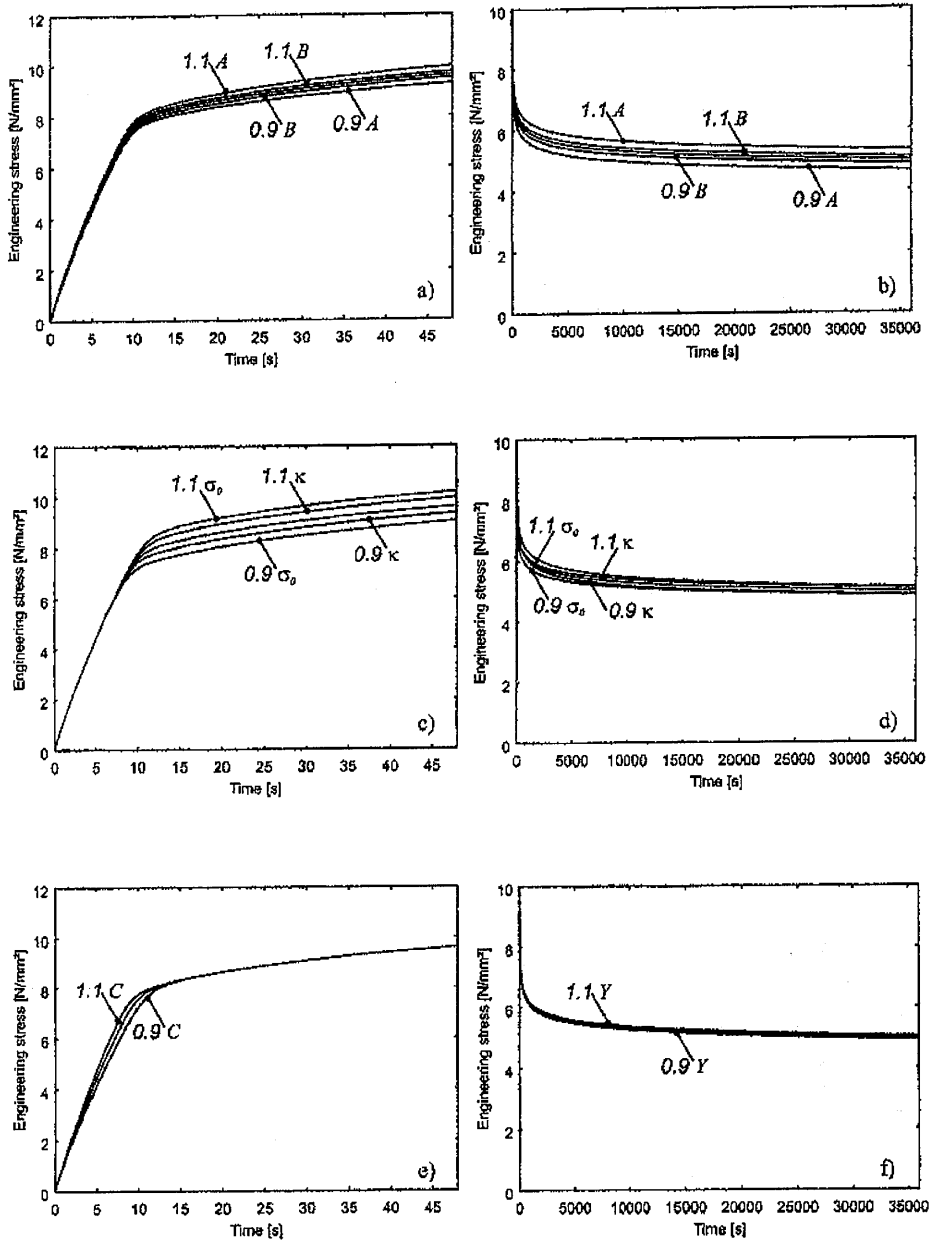


Figure 7. Sensitivity of model parameters in tension.

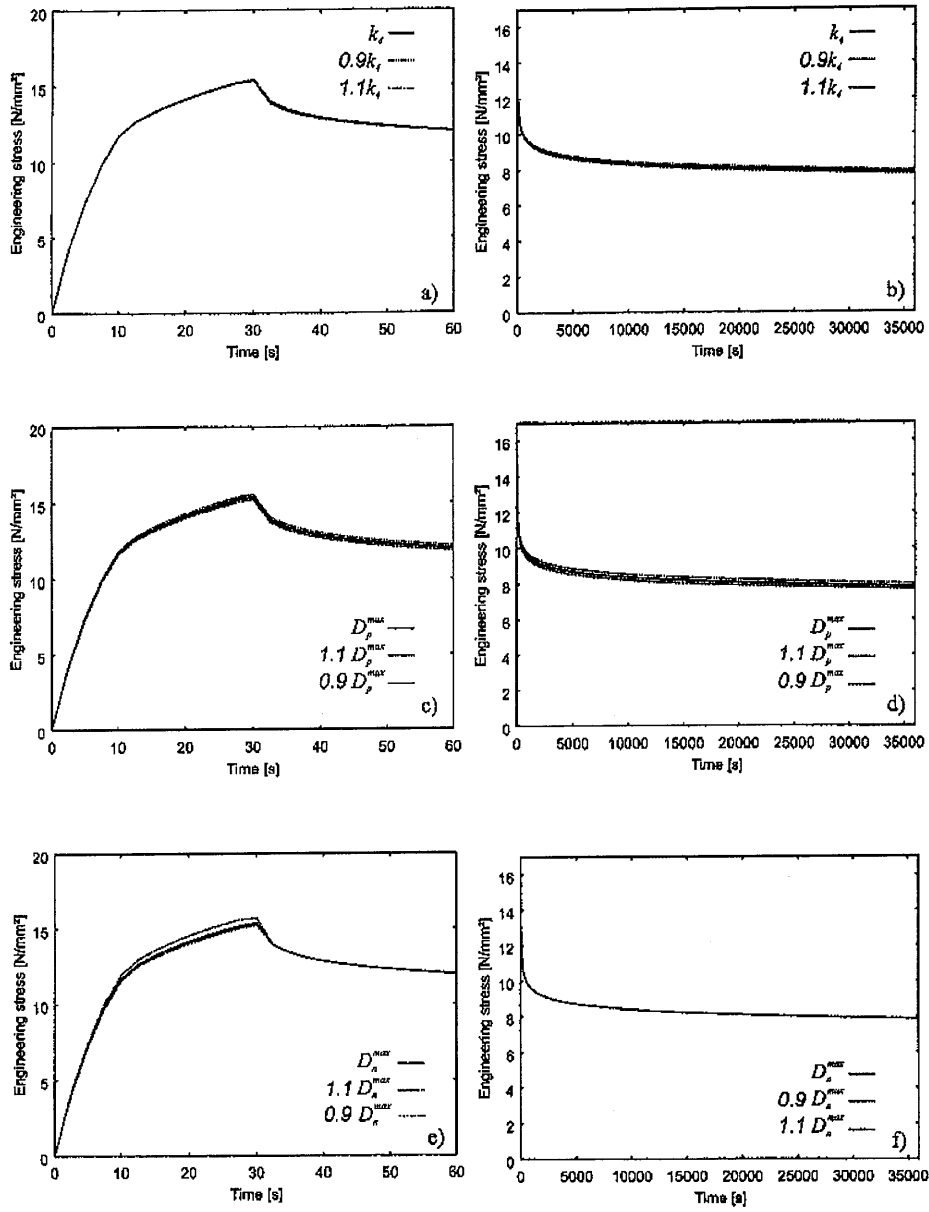


Figure 8. Sensitivity of model parameters in compression.

engineering structures made of materials with different behaviour in tension and compression.

Let \mathbf{S}^{dev} be the deviatoric stress tensor, \mathbf{E}_{ip} the plastic strain tensor, σ_V the equivalent von Mises stress, $\dot{\varepsilon}_V$ the associated equivalent strain rate and $\dot{\varepsilon}_{pV}$ an equivalent inelastic strain rate.

$$\sigma_V := \sqrt{\frac{3}{2} \text{tr}(\mathbf{S}^{\text{dev}} \mathbf{S}^{\text{dev}})}, \quad \dot{\varepsilon}_V := \sqrt{\frac{2}{3} \text{tr}(\dot{\mathbf{E}} \dot{\mathbf{E}})}. \quad (14)$$

If a generalized associated flow rule, see Kletschkowski et al. (2002), is applied to model inelastic phenomena of an isotropic solid, like

$$\dot{\mathbf{E}}_{ip} = \frac{3}{2} \dot{\varepsilon}_{pV} \frac{\mathbf{S}^{\text{dev}}}{\sigma_V}, \quad (15)$$

scalar valued rate equations like the endochronic flow rule (6) can be obtained from the three-dimensional formulation, if uniaxial stress fields are analyzed.

Proof. If the state of stress is determined by $\mathbf{S} = \sigma_{11} \mathbf{e}_1 \otimes \mathbf{e}_1$, the equivalent von Mises stress becomes $\sigma_V = \sigma_{11}$. The longitudinal component of $\dot{\mathbf{E}}_{ip}$ equals $\dot{E}_{ip11} = \dot{\varepsilon}_{pV}$ additionally. An equivalent inelastic strain rate $\dot{\varepsilon}_{pV}$ defined as

$$\dot{\varepsilon}_{pV} := \frac{1}{Y} \sigma_V \dot{\varepsilon}_V, \quad (16)$$

equals the uniaxial plastic flow $\dot{\varepsilon}_{ip}$, if the isochoric plastic flow is developed perfectly ($\sigma_V \approx Y \Rightarrow |\dot{\varepsilon}| = \dot{\varepsilon}_V$). Otherwise the relations $\dot{E}_{ip11} \approx \dot{\varepsilon}_{pV} \approx \dot{\varepsilon}_{ip}$ are valid for slightly compressible isotropic solids like PTFE compounds (Poisson's ratio $\nu = 0.46$).

That is why a three-dimensional generalization is presented, even if the experimental results are focused on uniaxial problems. \square

In order to generalize the SDE-concept to three dimensions we have to substitute $|\dot{\varepsilon}|$ by $\dot{\varepsilon}_V$. Furthermore one has to distinguish between tension and compression in multi-dimensional states of stress. Therefore the procedure outlined in Ehlers (1995) is used. If \mathbf{S} is the stress tensor, describing the state of stress in a material model, then Equation (17) gives the stress mode factor ξ by using the second (J_2) and third (J_3) principle invariant of the deviatoric stress tensor \mathbf{S}^{dev} .

$$\xi = \frac{\sqrt{27}}{2} \frac{J_3}{(J_2)^{3/2}}, \quad (17)$$

$$J_i = \frac{1}{i} \text{tr}\{(\mathbf{S}^{\text{dev}})^i\}, \quad i = 2, 3 \quad \text{with } \mathbf{S}^{\text{dev}} := \mathbf{S} - \frac{1}{3} \text{tr}\{\mathbf{S}\} \mathbf{I}. \quad (18)$$

The stress mode intensity functions w_t and w_c can be introduced to weight the stress contributions of the different stress modes (tension and compression)

$$w_t = \frac{1}{2} (1 + \xi), \quad (19)$$

$$w_c = \frac{1}{2}(1 - \xi). \quad (20)$$

The scalar valued evolution equations for the internal variables of the damage type D_p and D_n can be generalized to

$$\dot{D}_p = K_1 \sigma_V \dot{\epsilon}_V (D_p^{\max} - D_p) w_c, \quad (21)$$

$$\dot{D}_n = K_2 \sigma_V \dot{\epsilon}_V (D_n^{\max} - D_n) w_c - K_3 (D_n)^{K_4} w_c. \quad (22)$$

It follows that any material parameter M of a material model can simply be updated. $\hat{M} = M(1 + D_p + D_n)$, the modified material parameter allows to describe a material behavior that is different in tension and compression. If a rate for an internal variable due to different stress modes is needed, this evolution equation can be introduced as

$$\dot{\mathbf{q}} = \sum_{i=1}^n w_i \dot{q}_V \vec{\mathbf{N}}_i. \quad (23)$$

In Equation (19) the number of stress modes is given by n . The increment of an internal variable \mathbf{q} caused by the i -th stress mode is given by the product of the i -th stress mode intensity factor w_i , the amplitude of the evolution due to the i -th stress mode \dot{q}_V , and the direction of the evolution due to this stress mode $\vec{\mathbf{N}}_i$. In this context, using an associated flow rule, Equation (12) could be generalized to three dimensions as

$$\dot{\mathbf{E}}_{ip} = \frac{3}{2} \left(\frac{w_t}{Y} + \frac{w_c}{\hat{Y}} \right) \sigma_V \dot{\epsilon}_V \vec{\mathbf{N}} \quad \text{with} \quad \vec{\mathbf{N}} := \frac{\mathbf{S}_{\infty}^{\text{dev}}}{\sigma_V}. \quad (24)$$

6. Concluding Remarks

In this paper an endochronic viscoplastic material model for the description of materials with different behavior in tension and compression for a typical PTFE compound is presented. The inelastic phenomena of this compound are studied in isothermal deformation processes at ambient temperature in both tension and compression. To describe the nonlinear stress-strain characteristic, the strain rate dependence, the nonlinear stress relaxation and the SDE, a viscoplastic material model is proposed, which consists of an endochronic elastoplastic model coupled with a nonlinear Maxwell model in parallel. An additive decomposition of the total stress into an equilibrium stress and an overstress is applied. Because of the endochronic flow rule we do not need to evaluate a flow limit and a consistency condition during the numerical computations. This accelerates the identification and the simulations in general. The results of numerical simulations show the capability of the model to describe the inelastic phenomena observed in the tests. The proposed model is suitable to simulate the SDE of the analyzed PTFE compound.

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