Available online at www.sciencedirect.com
ScienceDirect
Polymer Testing 26 (2007) 1068–1081
POLYMER TESTING
www.elsevier.com/locate/polytest

Property Modelling

# A model for non-linear creep in polypropylene

G.D. Dean*, W. Broughton

*Industry and Innovation Division, National Physical Laboratory, Teddington, Middlesex TW11 0LW, UK*

Received 11 May 2007; accepted 17 July 2007

**Abstract**

Measurements of the creep behaviour of a polypropylene polymer under uniaxial tension have been modelled using a stretched exponential function with four parameters. Non-linear behaviour arises because one of the parameters, related to a mean retardation time for the relaxation process responsible for creep, is dependent on stress. Creep curves measured under a uniaxial tensile stress and a uniaxial compressive stress of the same magnitude are different. The differences can be described by relating the retardation time parameter to an effective stress that is determined by the magnitude of both the shear component of the stress and the hydrostatic component. This analysis has then been generalised to enable expressions to be formulated for creep behaviour under an arbitrary multiaxial stress state. This requires an assumption that either the Poisson's ratio or the bulk modulus is independent of time. The validity of this assumption has been evaluated through comparisons of predictions of creep under a pure shear stress with measurements, which show that a time-independent Poisson's ratio is the better approximation. Although not the main theme of the paper, examples are given illustrating the dependence of model parameters on the structure of the crystalline and amorphous regions of the polymer. This is particularly relevant to the application of the model to the analysis of the creep behaviour of welded polypropylene where properties will, in general, be influenced by the heat treatment.


*Keywords:* Creep of polypropylene; Creep model; Non-linear behaviour; Creep under multiaxial stress

## 1. Introduction

Many grades of polymers have been developed with attractive properties for a wide range of applications. In some of these applications, the polymer is required to support significant levels of stress for extended periods of time. For these applications, a knowledge of the stress and strain levels in the component would be beneficial for competent design A finite element analysis can be used to calculate these distributions, and the results of an analysis can enable variations in the design of a component to be explored in order to reduce stress or strain levels in regions of stress concentration. In conjunction with a valid failure criterion for the polymer, it should be possible to decide safe working limits for the component. Confidence in predictions from these analyses requires the use of models that accurately describe the deformation behaviour of the polymer as well as accurate and relevant materials property data. Molecular relaxation processes in polymers span a wide range of time at ambient temperatures and are responsible for viscoelastic behaviour and mechanical properties that depend on time and loading history. Under

*Corresponding author. Tel.: +44 20 8943 6779.
*E-mail address:* greg.dean@npl.co.uk (G.D. Dean).

0142-9418/$ - see front matter 
doi:10.1016/j.polymertesting.2007.07.011

long-term loading, stiffness will decrease progressively with time, and stress and strain levels in the polymer will be very different from values calculated using property data obtained from tests of short duration. In particular, if deformation behaviour is non-linear, then this will give rise to a redistribution of stress and strain with strain levels increasing more rapidly than expected from a linear analysis.

The viscoelastic behaviour of polymers is usually characterised using creep and stress relaxation tests, where properties depend on the time under load, or dynamic mechanical tests, where the storage and loss moduli are observed to depend on the frequency of the stress and strain. These tests reveal that at low strains, behaviour is generally linear viscoelastic. In a creep test, the stress is held constant, and, with increasing time under load, the stiffness of the material will decrease. In general, the rate of decrease increases with stress giving rise to non-linear behaviour [1,2]. This non-linear behaviour is evident at lower stresses as the time under load increases. Material models for non-linear creep that are currently available in finite element packages have been developed to describe time-dependent deformation arising from plastic flow. These models are not able to describe the deformation behaviour of polymers which results from viscoelastic relaxation processes in the molecular network of these materials.

In this paper, a model for the creep deformation of polymers is explained. The model is developed using data measured under uniaxial tension and demonstrates how non-linear behaviour results from a dependence of an effective retardation time parameter in the model on stress. Creep tests under uniaxial tension and compressive stresses of the same magnitude are observed to be different under stress levels where behaviour is non-linear. This is explained by invoking that the retardation time parameter is dependent on stress state as well as stress magnitude. In this way, the model is extended to enable relationships to be proposed between stress and strain components under a multiaxial stress. This is essential if the model is ultimately to be used in a finite element programme for undertaking long-term stress analyses in components. The predictive accuracy of the model is assessed through comparisons of measured and calculated creep deformation under an applied shear stress.

The presence of welded joints in any structure, such as a pipeline can adversely affect the structural integrity and life expectancy of the joined system. Although significant research has been carried out to optimise hot plate welding (i.e. fusion welding) of thermoplastics, the relationship between long-term creep rupture and process parameters is not fully understood [3–5]. This paper also explores issues that need to be considered in order for the creep model to be applied to welded polypropylene, and other welded thermoplastics.

The material selected for this study is a grade of polypropylene used for the production of pipes, which may be joined by fusion welding. A knowledge of the long-term performance of the pipe is required for many applications, especially in the vicinity of a welded joint. The model should also be applicable to a wide range of polymers either without modification or with a small modification to the form of the creep function, depending on the type of polymer.

## 2. Material

The polypropylene material studied here was a commercial grade homo-polymer supplied by Polypipe Civils Ltd, which was manufactured by Oadby Plastics Ltd. The polymer was supplied in the form of an extruded sheet with a nominal thickness of 4.5 mm. Differential scanning calorimetry was used to determine the crystallisation and melting temperatures and degree of crystallinity. The melting and crystallisation temperatures were 122 and 157 °C, respectively. The estimated degree of crystallinity was 50%. The polypropylene had a density of 909 $kg/m^3$ and a filler content of approximately 0.8 wt%.

It is known from other work, for example [6–8], that the creep behaviour of polymers depends on the state of physical ageing of the polymer, which is determined by the time elapsed since the material was subjected to an elevated temperature such as processing from the melt. At the elevated temperature, the high molecular mobility ensures that the polymer structure is in equilibrium. As the temperature is lowered, changes in molecular conformations that are needed to maintain structural equilibrium are inhibited by reductions in molecular mobility. At ambient temperatures, these non-equilibrium structures are frozen in but have sufficient mobility for conformational changes to take place leading, progressively and over long periods of time, to structures closer to equilibrium. As physical ageing progresses and structural