Polymer Testing 58 (2017) 40–47

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Property Modelling

Analysis of the cyclic tensile behaviour of an elasto-viscoplastic polyamide

H.S. da Costa Mattos [a, *], J.M.L. Reis [a], L.G.M.O. de Medeiros [a], A.H. Monteiro [a, b], S.C.S. Teixeira [b], E.G. Chaves [b]

[a] Laboratory of Theoretical and Applied Mechanics, Graduate Program of Mechanical Engineering, Universidade Federal Fluminense, Rua Passo da Patria 156, 24210-240, Niterói, RJ, Brazil

[b] PETROBRAS – Petróleo Brasileiro S.A, Research Center (CENPES), 21941-915, Cidade Universitária - Ilha do Fundão, Rio de Janeiro, RJ, Brazil

ARTICLE INFO

Article history:
Received 28 October 2016
Accepted 3 December 2016
Available online 8 December 2016

Keywords:
Polyamide
Cyclic tensile tests
Elasto-viscoplasticity
Ratcheting
Shakedown
Modelling

ABSTRACT

The present paper is concerned with the experimental and theoretical investigation of the progressive accumulation of inelastic deformation observed in cyclic tension tests performed on a particular polyamide. The elastic properties are not strongly affected by the strain rate, but the strain hardening induced by the plastic deformation is rate-dependent. Thus, the material behaviour is elasto-viscoplastic rather than viscoelastic or elasto-plastic. For the polymer studied in this paper, the kinematic hardening is much more significant than the isotropic hardening, and a negative plastic strain rate may occur even with a positive stress. The kinematic hardening is strongly dependent, not only on the accumulated plastic strain, but also on the loading rate. An elasto-viscoplastic mechanical model able to describe the cyclic inelastic behaviour for an arbitrary loading history is proposed. All parameters that arise in the theory are identified experimentally. The preliminary theoretical results concerning the modelling of cyclic load-unload tests are in good agreement with the experiments.

1. Introduction

The demand for polymeric materials in recent years has grown substantially. The commercial success of polymer-based products generated a demand that has overcome the total production of metals for more than 20 years [1]. Industrial applications include automotive, aeronautical and oil and gas industries. Polyamide polymers (PA 12 and 11) are often used as pressure sheaths for flexible pipes in oil exploration, along with polyvinylidene fluoride (PVDF) and polyethylene. Aliphatic polyamides with long alkyl chains such as polyamide 11 (PA11) or polyamide 12 (PA12) combine high strength with high deformation prior to failure (extremely resistant to cracking under stress), besides having good chemical resistance and low moisture absorption.

The understanding of the mechanical behaviour of the polyamide under different loading scenarios, such as cyclic tension, is important to guarantee structural integrity of flexible pipes. There are many studies regarding the effects of temperature and strain rate on polymers [2–5]. Polymers constitute a unique class of materials with high sensibility to changes in these variables, leading to viscoelastic or elasto-viscoplastic mechanical behaviour.

Despite their use in large scale industrial applications, there are still relatively few researches on cyclic plastic behaviour of polymeric materials. Chen et al. [6] conducted a series of cyclic compression tests under different loading frequencies on polytetrafluoroethylene (PTFE) specimens, studying its influence on the ratcheting behaviour. Bles et al. [7] showed another important use for thermoplastic polymers investigating elasto-viscoplastic behaviour of a polyamide 6-6 fibre strap subjected to cyclic tensile tests including creep and relaxation. Such behaviour was also observed by Drozdov [8] in an experimental investigation and constitutive modelling of a polyamide-6 reinforced with short glass fibres under cyclic tests. In da Costa Mattos and Martins [9], a study of the cyclic behaviour of an elasto-plastic epoxy polymer was presented, along with remarks concerning the strong influence of the kinematic hardening on the accumulation of cyclic plastic deformation in this type of polymer. Xia et al. [10] and Shen et al. [11], also contributed with experimental observations of the ratcheting behaviour in epoxy resins.

This paper is focused on investigation of the cyclic plastic behaviour of a particular polyamide used in deep-water and ultra-deep-water offshore oil exploration. Different to the study

* Corresponding author.
E-mail address: heraldo@mec.uff.br (H.S. da Costa Mattos).

http://dx.doi.org/10.1016/j.polymertesting.2016.12.009
0142-9418/

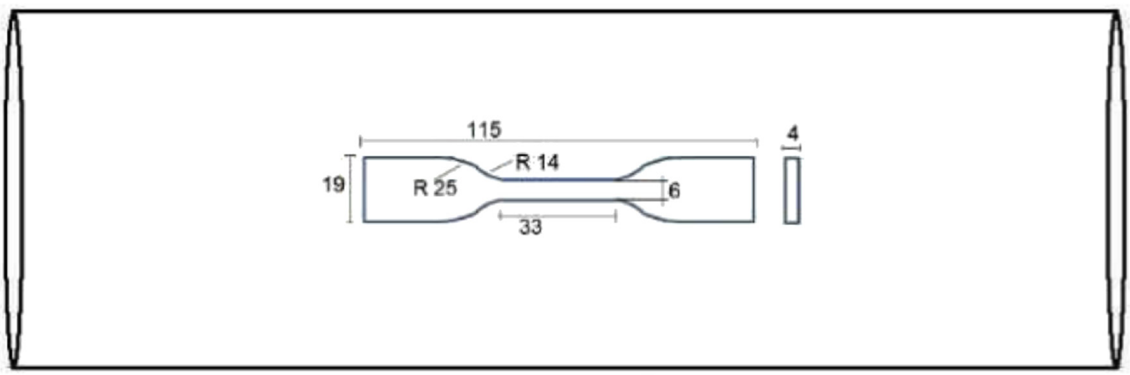

Fig. 1. Tensile test specimen machined from a pressure sheath of a flexible pipe.

performed in Refs. [9] and [12], the material behaviour is elasto-viscoplastic rather than elasto-plastic. In order to investigate the material's rate-dependency, different cross head velocities were used in monotonic tensile tests (0.5 mm/min, 5 mm/min and 50 mm/min). The elastic properties are not strongly affected by the strain rate, but the strain hardening induced by the plastic deformation is rate-dependent. A cyclic load-unload test was also performed with increasing force per cycle, starting from 400 N with a 50 N increment each cycle. For the polymer studied in this paper, similarly as in Ref. [9], the kinematic hardening is more significant than the isotropic hardening and a negative plastic strain rate may occur even with a positive stress. However, the kinematic hardening is strongly dependent, not only on the accumulated plastic strain, but also on the loading rate. The progressive accumulation of plastic deformation can be explained by the coupled effect of the kinematic hardening and the rate-dependency. Under cyclic loading and unloading, this polymer exhibits hysteresis and complex nonlinear behaviour may occur, such as ratcheting or shakedown.

An elasto-viscoplastic mechanical model is proposed for this particular polyamide. This model results in a non-linear system of ordinary differential equations. All parameters that arise in the theory are identified experimentally. These equations, together with an adequate set of initial conditions, are solved numerically by a semi-implicit integration method, and the preliminary theoretical results are in good agreement with the experiments.

2. Experimental procedures

Polyamide is a semi-crystalline thermoplastic with a combination of thermal and mechanical properties that allows it to be used in severe operation conditions. Therefore, the use of polyamides as pressure sheaths for flexible pipes is increasing in the oil and gas industry, where the operation conditions are particularly severe. Tensile test specimens were machined from an internal pressure sheath of a flexible pipe. A low water absorbing polyamide (nylon 12) was considered in the present study. The initial gage length L_o and cross sectional area A_o were, respectively, 33 mm and 24 mm^2, as shown in Fig. 1.

The mechanical response of thermoplastic polymers, such as this particular polyamide, are in general strongly dependent on the loading rate. To investigate the rate-dependency of the mechanical response, the specimens were initially subjected to monotonic tensile tests with different strain rates. The tensile test methodology followed the ASTM D638-08 standard. A load-unload cyclic test with increasing maximum load per cycle was also performed to investigate the cyclic plastic behaviour. Both monotonic and cyclic tests were performed using a Shimadzu® AG-X universal testing machine with 10 kN capacity and electro-mechanical sensors for the control of the longitudinal strain.

From now on, the classical uniaxial engineering stress and engineering strain will be denoted, respectively, σ and ε and will be called simply stress and strain

$$\varepsilon(t) = \frac{\Delta L(t)}{L_o} \quad ; \quad \sigma(t) = \frac{F(t)}{A_o} \tag{1}$$

$F(t)$ is the axial force necessary to impose an elongation $\Delta L(t)$ at a given instant t. L_o is the gauge length and A_o the cross-section area.

The tensile tests were performed at room temperature using three stroke velocities: 0.5 mm/min, 5.0 mm/min and 50.0 mm/

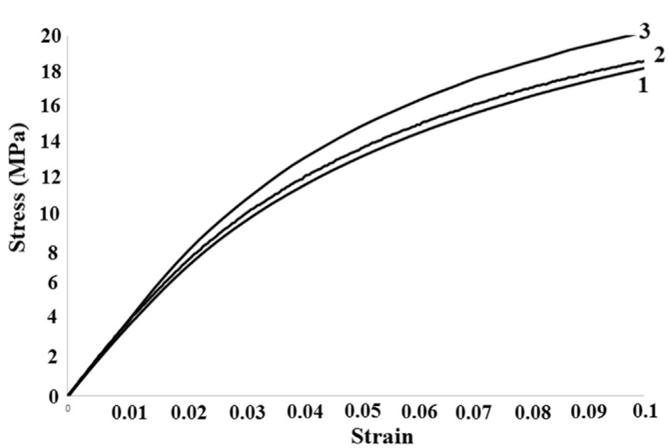

Fig. 2. σ x ε curves with different strain rates. (1): $\frac{d\varepsilon}{dt} = 1.6x10^{-4}\ s^{-1}$; (2): $\frac{d\varepsilon}{dt} = 1.6x10^{-3}\ s^{-1}$ and (3): $\frac{d\varepsilon}{dt} = 1.6x10^{-2}\ s^{-1}$.

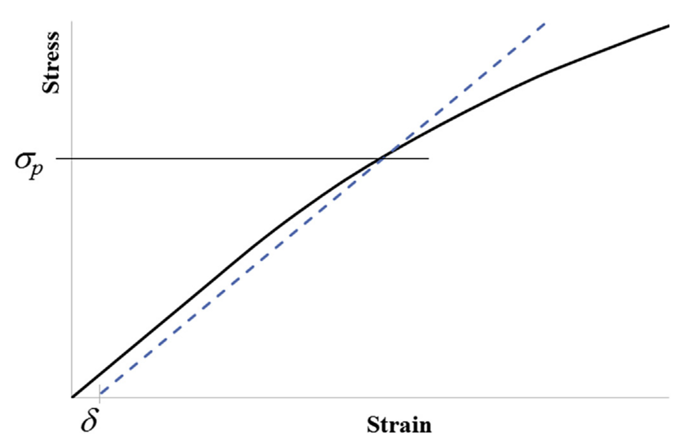

Fig. 3. Conventional definition of the proportional limit.