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Property modelling

Tensile properties of semi-crystalline thermoplastic polymers: Effects of temperature and strain rates

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ABSTRACT

This work deals with the study of temperature and time dependency of tensile properties of a PA 12-based polymer. The range of variation of parameters in experiments was linked to in-service conditions of components manufactured with this material (temperature interval from −25 °C to 50 °C and average strain-rate magnitudes from 0.00028 s^{-1} to 9.4 s^{-1}). For tests with different temperatures and low speed, an electro-mechanical machine, Zwick Z250, equipped with an incremental extensometer was used. To study the effect of strain rate at medium speeds, a servo-hydraulic system, Schenk PC63M, equipped with a strain-gauge extensometer was used, while at high speeds a servo-hydraulic machine, Instron VHS 160/20, equipped with a high-speed camera for strain evaluation by digital image correlation was employed. The changes of the rate of deformation with strain as well as elastic modulus variation with strain were studied. An increase in the elastic modulus and yield strength was observed with a drop in temperature and an increase in the strain-rate, temperature having a stronger influence on the variation of mechanical properties. The collected data was assembled in an elasto-plastic material model for finite-element simulations capable of rendering temperature- and strain-rate-dependency. The model was implemented in the commercial software Abaqus, yielding accurate results for all tests.

1. Introduction

The studied material is a polyamide 12-based semi-crystalline thermoplastic polymer primarily designed for low-temperature applications [1]. Due to its viscoelastic nature, test conditions such as temperature, strain rate or humidity can cause significant variations in mechanical properties [2–5]. The aim of this study is to develop a virtual material model capable of predicting the material's behaviour for various loading scenarios.

In recent years, the development of specialized numerical analysis software allowed the evaluation of complex structures with relative ease, thus becoming an indispensable tool for product design. Material modelling can be obtained with the help of the various constitutive formulations such as elasticity, hyperelasticity, hypoelasticity, inelasticity, damage initiation and propagation models, complex engineering features (fracture mechanics) etc., implemented in software [6]. These generic formulations may or may not produce accurate results for a given material and many require customized experimental procedures for parameter determination. This issue can be solved with the help of mathematical models that can be designed for specific material behaviour [7] and implemented by means of user-defined subroutines [6]. The drawback of this solution is that it requires additional programming skills as well as additional compiling software [6,8].

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In the case of isotropy, calibration of material models requires tensile data as input parameters. Thermoplastic polymers can be modelled through several approaches, using elasto-plastic, hyperelastic and viscoelastic formulations [6,8–11].

Elasto-plastic models consider Hookean elasticity as a constitutive relation linking stress and strain levels. Material softening with strain is modelled with a plasticity function (yield Kirchhoff stress – plastic strain) [10,12,13]. The advantages of this model are great stability and short simulation time. It also has a deficiency: it cannot account for cyclic loadings, and strain-rate dependency can only be modelled within the framework of plasticity [6].

Hyperelastic models derive the stress-strain response from a stored elastic potential function known as *strain-energy density function* [8,11]. Over the years, several hyperelastic functions were developed and implemented in specialized software, such as the Arruda-Boyce model [14], the Van der Waals (Killian) model [15], the Marlow model [16], the Ogden model [17] or the Mooney-Rivlin model [18], each aimed at a certain class of materials and applications. The advantages of hyperelastic models are simple material calibration [6] and an accurate response to cyclic loadings (with the help of additional sub-options such as **Mullins* effect or **Hysteresis* [6]). As drawbacks, strain-rate dependency can only be obtained with additional subroutines, and hyperelastic models are sometimes unstable beyond certain strain values.

Viscoelasticity considers a material behaviour as intermediate between those of elastic solids and viscous fluids [3,5]. Although present in most materials, viscoelasticity is most noticeable in polymers due to their chain structure [5,19] and low melting point. Due to its character, viscoelasticity is presented as a combination of an elastic component and a flow component (e.g., the Maxwell fluid and the Kelvin solid [3,5,19]). This formulation allows an accurate response in various loading scenarios such as creep, stress relaxation or high-frequency loading regimes [2,3,5,19]. There is one deficiency, due to their complex form: viscoelastic models are hard to calibrate, they have long simulation times and are rather unstable.

After evaluation of the material model, subsequent finite-element applications consist of simulations for product parts with complex geometries. Because of the large number of elements in such structures, long computation times are of concern; they can be reduced with a faster and more stable material model. Thus, the option was to choose the elasto-plastic model neglecting hyperelasticity and viscoelastic formulations.

For an accurate prediction of material behaviour in finite-element analysis, a wide range of experimental stress-strain curves are required, covering all possible in-service conditions. The testing range for the rate of deformation in polymers can vary from 0.0001 s^{-1} up to 500 s^{-1} [20]. Low strain rates (up to 0.1 s^{-1}) can be achieved with conventional screw-drive machines; intermediate rates (up to 1 s^{-1}) can be achieved with servo-hydraulic machines, while tests for the high end of the spectrum can only be performed with specialized servo-hydraulic systems [21], servo-hydraulic machines with clamp adaptations [22], impact testers (drop weight tests) [23] or Split Hopkinson pressure bars [23–25].

In the ISO standard for tensile testing, the procedures indicate a crosshead travel speed as low as 1 mm/min which, considering the standardized dumbbell specimen dimensions, translates to a strain rate of around 0.00015 s^{-1} [26]. Because the actual strain-rate of each test is hard to predict due to acceleration, non linear strain-displacement behaviour, yielding, etc, the tests were programmed in displacement control, with test speed increasing logarithmically. The strain-rate variation with deformation for each test was evaluated from the strain-time diagrams.

In the case of advanced experimental procedures, strain recording using conventional methods (strain gauges, extensometers, etc) is not possible or could result in inaccurate results. Non-contact (optical) strain recording procedures were developed to overcome impediments related to different scenarios such as complex loading patterns [27], high strain rate [24], high temperature [28] or unconventional materials [29,30]. Optical methods for strain recording have their limitation in the case of large deformations before fracture (over 10%). Xiao suggested a method of correlating FE simulation results to displacement data obtained from experimental procedures in order to determine the strain from the crosshead travel of the machine [31].

2. Experimental procedures

2.1. Preliminary dynamic mechanical analysis tests

The products manufactured from the studied polymer are meant to operate in a temperature range between

Fig. 1. Thermal chamber on Zwick Z250 machine.