Materials Science and Engineering A 385 (2004) 54–58

MATERIALS SCIENCE & ENGINEERING A

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Long-term bending creep behavior prediction of injection molded composite using stress–time correspondence principle

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Received 31 October 2003; received in revised form 6 April 2004

Abstract

In analogous manner to the time–temperature superposition principle, the stress–time superposition principle approach is used to predict long-term material creep behavior without extensive laboratory test time. The bending creep of the injection fiber glass reinforced polyamide is studied. An improved empirical model is used to construct the creep master curve, to take into account the strong non-linear behavior. An excellent superposition of curves is obtained and, in a long-term, an important curvature in the master curve is registered.

Keywords: Viscoelasticity; Creep; Bending; Superposition; Polyamide; Composite

1. Introduction

Prediction of the viscoelastic behavior of technical materials under given test condition is not only vital, but also a fine and a delicate problem. These difficulties are encountered with homogeneous materials such as neat polymers. Because of the complex morphology of composite materials, this attempt will be more complicated and therefore linear theories are useless. In this study the creep test under bending load is undertaken. Such loading configuration is encountered by many in-service technical composite components and gives a complex stress field in the specimen. Simple tests (traction, compression and shear test) give easier stress field but they cannot be combined to simulate the real bending state of the stress. Moreover simple tests are even difficult to conduct because of other extrinsic experimental effects.

2. Used models

In order to account for the non-linear viscoelastic behavior, several models are proposed in the literature. Green and Rivlin [1] proposed a combination of several multiple integrals, which include the non-linearity. Other representations use a simple integral formulation with a modification in the form to account for the non-linear behavior. Among these representations are, the modified superposition principle of Leaderman [2] and the non-linear form of Rabotnov [3]. Because of their complexity, these representations do not have a general solution and can only be used to treat specific cases. A recent non-linear representation is based on the irreversibility thermodynamic theory presented by Schapery [4,5]. In this representation the viscoelastic material is considered as a closed thermodynamic system maintained at a constant temperature. To overcome the difficulties encountered with the non-linear theoretical formulations, empirical approaches are quite often used. Many of these empirical approaches use the simple power law given by

$$\varepsilon(t) = r_0 t^n \tag{1a}$$

with

$$r_0 = k\sigma \tag{1b}$$

where $\varepsilon(t)$ is the creep strain, t the time, r_0 the power law coefficient and n is the power law exponent.

Among these approaches one could mention the form given by Nutting [6], in which an exponent greater than one affects the coefficient (the stress) in the simple power law.

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doi:10.1016/j.msea.2004.04.023

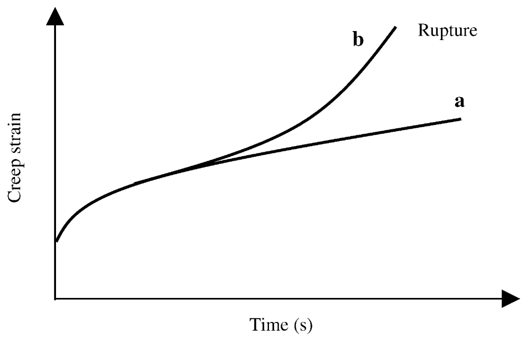

Fig. 1. Typical creep curve: (a) constant true stress, (b) constant load.

This leads to stress compliance sensitivity behavior of the material. Turner [7] gives a more general representation. He considers the coefficient of the power law as a function of stress and proposes a model given by the equation:

$$\varepsilon(t) = \varepsilon_0(\sigma) + f(\sigma)t^n \quad (2)$$

Andrade [8] demonstrates that under fixed load the creep curve has three stages. The first is characterized by a decrease in the strain rate. The second is characterized by a stationary strain rate, while the third is characterized by an increase in the strain rate up to rupture Fig. 1. The third stage is attributed to the variation of the real stress (contraction of the section). However, with a constant applied creep load, the specimen is really subjected to a variable true stress. It means that the increase in the creep strain is strongly affected by the material flaws (micro-cracks). The question relative to the existence of the third creep stage caused by a constant true stress remains unanswered. Andrade empirical law in unidirectional traction test has the following form:

$$\varepsilon(t) = \ln(1 + \beta t^{1/3}) + kt \quad (3)$$

where β and k are constants.

Plazek [9] notices that Andrade law agrees with experimental data of some polymers and glass for short time creep tests. However for long time creep tests, a misfit of the model to the experimental data is observed. To take into account the delayed elasticity and viscosity, Plazek modified Andrade's equation and proposes the following equation:

$$\varepsilon(t) = \left(C_g + C_0\psi(t) + \beta t^{1/3} + \frac{t}{\eta}\right)\sigma \quad (4)$$

where C_g is the instantaneous compliance; C_0, β the constants; η the viscosity; $\psi(t)$ the normalized function for the retarded elasticity.

Recently Hadid et al. [10] have proposed an explicit expression for bending creep of reinforced polyamide. The model is based on an improved power law. This model is found to give a good fit of the experimental data. The proposed model is given by the following equation:

$$\varepsilon(t) = a\sigma^b t^{c\,\exp(e\sigma)} \quad (5)$$

where a, b, c and e are fitting parameters.

In this formulation the two power law parameters are strongly affected by the stress level which agrees with the experimental study conducted on fiber glass reinforced polypropylene under bending load [11]. Karian [11] used the simple power law function to fit the creep of the material and found that the coefficient and the exponent of the power law vary with the applied stress.

Lou and Schapery [12] and Strganac and Hunter [13] used Schapery form given by the equation below to represent the creep behavior:

$$\varepsilon(t) = g_0C_0\sigma + g_1g_2C_1\left(\frac{t}{a_\sigma}\right)^n\sigma \quad (6)$$

where g_0, g_1, g_2 are non-linear material functions; a_σ the stress-dependent shift factor; C_1 and C_0 are compliance and initial compliance, respectively.

In Eq. (6), the non-linearity is represented by the material function and a constant exponent affects the time on one hand. On the other hand the $(g_1, g_2/a_\sigma^n)$ term has a hyperbolic sine function curve shape [12], which is close to the power function curve shape of the $(a\sigma^b)$ term given in Eq. (5).

The creep test measurement requires an extensive laboratory test time. The application of the time–stress superposition principle provides the capability to predict long-term material performance without a lengthy experimentation program. The compliance measured at a given stress is equivalent to the measurement of the compliance at another stress but at a compressed or an expanded time scale. This technique will be applied to predict the creep of the injection-reinforced polyamide 66 by the usage of the model proposed in Eq. (5).

3. Results and discussion

3.1. Experimental

The tested material is 43 wt.% fiber glass reinforced polyamide 66 Zytel 70G43L. Samples are produced by an Battenfeld BA-C 750/300 CNC press injection machine. The performed test is the three points bending creep test. Test specifications and specimen dimensions are in accordance with the ASTM D790 and the ASTM D2990 standards. The creep test duration is 30 min. Stress levels of 69, 132, 164, 195, 227, 240 and 259 MPa are applied. All the specimens are conditioned in 50% humidity atmosphere, and at a temperature of 23 °C until the specimen saturation is reached. The tests are performed on a JJ instrument M30K universal test machine. A computer equipped with a DT2820 Data translation card is used and data acquisition is accomplished with the ASYST 3.0 software program.

3.2. Results

The bending creep test of the 43 wt.% fiber glass reinforced polyamide, obtained at different stress levels, are

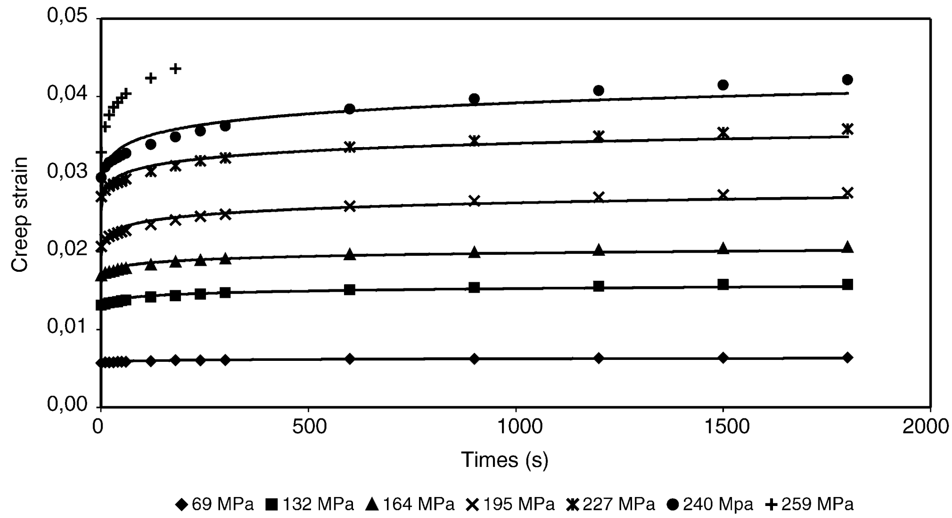

Fig. 2. Creep tests for reinforced polyamide 66.

shown in Fig. 2. The last applied stress (259 MPa) produces failure after 3 min and 30 s which is well before the end of the test duration. The solid points represent experimental data while the solid lines represent the power function interpolation for each stress level. The values of the power law parameters are reported in Table 1. The power law gives a good representation of the real creep behavior for all stress levels. In addition, the exponent increases with increasing stress level.

The creep prediction model given by Eq. (5) is calculated and compared to the experimental data as shown in Fig. 3. These results show a good creep strain prediction over a large stress range. It is noticed that the last creep stress level (240 MPa) is very close to the ultimate stress. For instance, for a stress level of 259 MPa, the test specimen breaks after only 3 min and 30 s. Except for the first 20 s of the creep test, the deviation between the model predictions and the experimental data does not exceed 4%.

3.3. Superposition principle

Initially the superposition principle was used to predict the viscoelastic material response at very large time scale. To reduce the time scale, the test temperature is raised. One can observe that a horizontal shift of a creep curve obtained at one temperature will result in an exact superposition of a creep curve measured at another temperature, which offers an extension of the curve measured at the second temperature. Mathematically this idea may be expressed as

$$\varepsilon(T_1, t) = \varepsilon\left(T_2, \frac{t}{a_T}\right) \tag{7}$$

where T_1, T_2 are the test temperatures; a_T the temperature shift factor.

Plazek [14] has shown the limitation of this procedure in a time–temperature range, moreover this technique is not accurate when applied to multiphase or semi-crystalline polymers. One notices that the change of the testing temperature leads to a variation in the volume of the material, which results in the material density change. As a consequence an additional correction of the shifting experimental data is necessary. Tobolsky [15] proposed a model to account for these considerations by adding further a slight vertical curve shift due to the variation of the material density.

In an analogous manner to the time–temperature superposition, a stress–time superposition approach is used, which

Table 1
Power law parameters

	Stress (MPa)					
	69	132	164	195	227	240
r_0	0.005	0.011	0.014	0.016	0.021	0.022
n	0.027	0.041	0.041	0.057	0.059	0.078

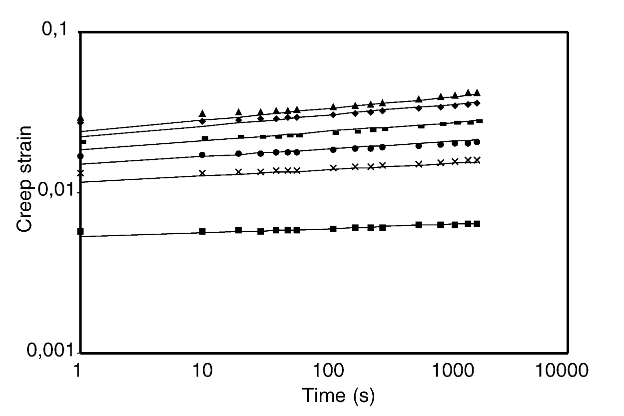

Fig. 3. Reinforced PA 66 creep model representation.

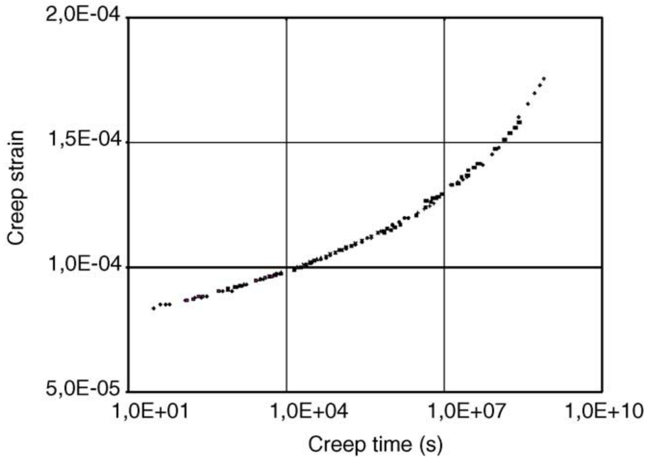

Fig. 4. Master creep curve for stress of 69 MPa.

may be expressed as

$$\varepsilon(\sigma_1, t) = \varepsilon\left(\sigma_2, \frac{t}{a_\sigma}\right) \tag{8}$$

where σ_1, σ_2 are the creep applied stresses; a_σ the stress shift factor.

Fig. 4 shows the master curve constructed from the experimental data of Fig. 3. Two aspects can be pointed out:

(i) A good superposition of the curves with a low data dispersion.
(ii) The apparition of an important curvature at the end of the master curve.

This curvature can be assimilated to the third stage creep as described by Andrade [8]. The use of the model given by Eq. (5) leads to an original contribution. One would like to recall that the conventional superposition principle uses a horizontal and a vertical curve shifting. However, in the Eq. (5) the exponent of the power law is stress sensitive and the curves in Fig. 3 do not have the same slope. Due to the change of the curve slope, the master curve in this case is not only obtained by a horizontal shift as explained in the previous paragraph, but each curve slightly rotates with respect to the next curve. The other empirical models do not allow this fact because of the constant exponent used in the modified power law.

The curvature in the master curve demonstrates the strong non-linearity behavior at long-term testing time, which can be attributed to several factors including:

(i) The multiplicity of the internal reorganization processes related to the material memory and the phases multiplicity.
(ii) The intrinsic non-linearity of the material.
(iii) The bending test itself. Because of the nature of the bending test, the matrix behavior predominates the response of the compressive side of the tested specimen [16].

Fig. 5 shows the variation of the shift factor versus the applied stress in a log–log scale. The plots are obtained as a result of the horizontal shifting curves of Fig. 3. The best fitting curve regression for plots suggests that the relation between the shift factor and the corresponding applied stress obeys to an exponent function. Strganac and Hunter [13] found similar curve tendency between the shift factor and the applied stress. The material studied was a technical film used in high altitude scientific balloons.

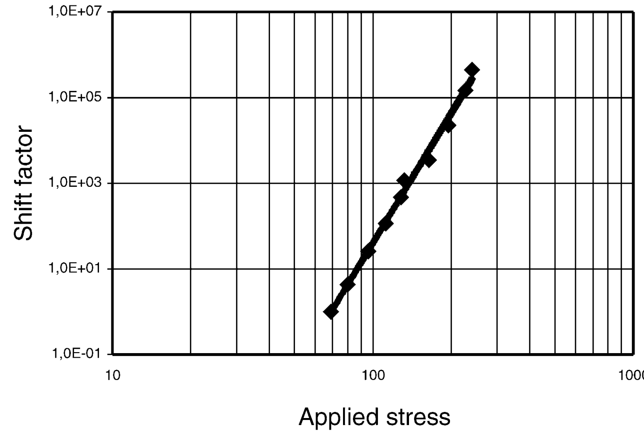

Fig. 5. Shift factor vs. stress.

Moreover by the use of the superposition principle one can predict the creep time rupture. Fig. 6 shows the variation of the creep rupture time versus the applied stress in a log–log scale. The solid line is an exponent law fitting function. It gives the curve tendency of the creep time rupture with respect to the applied stress. Fisher and Roman [16] have used a viscoelastic–plastic analysis to study a composite beam under bending load and they found that the logarithm of the lifetime creep is linear with the apparent creep stress, which agrees perfectly with the results shown in Fig. 6.

4. Conclusion

The study of the bending creep of injection fiber glass reinforced polyamide was conducted. The superposition

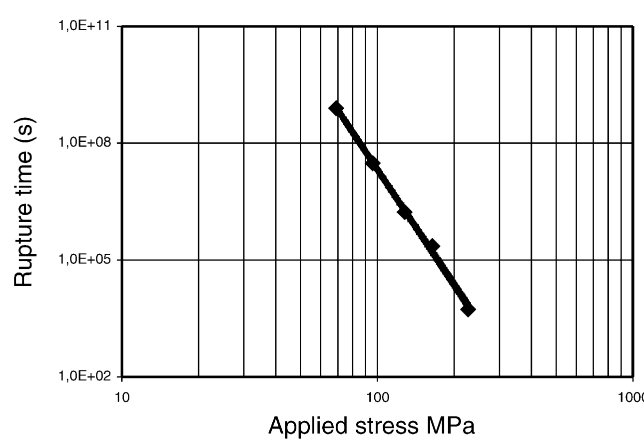

Fig. 6. Rupture time vs. applied stress.

stress–time principle is used to predict long-term material strain creep. The strong non-linearity of the viscoelastic behavior of the material on one hand and the stress field of the bending load on the other hand suggest that an improved creep empirical model has to be considered. The use of a proper model leads to a horizontal shift and a slight revolve of the creep curve with respect to the previous one, when constructing the master curve. The master curve is built and a perfect superposition of the curves at several stress level is obtained. The adequate model gives an important curvature of the master curve, due to the stress sensibility exponent of the model. With the present approach, an attempt is made to treat an important and a practical problem, which is not sufficiently explored.

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