

Predicting the fatigue life of polycarbonate

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Predicting the fatigue life of polycarbonate

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Summary: In this study a constitutive modelling approach is used to predict the fatigue life of polycarbonate. After a thorough investigation on the heating effects, accurate lifetime predictions are made under isothermal as well as non-isothermal conditions. Moreover, it is shown that cyclic fatigue has an accelerated effect on the ageing behaviour.

Introduction

The use of constitutive equations to predict deformation and failure of polymers based on the material's intrinsic behaviour, recently led to accurate creep-lifetime predictions of polycarbonate (PC) [1], as shown in figure 1a. The authors observed that the ductile failure under constant load is governed by the strain softening behaviour, which is triggered by a time-dependent accumulation of plastic strain. This is illustrated in figure 1b, which shows the strain response of PC under a constant load of 55 MPa. It can be seen that just after applying the load, the sample deforms homogeneously with a moderately increasing strain. However, suddenly the creep rate starts to increase until a neck has formed, which is considered as failure of the sample. Another key observation was that the ageing kinetics are accelerated by stress [2], and therefore essential for quantitative creep-lifetime predictions. Samples exposed to cyclic fatigue show similar failure behaviour. Therefore in this study, the same numerical approach is followed in an attempt to predict the cyclic fatigue life of PC. However, due to the visco-elastic behaviour of polymers and their low thermal conductivity hysteretic heating as a result of cyclic loading will greatly affect the failure behaviour. An extensive review on the fatigue behaviour of polymers is written by Lesser [3], where he distinguishes two failure mechanisms, a thermally dominated and a mechanically dominated mechanism for polyacetal and nylon-6,6. In order to evaluate the failure mechanisms of fatigue loading in PC, the experimental procedure as applied by Lesser is repeated. Firstly, this study investigates the heat generation during fatigue of PC samples with different thermal histories by infrared thermography. Subsequently, lifetime predictions, both isothermal and including heating, are compared to results of the fatigue experiments.

Numerical Modelling

An elaborate description of the elasto-viscoplastic model used in this study is given in the work of Klompen et al. [2]. An important function in this model describing the flow behaviour is the viscosity η , which depends on the equivalent stress $\bar{\tau}$, pressure dependence μ and intrinsic strain softening $R(\bar{\gamma}_p)$:

$$\eta = \eta_{0,\alpha} \cdot \frac{\bar{\tau}/\tau_0}{\sinh\left(\bar{\tau}/\tau_0\right)} \cdot \exp\left[\frac{\mu p}{\tau_0}\right] \cdot \exp\left[S_a R(\bar{\gamma}_p)\right]$$

where S_a represents the thermo-mechanical history of the material. This is the only parameter which is changed, according to the initial thermal history of the samples, to make the fatigue life predictions.

Materials and Methods

The material investigated is polycarbonate, specifically the grades Lexan141R and 101R, which were kindly supplied by GE Plastics. The Lexan141R material was injection moulded into tensile bars according to ASTM-D638, having a gauge length of 100 mm and cross-sectional area of $3 \times 10 \text{ mm}^2$. Samples of different age are produced by cooling the samples at a mould temperature of 30°C and 130°C . All Lexan101R samples (gauge length: 50 mm, cross-sectional area: $1 \times 5 \text{ mm}^2$) are cooled in the mould at 30°C . Subsequently, a number of these samples are aged at 120°C in an air circulated oven for 72 hours. In this approach, the thermal history of the samples is represented by the state parameter S_a , which is directly related to the yield stress of the material. The S_a -values, determined by a tensile test at 10^{-3} s^{-1} , are presented in table 1. Tensile tests and fatigue tests were performed on a servo-hydraulic MTS Elastomer Testing System 831. During these experiments the temperature was kept in a temperature chamber. The infrared temperature measurements were performed with a ThermaCAM 575 (FLIR Systems AB). Prior to use, the camera was calibrated by comparing its temperature to that of a thermocouple embedded in a sample of about 40°C .

Table 1: Thermal history of the PC samples represented by the state parameter S_a .

| | Lexan141R | | Lexan101R | |
|-------------------|-------------------------------------|--------------------------------------|-------------------------------------|------------------------------|
| thermal treatment | $T_{\text{mould}} 30^\circ\text{C}$ | $T_{\text{mould}} 130^\circ\text{C}$ | $T_{\text{mould}} 30^\circ\text{C}$ | annealed 120°C |
| S_a | 29.5 | 33.8 | 27.3 | 43.6 |

Results

Thermally dominated and mechanically dominated failure

In order to evaluate the failure mechanisms of fatigue loading in PC, the experimental procedure as applied by Lesser [3] is repeated; at a frequency of 2 Hz, a sine-wave of minimum stress σ_{min} of 2.2 MPa and variable maximum stress σ_{max} is applied. Figure 2a shows the time-to-failure of the two different sets of Lexan141R samples. Identical to Lesser's observations a thermally and a mechanically dominated regime are recognized. The stresses at which the transition occurs are 56 MPa and 61 MPa, respectively. In addition, heating of the samples is recorded by infrared thermography. In figure 2b it can be seen that indeed there is a large temperature rise for stresses in the thermally dominated regime until failure occurs. Also at the transition stresses of 56 MPa and 61 MPa and below the sample temperature increases, but stabilises before thermal failure occurs.

Fatigue loading under isothermal conditions

To elucidate the effect of hysteretic heating on failure, the two sets of 1 mm thick Lexan101R samples are dynamically loaded in air at 22°C and compared to similar samples loaded under isothermal conditions. The isothermal conditions are approached by loading the samples in a Plexiglas cylinder filled with water of 21.5°C flowing at a rate of 0.045 m/s. Figure 3a shows the lifetime curves for both sets of samples. First, the samples with a S_a -value of 27.3 are regarded. The samples fatigued in air typically exhibit failure behaviour, which can be distinguished by a thermally dominated regime and a mechanically dominated regime. The transition occurs at 55 MPa. The same figure shows that the isothermal conditions have a profound, but expected effect. The fatigue life increases substantially at stresses above the transition stress of 55 MPa, indicating that the effect of thermal heating on failure is significantly reduced. Concerning the Lexan101R with a S_a -value of 43.6, there is hardly any difference in lifetime between the samples fatigued in air or flowing water. Hence, the role of hysteretic heating on fatigue life decreases with increasing initial age of the sample.

Lifetime predictions

The performance of the model is examined by assuming isothermal conditions and by including hysteretic heating (non-isothermal). To simulate the heating, the temperature observations recorded by an infrared camera during the experiments are implemented in the

model. Figure 3b shows the initial heating rate vs. the applied maximum stress for both sets of Lexan101R samples (symbols). The solid lines in the figure represent an exponential fit through the experimental data. The experimental heating is simulated by implementing the heating rate given by the fit up to 150 cycles. According to experimental observations, this was the point at which the temperature stabilised. Figure 4a compares the fatigue life predictions to the experimental results. First, the samples with a S_a -value of 43.6 are considered. It can be seen that the predictions under isothermal conditions (solid line) closely resemble the experiments performed in water and air. Since this isothermal model also predicts the failure of samples under non-isothermal conditions, it confirms that for samples with a high initial age, heating of the sample hardly has any effect on the time-to-failure. Only at lower stresses, and hence larger cycle times, a subtle overestimation of the time-to-failure is made. This is explained by the fact that in the course of time the temperature of the water (in which the sample is loaded to approach isothermal conditions) increased from 21.5°C to 23°C due to a higher ambient temperature. Since at the lower S_a -value of 27.3 heating strongly affects the fatigue life, both isothermal and non-isothermal predictions are made. Even though the isothermal model (solid line) slightly underestimates the time-to-failure of the samples fatigued under isothermal conditions (squares) at high stresses, the slope of the curves is the same. The same can be observed for the predictions (dashed line) and experiments (circles) under non-isothermal conditions. However, at lower stresses and thus larger times, it appears that the experimental and predicted fatigue life diverge from each other, which was not observed for the samples with the S_a -value of 43.6. This can be rationalised by the fact that stress accelerates the ageing behaviour of PC, as already pointed out by Klompen et al [2]. Apparently, the initial age of a samples annealed at 120°C for 3 days ($S_a = 43.6$) is too large for ageing effects to occur within the experimental timescales, in contrast to the samples with a low S_a -value. To validate this hypothesis, the yield stress evolution of these samples during fatigue loading is studied. Therefore, fatigue tests were performed at $\sigma_{\max} = 50$ MPa and $\sigma_{\max} = 55$ MPa and interrupted at 10^2 , 10^3 , 10^4 and 10^5 s. Next, the yield stress is determined by a tensile test at 10^{-3} s^{-1} and compared to the yield stress of non-fatigued samples. From figure 4b, it becomes clear that the yield stress increases substantially (up to 4MPa) during fatigue loading. This means that the ageing kinetics, as for creep testing, have a significant effect on the time-to-failure. Similar observations on PC samples with a S_a -value of about 30.8 were made by Li et al. [4]. They only observe a modest increase in yield stress, since their maximum applied σ_{\max} was only 30 MPa. In conclusion, to make quantitative accurate lifetime predictions, not only a proper understanding of the thermal effects is required, but also the accelerated effect of fatigue on ageing needs attention.

References

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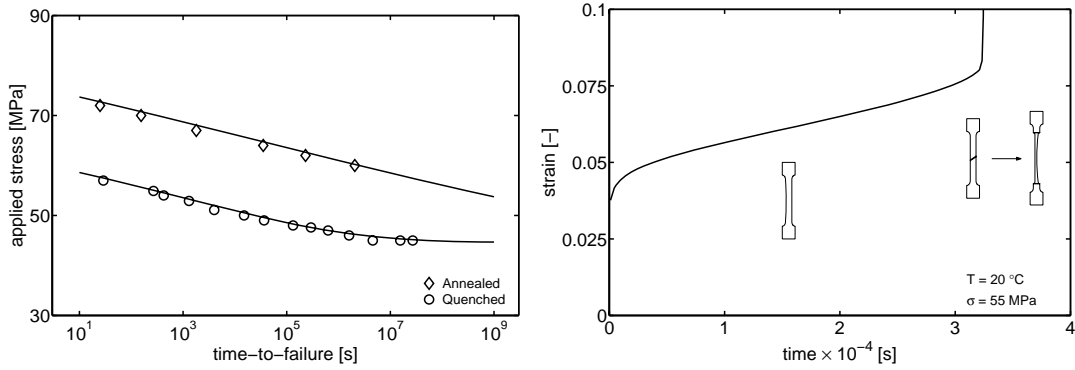


Figure 1: a) Creep-lifetime predictions on PC by constitutive modelling [2], b) Failure of PC is triggered by the accumulation of plastic strain.

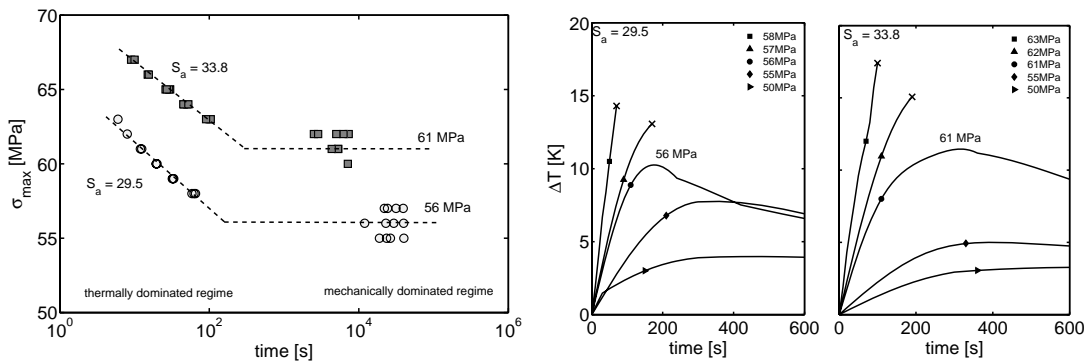


Figure 2: a) A thermally and mechanically dominated regime can be recognised in the failure of PC, b) Heating of PC during fatigue measured by infrared thermography.

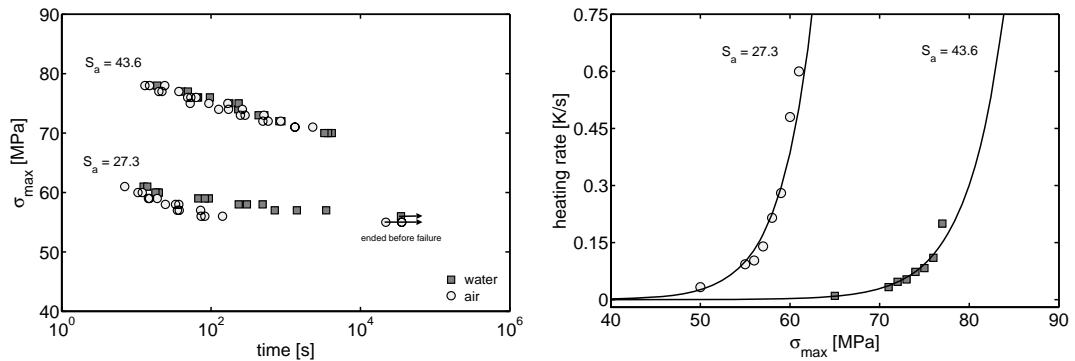


Figure 3: a) The influence of thermal history on the fatigue failure of Lexan101R under isothermal and non-isothermal conditions, b) Influence of maximum stress on the rate of hysteresis heating for two different thermal histories.

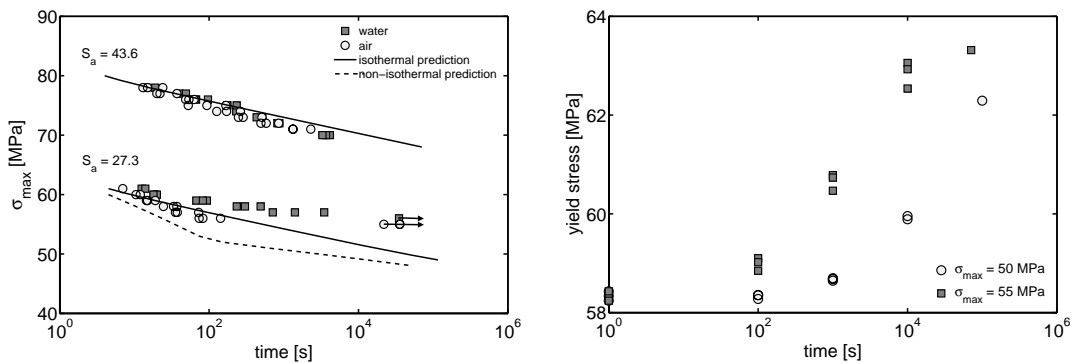


Figure 4: a) Fatigue-life predictions on Lexan101R, b) increase of yield stress as a result of fatigue-accelerated ageing.