NORMALIZATION OF FATIGUE CRACK PROPAGATION BEHAVIOR IN POLYMERS

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ABSTRACT

Several empirical correlations of FCP data for semi-crystalline and amorphous polymers were attempted as a function of $\Delta K/E$, $\Delta K/COD$ and $\Delta K/K_{cf}$. Only normalization with respect to toughness seemed to provide a reasonable correlation of fatigue data from numerous polymers. A linear relationship was found between ΔK^* (the value of ΔK required to drive a crack at a constant value of da/dN) and K_{cf}. These results suggest basic similarities between the mechanisms of fatigue fracture and final failure in polymeric materials.

KEYWORDS

Fatigue crack propagation, fracture mechanics, polymers, fracture toughness, elastic modulus, COD, normalization.

INTRODUCTION

Within the past decade, the empirical modelling of fatigue crack propagation (FCP) in polymers in terms of fracture mechanics concepts has been quite successful (Hertzberg and Manson, 1980). Thus, while more elaborate formulations have been proposed, FCP response can often be characterized (at least over a reasonable range of ΔK) in terms of the Paris-Erdogan (1963) relationship:

$$da/dN = C\ \Delta K^n \qquad (1)$$

where da/dN is the crack growth rate per cycle, ΔK is the range in stress intensity factor, and C and n are material constants. Equation 1 has also been used successfully to describe the behavior of many metals.

The range of behavior (Fig. 1) expressed by Eq. 1 is larger for polymers than for metals. In the case of polymers, ΔK for a given growth rate may vary by more than an order of magnitude from one polymer to another; the behavior of most metals would be encompassed by a smaller ΔK increment (about six-fold). Figure 1 illustrates the considerable differences in fatigue crack propagation (FCP) resistance among numerous

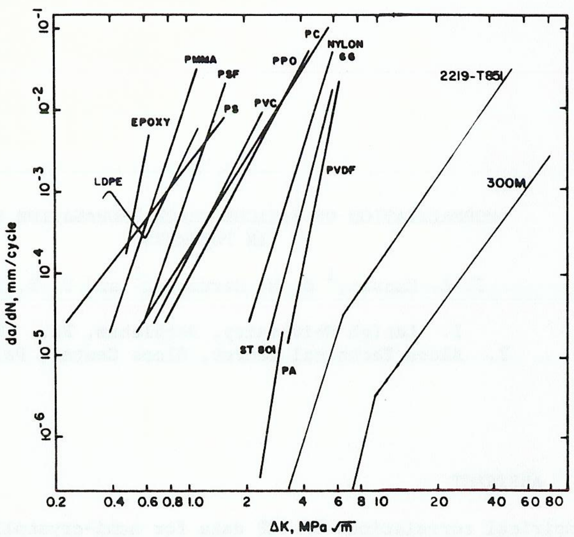

Fig. 1. FCP behavior of amorphous and semi-crystalline polymers (Hertzberg and Manson, 1980), 2219-T851 wrought aluminum alloy (Bucci, 1979) and 300M high strength steel alloy (Ritchie, 1977).

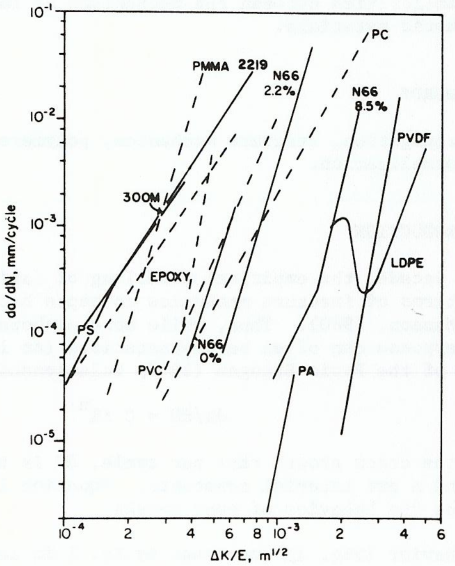

Fig. 2. FCP behavior of plastics and metals as a function of ΔK/E. Dotted lines represent amorphous plastics. Aluminum and steel alloys referenced in Fig. 1. Note superiority of semi-crystalline polymers.

polymeric solids. It is evident that with the exception of low density polyethylene (LDPE), semi-crystalline polymers are more fatigue resistant than are amorphous polymers. This observation confirms the results of several preliminary studies (the behavior of LDPE is reconsidered below) (Hertzberg and Manson, 1973, 1978; Hertzberg, Nordberg and Manson, 1970; Hertzberg, Skibo and Manson, 1978). It is also interesting to note from Fig. 1 that FCP rates at a given ΔK level are much lower in typical aluminum and steel alloys than in any polymeric solid. From an empirical point of view then, a question arises: can one normalize these results in a manner that could simplify the correlation of data?

ANALYSIS

One approach is to normalize ΔK with respect to Young's modulus E (if, in fact, E differs from one material to another) (Pearson, 1966). Such a normalization with respect to modulus provides a comparison of cyclic response on the basis of equal strains. When this is done, the ranking of metals versus polymers is changed drastically (Fig. 2). Now we find that metal data (which are normalized quite nicely) compare with the poorest amorphous polymers; the semi-crystalline polymers are decidedly superior to both metals and amorphous plastics in terms of their FCP resistance. With the exception of LDPE which ranks higher on a normalized ΔK/E basis (note that LDPE now conforms to the overall superior response of semi-crystalline polymers), there still remain very large differences in FCP response among most polymers. The inability to correlate polymer fatigue data on the basis of modulus has been noted previously (Manson and Hertzberg, 1973), and seems to indicate some fundamental differences in crack growth behavior among different polymers. On the other hand, when ΔK data for a given material (e.g., nylon 66 with variable water content) are normalized with respect to E, a strong correlation in FCP rates is obtained (Bretz, 1980).

The relative differences in FCP behavior when compared on the basis of ΔK and ΔK/E have important implications with regard to component design. Some engineering structures experience load-controlled conditions, while others are subjected to strain or deflection-controlled cyclic histories. In the case of load-controlled situations, the most fatigue-resistant material is one which exhibits the lowest FCP rates at a given stress (i.e., ΔK) level. Therefore, a material for load-controlled applications should be chosen by comparing FCP behaviors on the basis of ΔK. In a strain-controlled component, however, maximum fatigue resistance is achieved by minimizing the crack growth rates for the operating strain range, Δε, which requires a comparison of crack growth rates on the basis of ΔK/E. For example LDPE appears to be a poor material for load-controlled conditions (Fig. 1) but a good choice for applications involving cyclic strain control (Fig. 2). This important distinction must be kept in mind when making decisions involving materials selection for component design.

Proceeding further, an attempt was made to normalize FCP data as a function of the crack opening displacement (COD) where COD = $\Delta K^2/E\sigma_{ys}$ (see Fig. 3). While the data for metal alloys is again normalized and found once more to be comparable to the results for the amorphous polymers, the range of fatigue response of polymers as a class is, indeed, great. For example, at a crack growth rate of 10^{-4} mm/cyc, COD values in polymers vary by more than two decades! Clearly, variations in polymer fatigue response cannot be rationalized in terms of differences in COD for the various materials.

Whereas the normalization of polymer FCP data with respect to E and COD did not appreciably narrow the range of fatigue behavior (i.e., the horizontal span from

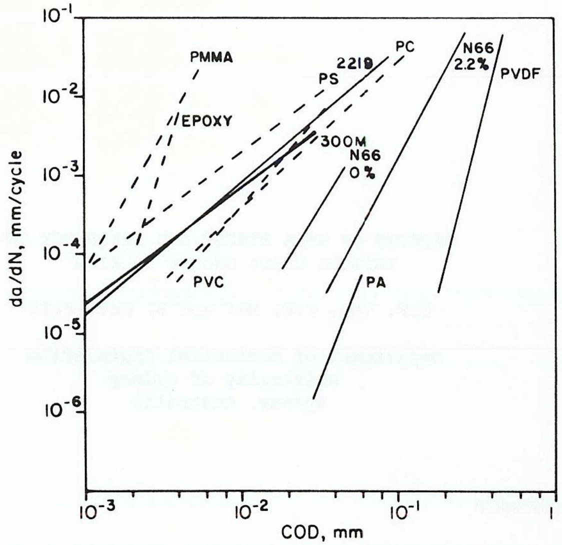

Fig. 3. Crack growth rates as a function of crack opening displacement (COD). Poor correlation is noted except for metal alloys.

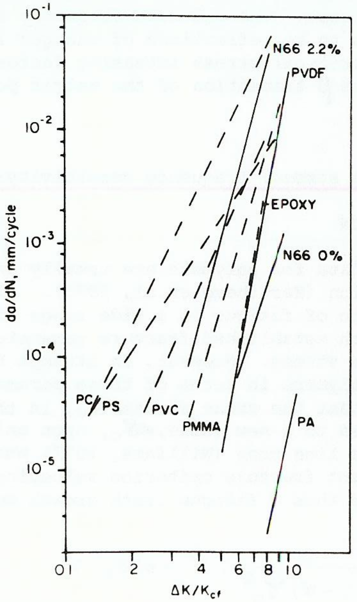

Fig. 4. Polymer FCP data normalized with respect to K_{cf}. Note general narrowing of data band as compared with Figs. 1-3.

the "best" polymer to the "worst"), a comparison based on $\Delta K/K_{cf}$ (Fig. 4) did reduce this span.[+] For example, at $da/dN = 10^{-4}$ mm/cyc, the data in Fig. 1 cover a range of one decade in ΔK, while this range is roughly 1/2 decade when normalized with respect to K_{cf}. Furthermore, even better data agreement is indicated at higher crack growth rates. This correlation, though admittedly broad, nevertheless illustrates that there is a correspondence between increased fatigue resistance and increased toughness in polymeric materials. These results suggest some basic similarities between the mechanisms of fatigue fracture and final failure in polymeric materials.

A companion approach is to plot ΔK^* (the value of ΔK required to drive a crack at a constant value of da/dN) against K_{cf} (Manson and Hertzberg, 1973); as a result, a striking linear correlation was obtained for a broad group of polymers. Since the publication of these results, many more fatigue data have become available in this laboratory for a greater range of both materials and test conditions.

Figure 5, which includes data from both the original study and subsequent research amply confirms the remarkable and general correlation between ΔK^* and K_{cf} in polymers--i.e., between the driving force for crack extension under fatigue loading and the quasi-static fracture toughness (K_{cf}). The greater the fracture toughness, the greater the driving force required to drive a crack at constant speed. In addition, both Martin and Gerberich (1976) and Mostovoy and Ripling (1975) reported a general well-behaved relationship between ΔK and K_c (or fracture energy). Intuitively, this implies that the mechanism controlling unstable and catastrophic fracture also controls stable crack extension.

From a phenomenological point of view this observation is consistent with frequent findings that a variety of large-deformation (inelastic) processes in polymers are closely related to small-deformation (linearly elastic) characteristics such as dynamic mechanical response. For example, a number of properties can be correlated in various ways with damping behavior, often with the occurrence of β-transitions at low temperatures; examples include impact strength, yield stress, fracture energy, crack speeds and time-to-failure. Similarly, the effect of frequency on FCP rates has been correlated with the dissipative processes associated with the β-transition.

Finally, it is interesting to note that normalization of FCP data with respect to K_{cf} had previously been postulated by Wnuk (1971) with an equation of the form $da/dN \ \alpha \ (\Delta K/K_c)^m$.

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[+] Kcf was estimated from the values of Kmax, the last value noted in the FCP test prior to catastrophic fracture. While Kcf should be closely related to Kc, the true fracture toughness of the material, Kcf was not measured by the methods prescribed for Kc.

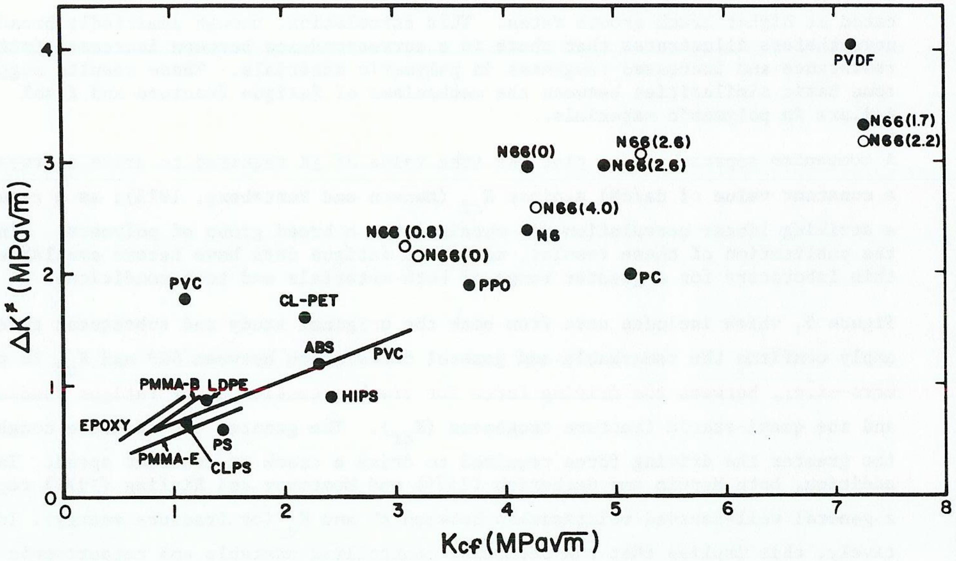

Fig. 5. Correlation between K_{cf} and ΔK^* corresponding to a crack growth rate of 7.5×10^{-4} mm/cyc. Note that fatigue resistance increases with increasing toughness. Open nylon 66 data points correspond to MW=17,000 and closed points to 34,000. Numbers in parenthesis correspond to percent absorbed water.

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