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Characterizing and modeling the non-linear viscoelastic tensile deformation of a glass fiber reinforced polypropylene

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ABSTRACT

On the basis of comprehensive experimental investigations on a long glass fiber reinforced polypropylene (PP-LGF) a novel rheological material model is developed. It features a decomposition of the stress into a time independent quasi-static and a time and strain dependent viscous contribution. Furthermore it allows for plastic deformations starting from the very beginning of straining and is thereby able to reproduce the absence of a purely linear elastic domain going along with the nonexistence of a defined yield point, characteristic for many fiber reinforced thermoplastic polymers. In order to approach the true quasi-static material behavior, various tensile tests were carried out. The viscous material behavior was deduced from a series of stress relaxation experiments and is described by Eyring's equation with strain dependent viscosity parameters.

1. Introduction

During the last decades many attempts have been made in characterizing and modeling the mechanical properties of different polymeric systems with special focus set on the investigation of the time dependence of the viscous material behavior and the formation of irreversible plastic flow. The general objective of most of these works is the development of a mathematical formulation describing the observed rheological phenomena with the aim of being able to predict the material behavior under arbitrary load conditions. In the course of this endeavor, a number of different approaches were developed by various authors. Among these are micromechanical models [1–10], models based on thermodynamic principles [11–13], continuum mechanical constitutive formulations [14–18], and methods working with potential functions [19]. Common to most of the research work published in the fields mentioned above are the quite elaborate and sophisticated models often going along with a complex mathematical formulation preventing them from a broader adaptation and application especially in the domain of numerical simulations. This motivates the development of a novel material model that is both capable of reproducing all relevant characteristic mechanical properties of the fiber reinforced polymer under study and additionally provides a manageable analytical mathematical formulation of the associated stress–strain relation.

The approach of the present work differs from those of the above mentioned authors and proposes a non-linear rheological model in the manner done by So and Chen [20]. The setup of the proposed model was motivated by works of Strobl et al. [21,22], Strobl and Hong [23], who investigated the quasi-static tensile stress–strain behavior and viscous stresses of semi crystalline thermoplastic polymers. Assuming that the viscous forces apparent in a PP-LGF are dominated by the thermoplastic matrix, parts of the model proposed by Strobl et al. were adopted and a new rheological model, adjusted to the special features of the composite material, was set up. Based on experimental observations the model features a decomposition of the stress into a time independent quasi-static and a time and strain dependent viscous contribution represented by two different branches of the rheological model. The quasi-static stress–strain relationship includes an irreversible plastic deformation and accounts for a strain dependent damage. The viscous forces are described by Eyring's law of viscosity following other authors' treatment of thermoplastic polymers [24–26]. Part of the non-linearity of the material behavior is to be attributed to strain dependent viscosity parameters.

2. Experimental

The material under study is a long glass fiber reinforced polypropylene (PP-LGF) with a volumetric fiber content of 20%, injection-molded to form square plates of 2.8 mm thickness. Specimens for tensile tests were cut out from these plates. A bone shaped specimen geometry was chosen in analogy to DIN-EN-527-2-1B, with an

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increased width of the proportional part of 15 mm. The increased width was necessary to be able to capture the correct fiber length distribution of the material with the longest fibers still having the initial length of 12.7 mm (0.5 in.). The experiments were run using an Instron 8801 universal testing device.

The quasi-static material behavior was derived by two types of tensile tests, in which the straining process was interrupted by a number of dwell times. During these, the global strain was kept constant and the sample was allowed to relax towards the mechanical equilibrium state before being strained to a higher value. In Figs. 1 and 2 display the strain versus time characteristics of these cyclic step-relaxation (Fig. 1) and step-cycle tests (Fig. 2). For both experiments the dwell times of constant strain are of 10,000 s duration, which is sufficient for almost all viscous stress contributions to relax. The viscous material behavior was deduced from the characteristic time dependence of the stress decay measured for a series of stress relaxation experiments. In these experiments samples were strained to various but constant strains where they were kept fixed and the stress decay was monitored.

3. Results

Fig. 3 displays the experimental results of tensile tests, whereby the stress is plotted versus the true local strain, also known as 'Hencky strain' ε_H, given by $\varepsilon_H = \ln\left(\frac{L_0+\Delta L}{L_0}\right)$. L_0 is the reference length before straining, and ΔL is the change in length. The tensile tests were carried out for various strain rates $\dot{\varepsilon}_H$, starting from $2 \times 10^{-5}\ \mathrm{s}^{-1}$ up to $2\ \mathrm{s}^{-1}$in equidistant steps of one order of magnitude. All stress–strain curves exhibit both a high stiffness as well as a brittle failure at low failure strains of about 3%. For all investigated strain rates the stress–strain curves never follow a linear elastic relation, even for very small strains. Instead they all exhibit a continuously decreasing slope, each starting with a certain initial value, depending on the rate of deformation. Consequently no defined yield point can be found in any of the measured stress–strain diagrams. For increasing strains the curves of different strain rates show an increasing deviation from each other. This higher strain rate sensitivity at higher strain values implies a change of the viscosity parameters of the material throughout the straining process. Motivated by these experimental observations a detailed analysis of the rate dependent viscous forces of the material and the material behavior under quasi-static loading conditions was carried out and will be presented in the following chapters.

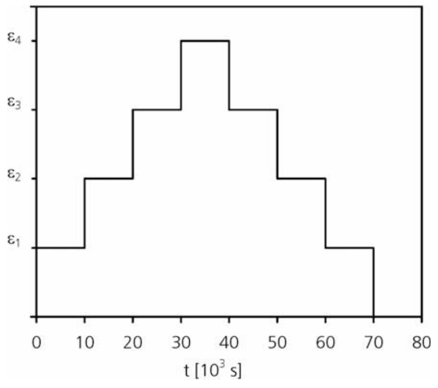

Fig. 1. Strain versus time of a cyclic step-relaxation test.

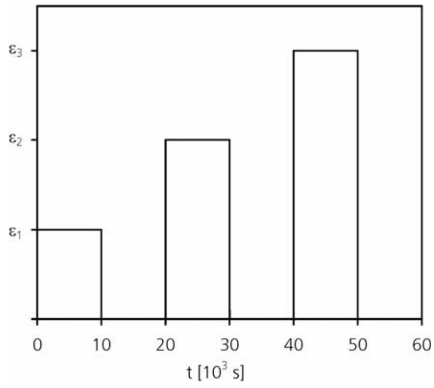

Fig. 2. Strain versus time of a step-cycle test.

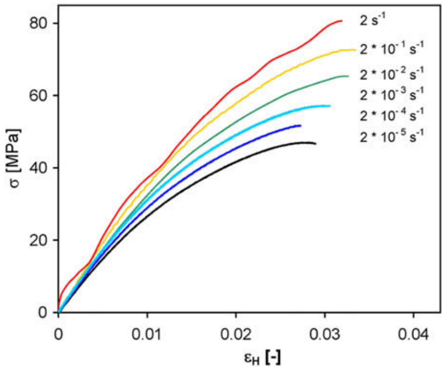

Fig. 3. Stress–strain dependence obtained for the PP-LGF for various strain rates as indicated in the diagram. The stress is plotted against the local Hencky strain.

3.1. Quasi-static material behavior

The quasi-static material behavior denotes the stress response of a material in the limit of a zero strain rate $\dot{\varepsilon}_H \to 0$. Even by setting the piston velocity of the universal testing machine to the smallest possible value, this limit cannot be reached. In order to approach the true quasi-static material behavior, cyclic step-relaxation tests (see Fig. 1) were carried out. Fig. 4 displays the results of a cyclic step-relaxation experiment, in which the loading and unloading process was interrupted by several dwell times of 10,000 s duration. During these time intervals the global strain was kept constant and the sample was allowed to relax towards its mechanical equilibrium state. For the loading process we observe a decrease of the stress during the dwell times due to stress relaxation. For the unloading process we find an increase

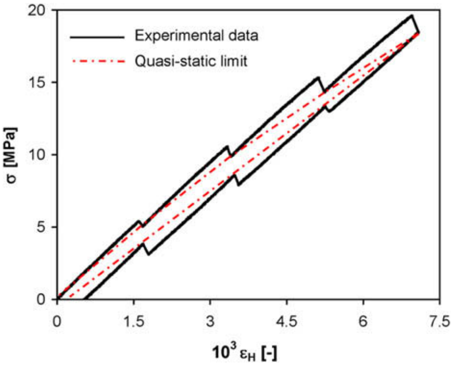

Fig. 4. Cyclic step-relaxation test. The continuous line represents the experimental data. The loading and unloading steps were performed at a strain rate of $\dot{\varepsilon}_H = 2 \times 10^{-5}$and interrupted by dwell times of 10,000 s duration. The dash-dotted line sketches the extrapolated quasi-static material behavior in the limit of a vanishing strain rate.