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Test method

Assessment of the stepped isostress method in the prediction of long term creep of thermoplastics

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ABSTRACT

To predict long term creep of thermoplastics, methods based on the time–temperature superposition principle (TTSP) or on the time–stress superposition principle (TSSP) are commonly used. These methods enable the construction of a creep master curve without a lengthy experimental program. Recently, a new accelerated creep testing method, termed the stepped isostress method (SSM), was proposed and used to predict long term creep of technical yarns. This paper focuses on the processing aspects of the SSM test data and its validity in the creep prediction of thick thermoplastic specimens. Excellent correlation is obtained between the master curves constructed by the classical TSSP method and those constructed by the SSM method. The variation of the SSM testing parameters has no significant effect on the obtained master curves, which constitutes proof of the SSM robustness. Further, the trend of the SSM shift factors in terms of the creep stress obeys the Eyring equation.

1. Introduction

Thermoplastics materials are widely used in structural components subjected to high load levels. Because of the weak cohesion between the molecules of the thermoplastic polymers, those materials allow sliding of the polymer segments and exhibit significant viscoelastic behavior, even at ambient temperatures and under moderate stress levels. Furthermore, an increase in the operating temperature or in the stress level quickly brings on nonlinear viscoelastic behavior.

A creep test is conducted in order to characterize the tendency of the material to deform permanently under constant loading. The rate of the creep deformation is a function of material properties, exposure time, exposure temperature and applied loads. The risk over time rises when the creep deformation becomes large enough to exceed the design limit for an in-service part. In order to predict the long-term material creep, the testing needed may require extensive laboratory time. The application of time–temperature or stress–temperature superposition principals provides the capability to predict the long-term material performance very much beyond the creep test period.

1.1. Time–temperature superposition principle

Leaderman [1] was among the first to emphasize that a portion of the creep curve obtained at temperature T_r is identical to a creep curve obtained at temperature T_i, if all the time values at T_i are multiplied by a constant factor. This means that the creep curves plotted versus log time at T_i temperatures are identical to a corresponding portion of a

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creep curve at T_r but with a shift in the origin of the log time axis. Mathematically, this idea is expressed by the following equation:

$$\varepsilon(T_r, t) = \varepsilon(T, t.a_T) \tag{1}$$

where T_r and T are the test temperatures while $\boldsymbol{a_T}$ is the temperature shift factor.

Tobolsky et al. [2] were the pioneers in the use of the time–temperature superposition principle in the construction of the master curve representing the creep relaxation modulus over a very long time period. Plazek [3] analyzed the temperature dependency of creep in term of free volume. He proposed a relationship of the relaxation modulus E_T at temperature T in term of the relaxation modulus at the reference temperature T_r, as follows:

$$\frac{T\rho_r}{T_r\rho}E_T(t.a_T) = E_{T_r}(t) \tag{2}$$

The quantity a_T is a function of temperature only and, from Eq. (1), is defined as equal to unity at T_r. The quantities ρ_r and ρ are the material densities at T_r and T respectively. The ratio ρ_r/ρ allows one to take into account the variation of the density of the polymer due to temperature. However the T_r/T ratio, allows an adjustment regarding the kinetic aspect of the creep process. It is assumed that the material does not change its structure with time, so that the time–temperature superposition (TTS) principle is still valid.

1.2. Time–stress superposition principle

In an analogous manner to time–temperature superposition, a time–stress superposition principle (TSSP) approach is used to build creep master curves. The TSSP assumes that an additional stress provides energy to the tested material similar to the heat effect. Mathematically, the TSSP can be expressed as follows:

$$\varepsilon(\sigma_1, t) = \varepsilon(\sigma_2, t.a_\sigma) \tag{3}$$

where σ_1 and σ_2 are creep stresses while a_σ is the stress shift factor.

The TSSP has been used [4–9] to predict the long term creep of viscoelastic materials. Luo et al. [4] used the TTSP to construct, for a PMMA commercial grade, a smooth master creep compliance curve for a period of 290 days from creep curves achieved over 4000 seconds and under various stress levels. The authors verified that the time–temperature shift factors are dependent on stresses at which the shifts are applied, and that the time–stress shift factors are dependent on temperatures at which the shifts are applied. Jazouli et al. [5] evaluated the long term non-linear creep of a polycarbonate at room temperature. Compliance creep tests, obtained at nine different stress levels of one hour duration, were determined and shifted along the logarithmic time axis to get a master compliance curve. Qaiser et al. [6] generated a creep curve for an extended time period for an amorphous polycarbonate from short-term creep curves obtained at different stress levels. Additionally, they checked the effects of physical aging on the master curve. Hadid et al. [7] investigated the non-linear creep of fiber reinforced polyamide by the use of an improved empirical creep model [8], on its basis they constructed a smooth creep master curve [7]. Considering a nanocomposite with polyamide matrix, Starkova et al. [9] were able to build a master curve for time periods more than 60 times than the test time.

Furthermore, it should be mentioned that the stress–time shift factor can be interpreted as the transition from the laboratory testing time to the intrinsic time of the material. In the construction of the master curve, Hadid et al. [7] found an exponential relationship between the stress shift factor and the applied creep stress:

$$Log(a_\sigma) = b.\sigma \tag{4}$$

However, Jazouli et al. [5] and Qaiser et al. [6] proposed another expression for the stress shift factor using the free volume approach. The expression assumes an exponential relationship in terms of stress:

$$Log(a_\sigma) = \frac{C_1(\sigma + \sigma_r)}{(C_2 + \sigma - \sigma_r)} \tag{5}$$

where C_1 and C_2 material constants

In summary, the works mentioned above [4–9] constitute examples of the use of the classical time–stress superposition principle for different kind of materials; neat polymers, reinforced polymers and nanocomposites. This confirms the huge interest and the need for the superposition tool in the prediction of the viscoelastic material behavior in the very long term.

1.3. The stepped isothermal method SIM

Stepped Isothermal Method (SIM) is a derivative of the classical TTSP method. The SIM was first established by Thornton et al. [10] to predict the long-term creep behavior of geogrids used in soil reinforcement applications. Later, Alwis [11,12] applied this technique to characterize the creep of Kevlar 49 yarns.

In TTSP testing, a single specimen is subjected to a constant load at a certain temperature and a plot of creep strain vs. log (time) is produced. Similar experiments are conducted on different specimens at different temperatures. A reference temperature is selected, by applying the principle of superposition, all individual curves are shifted along the log time axis. Then, a creep master curve is produced at the reference temperature. In contrast to TTSP, SIM involves loading a single specimen subjected to a constant load. The test temperature is increased in a series of controlled steps. At each temperature step, a creep curve is obtained; those curves are processed and transformed in several independent creep curves for each temperature level. A creep master curve, at a reference temperature, is then created in analogous manner to the TTSP method.

Several authors used the SIM technique to predict the long term creep or the creep rupture time [13–20]. SIM exploits a specificity of technical yarns, the high surface-to thickness ratio, which allows very fast heating of the whole specimen. When dealing with thick specimens concern regarding the rapid heating and the non-uniform temperature distribution in the specimen needs to be investigated.