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Competition between plasticity-controlled and crack-growth controlled failure in static and cyclic fatigue of thermoplastic polymer systems

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ABSTRACT

Creep rupture (plasticity controlled failure) and slow crack growth are two important failure mechanisms that limit the lifetime of polymer constructions under load. Since both require different approaches to predict lifetime or improve the materials performance, the identification of the active mechanism is essential. Problems arise when the macroscopic failure mode is identical (i.e. brittle) in both cases (e.g. in composite systems).

In this study, it is shown that both mechanisms can be distinguished effectively by comparing lifetimes in static and cyclic fatigue. At equal value of the maximum load, plasticity-controlled failure is postponed in cyclic loading, whereas crack propagation is significantly accelerated. The origin of this specific response is discussed, and its generic character demonstrated for a great variety of engineering polymers.

1. Introduction

Failure under static or cyclic loading conditions is a major concern in the application of polymers in structural applications; it is not the question *whether* it will fail, but rather *on what time scale*. From efforts to develop predictive methods, and work on pressurized polyethylene pipes in particular, it is known that there are three failure mechanisms that limit the lifetime of polymers under load: I) plasticity controlled failure (creep rupture, delayed yielding), II) slow crack growth, and III) molecular degradation [1,2]. All three mechanisms act in parallel, creating three distinct regions in time where failure is dominated by one of them. In engineering practice, the focus is mostly on regions I and II, since, with advancement in stabilization chemistry, molecular degradation is no longer regarded as a limiting factor [3].

In many cases, these two failure mechanisms are easy to distinguish, since plasticity controlled failure is often accompanied by a ductile macroscopic failure mode, displaying large local plastic deformation zones [4,5], whereas in crack growth brittle macroscopic dominated failure mode is observed; precursors of cracks grow until one of them becomes unstable or causes functional problems [2,6,7]. Unfortunately, however, this strong and obvious contrast between them is not universal. In some cases of plasticity controlled failure the strain localization can be extreme, resulting in a “brittle” macroscopic appearance [8]. This can be related to changes in thermal history (progressive physical ageing [9,10], cooling rate [11]), a decrease in molecular weight [5,12], or to fibre reinforcement [13]. In such cases, one could erroneously conclude that the lifetime is dominated by slow crack growth, while its origin is actually local accumulation of plastic strain. A misinterpretation of the active failure mechanism may have serious consequences. On the one hand, the prediction of the lifetime requires a quite different approach for plasticity controlled failure [14–16] compared to slow crack growth [2,7,9]. On the other hand, strategies to improve the slow crack growth performance are generally not effective, or even counterproductive, for the plasticity-controlled failure mode. A prime example is the introduction of a soft dispersed phase in the matrix material. Although this effectively improves crack growth resistance [17,18], it strongly reduces the yield stress leading to a decreased lifetime in the plasticity-controlled region [19,20]. It is, therefore, evident that the correct identification of the active failure mechanism is of the utmost importance.

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In this study, we will present an easy method that can unambiguously identify the active failure mode in all cases, and proves especially useful in those where the macroscopic failure mode does not allow clear differentiation. The method is based on direct comparison of the lifetime in static and cyclic fatigue, at equal value of the maximum stress applied. To clarify why plasticity-controlled failure and crack-growth show a quite different response upon a change in loading history from static to cyclic loading, the phenomenology of each failure mechanism will be elucidated, along with the basic principles of the predictive methods applicable. Subsequently, the versatility of the method will be demonstrated on a large selection of engineering plastics, including a number that are fibre-reinforced.

2. Phenomenology of time-dependent failure

2.1. Crack-growth controlled failure

Small initial flaws within or on the surface of the material result in local stress concentrations that can initiate/form cracks that can, subsequently, gradually grow to a critical size and lead to a loss of structural integrity [2,6,7].

Stresses around a crack tip are quantified using Linear Elasticity Fracture Mechanics (LEFM) [21], and scale with the stress intensity factor, K, which for a crack opening loading (mode I) is defined by:

$$K_I = Y\sigma\sqrt{\pi a} \tag{1}$$

where σ is the remote stress, a the crack length and Y a geometry factor that usually depends on the crack length a. The crack propagation rate $\dot{a}$, is related to the stress intensity factor by a power law relation known as the Paris law [22]:

$$\dot{a} = A \cdot K_I^m \tag{2}$$

In a double logarithmic plot of the crack propagation rate versus the stress intensity factor, the pre-factor A is the intersection at $K_I = 1$, while m is the slope. Using these crack propagation kinetics, the time to failure, t_f, caused by slow crack growth in a specimen under constant load, can be determined by integration of the crack propagation rate, Equation (2), from the initial flaw size, a_i, to the crack length at which failure occurs, a_f [2,7,23]. In combination with Equation (1), this yields:

$$t_f - t_i = \frac{1}{A\sigma^m} \int_{a_i}^{a_f} \frac{da}{\left(Y\sqrt{\pi a}\right)^m} \tag{3}$$

It is often assumed that initial cracks of length a_i are already present in the material, implying that the time to initiate a crack $t_i = 0$. In that case, Equation (3) reduces to:

$$t_f = \left(\frac{\sigma}{c_f}\right)^{-m} \text{ with } c_f = A^{-\frac{1}{m}} \cdot \left(\int_{a_i}^{a_f} \frac{da}{\left(Y\sqrt{\pi a}\right)^m} \right)^{\frac{1}{m}} \tag{4}$$

The application of this approach, where a_i is essentially used as a fitting parameter, usually yields an accurate description of the failure kinetics (dependence on applied load and temperature) [2,7,24]. This clearly suggests that, even if an initiation process occurs, the time required has to be negligible compared to the total lifetime.

Equation (4) illustrates that the time-to-failure is also presented by a power law, with a scaling factor, c_f, representing the applied stress that leads to a lifetime of 1 s. In a double logarithmic plot of applied stress versus the time-to-failure, a linear relation is typically found, while the slope equals the reciprocal of the Paris law exponent m.

From experimental studies on crack growth kinetics, it is known that in cyclic loading the crack propagation rate is significantly enhanced [23–28]. In cyclic fatigue, one can vary the minimum load, mean load, maximum load, load amplitude, and of course frequency. In this work, the cyclic load signal is characterized by the frequency, f, the load maximum, and the load amplitude, expressed as the load ratio, R:

$$R = \frac{F_{min}}{F_{max}} \tag{5}$$

As illustrated in Fig. 1, $R = 1$ represents static loading conditions, while a decreasing R-value increases the load amplitude. The stress intensity factor at the load maximum, K_{max}, is used here as a reference for the load applied, and the corresponding fatigue crack propagation rate (Equation (2)) is, consequently, redefined to:

$$\dot{a} = A \cdot K_{max}^m \tag{6}$$

The pre-factor A shows a clear dependence on load ratio, frequency, temperature and molecular weight, whereas the slope m remains approximately unchanged [25,28–31]. Likewise, in the prediction of time-to failure, Equation (4), only the scaling factor c_f will vary with load ratio and frequency.

When cyclic fatigue is performed on Compact Tension specimens (CT-specimens, made of polyetherimide (PEI 1010), here just as an example), the crack propagation rate increases with decreasing load ratio R (increasing load amplitude), see Fig. 2a. As a result, the time-to-failure of smooth unnotched bars in cyclic fatigue also decreases with decreasing load ratio (Fig. 2b).

This enhanced crack propagation was suggested to be related to failure of fibrils bridging the craze zone proceeding the crack tip [31,32]. The fibrils support part of the load, which, in static loading, causes them to slowly break down due to disentanglement or chain scission [33]. During cyclic loading, the fibrils at the crack tip are alternatingly stretched and compressed. This can lead to bending and, for sufficiently large amplitudes, buckling or even crushing of fibrils [34], which provokes fibril failure and increases the crack propagation rate. As a result, the times-to-failure decrease under cyclic loading with larger load amplitudes (smaller load ratio's R) and at higher frequencies [34,35].

Fig. 2a and b clearly show that the slope, determined by the Paris law exponent, m, is independent of R-value, and the only variable changing with the load ratio is A and, consequently, c_f. The same

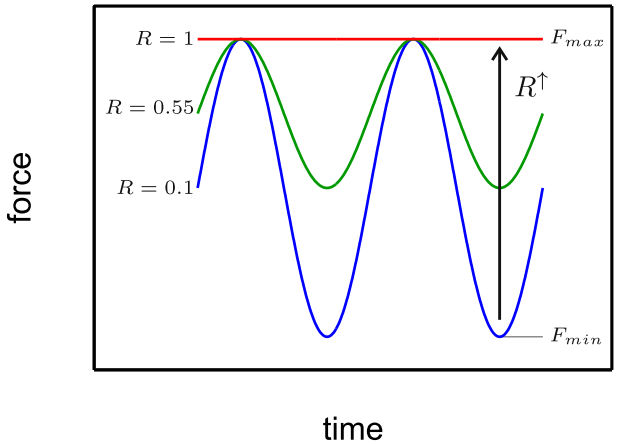

Fig. 1. Schematic illustration of the static and cyclic loading and how the load ratio R effects the load amplitude.