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Crack tip heating in short-fibre composites under fatigue loading conditions

R. W. LANG*, J. A. MANSON
Materials Research Center, Lehigh University, Bethlehem, Pennsylvania 18015, USA

Crack tip heating in cyclically loaded short-fibre polymer matrix composites occurs by a combination of hysteretic heating and frictional heating. While the former mechanism is caused by plastic and viscoelastic deformations within the polymeric matrix, the latter is due to interfacial friction between matrix and fibres, and crack surface interference associated with crack closure. The relative contribution of these two principal mechanisms depends upon a number of variables including the viscoelastic and plastic characteristics and frictional properties of the matrix polymer, the degree of interfacial adhesion, the fibre content and fibre orientation distribution and the loading conditions. The results confirm that even in a tension/tension loading mode, frictional heating may play a dominant role, at least in some systems.

1. Introduction

The possibility and significance of a finite temperature rise at crack tips in polymers under fatigue loading conditions has long been recognized [1, 2]. More recently the effects of several material and testing variables on crack tip heating have been investigated, making use of thermocouple or infrared techniques [3–7]. For short-glass-fibre reinforced (sgfr) nylon 66 it was found that the tendency for heat generation under a given set of test conditions decreases as the fibre content increases [6]. Since the matrix in these composites was rather lossy, the results have been interpreted using basic concepts of hysteretic heating. The purpose of this paper is to identify and to discuss additional mechanisms that may induce crack tip heating in cyclically loaded short-fibre (sf) composites.

2. Materials and experimental details

The materials used in this investigation are identical with those tested previously in fatigue crack propagation (FCP) experiments (6, 8–10) and are summarized in Table I along with their sources and designations. From the matrix materials listed, N66(B) (1.7 wt % H_2O) and PS(B) were the most ductile and the most brittle, respectively. Moreover, fractographic studies revealed a higher degree of fibre–matrix adhesion for the materials of Series A than for those of Series B [10].

Fatigue experiments with a minimum/maximum load ratio R of 0.1 were performed under ambient conditions ($T = 24 \pm 1^\circ$C) using compact-type specimens. Maximum crack tip temperatures and temperature profiles along the crack plane were recorded as a function of the applied stress intensity factor range, ΔK, by means of an infrared microscope with an estimated effective spot size of several hundred micrometres. In addition, values for the dynamic loss compliance, D'', were obtained from dynamic mechanical measurements using an Autovibron DDV III apparatus (Imass, Inc.). Although an estimated consistent error in the absolute magnitudes of D'' caused by an as-yet unresolved problem of systematic nature with the test equipment may be as high as 20%, the relative ranking of the D'' values for the various materials investigated (which is relevant for the present discussion) is correct. Further details on test procedures are described elsewhere [6, 11, 12].

3. Sources of crack tip heating

3.1. Hysteretic heating

Crack tip temperature elevations in fatigue-loaded unreinforced polymers are usually interpreted in terms of *hysteretic heating* caused by plastic or viscoelastic deformation processes associated with the high cyclic stresses in the vicinity of the crack tip. Assuming a stabilized, symmetrical, cyclic hysteresis loop for plastic deformation whose non-linear portion during loading obeys a power relationship of the form $\sigma = \text{const.} \times \varepsilon_p^n$ (where σ is the true stress, ε_p is the true plastic strain, and n is the strain hardening coefficient), the following expression can be deduced for the plastic energy dissipation rate per unit volume, $\dot{W}_p$:

$$\dot{W}_p = f\,\Delta\sigma\,\Delta\varepsilon_p\,\frac{1-n}{1+n} \qquad (1)$$

where f is the loading frequency, and $\Delta\sigma$ and $\Delta\varepsilon_p$ are the plastic stress and strain range of the cyclic hysteresis loop, respectively.

Using a vibrational stress tensor it can be shown [2] that the purely viscoelastic contribution of the heat generation rate per unit volume outside the plastic zone boundary of a homogeneous, linear viscoelastic solid is

$$\dot{W}_v = f\,D''(f, T)\Delta K^2\,\phi(r, \theta, v) \qquad (2)$$

where D'' depends on the frequency f and the

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*Present address: Kunststofflaboratorium, BASF AG, D-6700 Ludwigshafen, FRG.

TABLE I Materials and specimen designations

Material designation*	Commercial designation	Matrix type	Glass fibre† content (vol (wt) %)	References
N66 (A)	Zytel 101	nylon 66‡	–	[8]
N66-18G (A)	Zytel 70G33	nylon 66‡	18(33)	[8]
N66 (B)	R-1000	nylon 66§	–	[6, 8]
N66-16G (B)	RF-1006	nylon 66§	16(30)	[6, 8]
N66-31G (B)	RF 10010	nylon 66§	31(50)	[6, 8]
PS (B)	C-1000	poly(styrene)	–	[9]
PS-18G (B)	CF-1007	poly(styrene)	18(35)	[9]

*Series A (duPont, Wilmington, Delaware) and B (LNP-Corporation, Malvern, Pennsylvania) supplied as end-gated and side-gated injection-moulded plaques, respectively; symbols L and T added to the material designation refer to the direction of applied load relative to the major flow direction (L = longitudinal, T = transverse).

†E-glass.

‡Dry-as-moulded (0.2 to 0.6 wt % water).

§1.7 wt % water.

temperature T, and ϕ is a function of the polar coordinates r and θ (measured from the crack tip) and Poisson's ratio, ν.

3.2. Frictional heating

In the case of short-fibre reinforced plastics additional mechanisms, those related to *frictional heating*, must be considered. One obvious source of frictional heating is fibre–matrix sliding ("interfacial friction") either during fibre pull-out and push-in (on unloading) in the wake of the crack front or within the crack tip damage zone. A second possible mechanism, termed "fracture surface friction", is related to the occurrence of fracture surface interference or crack closure whenever the cyclic load approaches the minimum applied load level.

Fractographic evidence for fibre sliding and crack closure is illustrated in Fig. 1 for N66-18G(A-L). Although a wedge was introduced into the notch of this specimen prior to observation at a load level corresponding to 25% of the previously applied maximum cyclic tensile load, the two crack faces clearly interfere. An explanation for this phenomenon has been given most recently in terms of the roughness-induced crack closure concept [13] which has been used frequently in the literature on metal fatigue [14–16]. Additional support for repetitive crack face impingement and the associated friction during cyclic loading can be obtained from an examination of stable FCP fracture surfaces. Wear products such as the fracture surface debris visible in Fig. 2 are frequently observed [10].

An approximate expression for the energy dissipation rate per unit area associated with the sliding friction between two surfaces is

$$\dot{W}_{\mathrm{f}} = \mu v p \qquad (3)$$

where μ is the coefficient of friction, which may depend to some degree on v, the sliding velocity, and p is the normal pressure acting on the surfaces. For our case it is useful to modify Equation 3 to account for the cyclic nature of the crack opening displacement (COD). Assuming an average sliding speed that is proportional to the average COD rate in a cycle we obtain

$$v \propto f\,\Delta\mathrm{COD} \propto f\,\Delta K^2$$

where f is again the frequency, and ΔCOD is the range in the crack opening displacement corresponding to the applied range in the stress intensity factor, ΔK

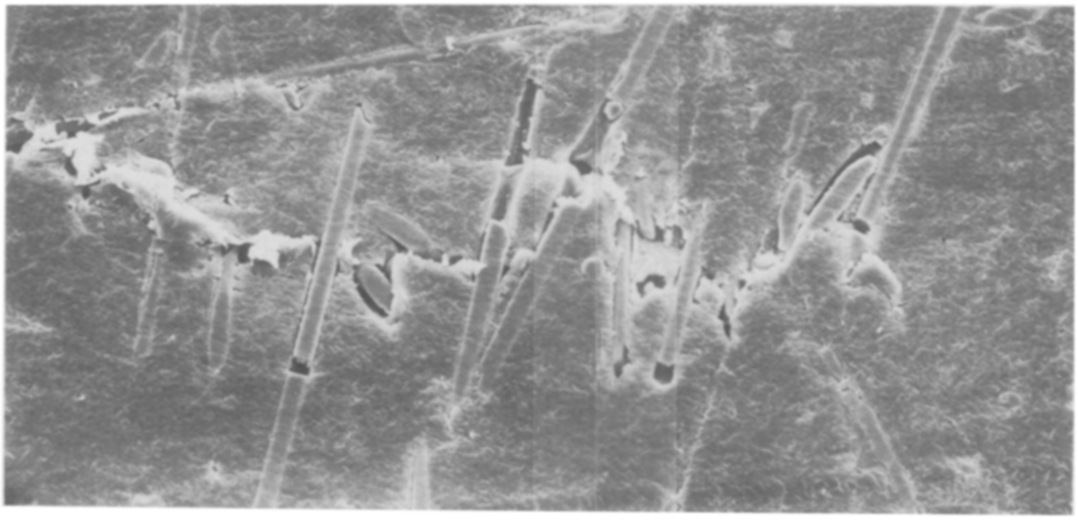

Figure 1 Crack tip region of a partially wedged open fatigue crack taken from a polished side surface of sgfr-N66 (N66-18G(A-L)). Note the overall crack face contact and the debonded and broken fibres bridging the crack (fibre diameter ≈ 10 μm).

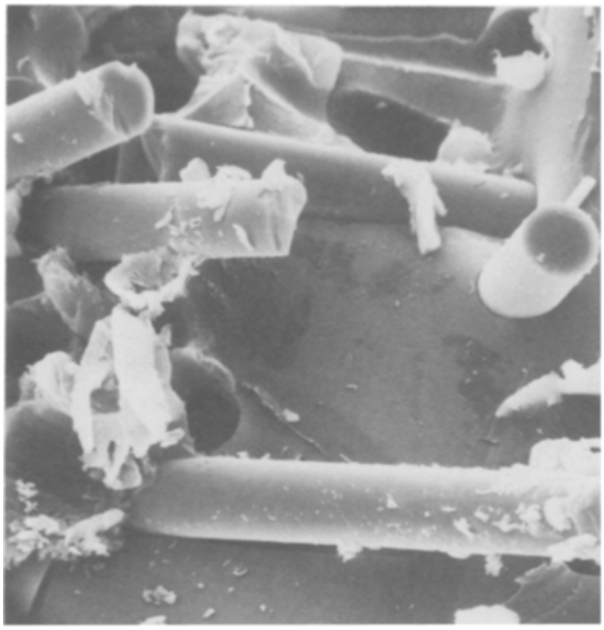

Figure 2 Scanning electron micrograph from the stable FCP region in sgfr-PS (PS-18G(B-T)) showing the fracture surface debris produced by crack surface interference (fibre diameter $\approx 10\,\mu$m).

(ΔCOD $\propto \Delta K^2$ [17]). Hence we may rewrite Equation 3 as

$$\dot{W}_\mathrm{f} \propto f\,\mu\,\Delta K^2\,p \tag{4}$$

which is apparently very similar to Equation 2.

3.3. General considerations

In a strict sense it is not easy to separate hysteretic heating from frictional heating, since any mechanism of friction also includes plastic and viscoelastic deformation components which are hysteretic in nature [18, 19]. Similarly, hysteretic energy dissipation is often thought of as "internal friction" between molecules and molecular segments within the material. Hence for the purpose of this discussion "frictional heating" is defined as being due to all the mechanisms associated with the rubbing action of two surfaces, whereas "hysteretic heating" is defined as being due to the applied cyclic stresses and their corresponding plastic and viscoelastic deformations within the polymeric matrix.

It is, of course, recognized that Equations 1 to 4 cannot provide a quantitative description of the rather complex situation of crack tip heating in sf-composites, due to the many assumptions and simplifications in the derivations. Nevertheless they are useful for a qualitative discussion of our results in that they identify the major variables involved in the crack tip heat-up process. Assuming that almost all of the energy dissipated appears in the form of heat we can expect for the maximum temperature rise at the crack tip, ΔT_max,

$$\Delta T_\mathrm{max} \propto \dot{W}_\mathrm{p},\ \dot{W}_\mathrm{v},\ \dot{W}_\mathrm{f},\ V_\mathrm{p},\ V_\mathrm{v},\ A_\mathrm{f},\ 1/h_\mathrm{t}$$

where V are the volumes and A is the area of the corresponding heat generating processes (designated by the subscripts), and h_t stands for the heat transfer characteristics.

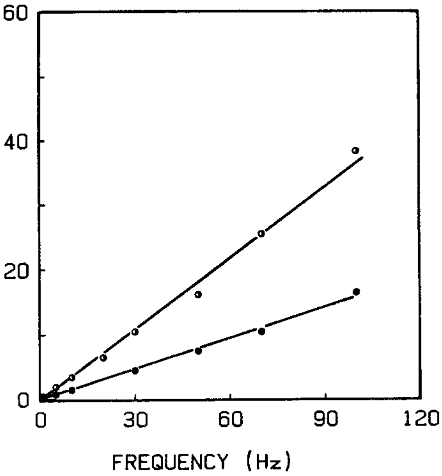

Figure 3 Effect of test frequency on the maximum crack tip temperature rise, ΔT_max, in sgfr-N66 (B-T) with 1.7% H_2O (data replotted from [6]): (◑) N66-16G, (●) N66-31G. $\Delta K = 3.1\,\mathrm{MPa\,m^{1/2}}$, $R = 0.1$.

4. Results and discussion

Typical results of the cyclically induced, maximum temperature rise at the crack tip are plotted in Figs 3 and 4 for several of the materials investigated as a function of frequency and ΔK, respectively. The rather linear dependence of ΔT_max on frequency, although apparently consistent with the explicit first-order frequency dependence in Equations 1, 3 and 4, may also well reflect a balance in the implicit frequency and temperature dependence of several of the material variables involved. On the other hand, the dependence of ΔT_max on ΔK shown in Fig. 4 for some of the composites is evidently less than second-order. This is not surprising, however, considering that not the entire range of the applied ΔK may actually be effective in the heat generation by the various mechanisms.

For example, heat generation by crack surface friction will presumably be important only in the lower part of the fatigue cycle where severe fracture surface interference takes place. The contribution of heating by surface friction may therefore actually be favoured by lower ΔK values (fixed R-ratio) due to the

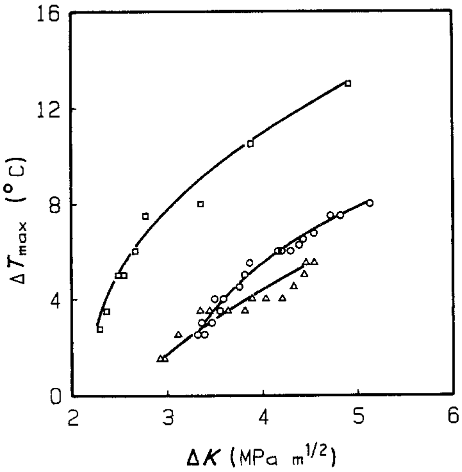

Figure 4 Effect of stress intensity factor range, ΔK, on the maximum crack tip temperature rise, ΔT_max, in various sgfr plastics of similar glass content: (△) N66-18G (A-L), (○) N66-16G (B-T), (□) PS-18G (B-T). $R = 0.1$, $f = 10$ Hz.

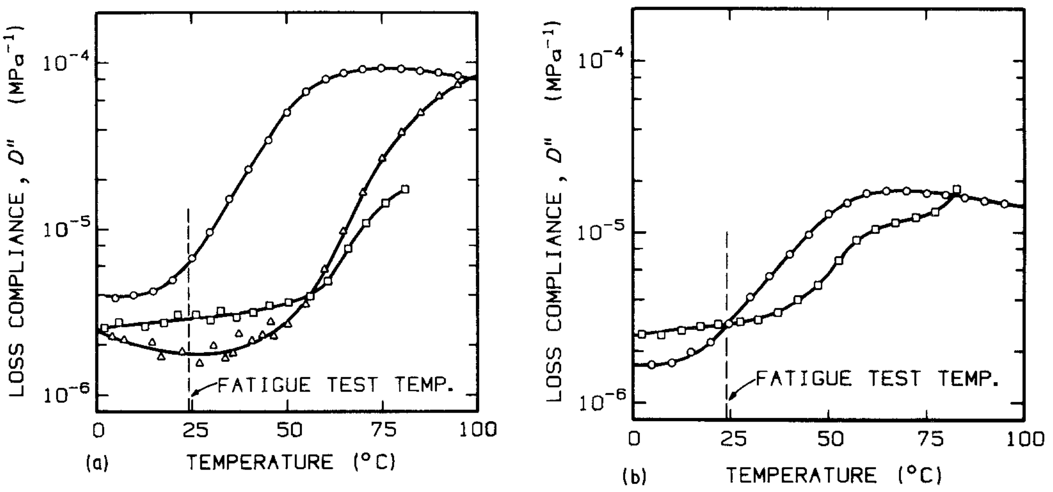

Figure 5 Temperature dependence of the dynamic loss compliance, D'', measured at 110 Hz. (a) Neat matrix systems: (○) N66 (B), 1.7% H_2O; (△) dry N66 (A); (□) PS (B). (b) Composites: (○) N66-16G (B-T); (□) PS-18G (B-T).

associated stronger closure effects. In contrast, interfacial friction and hysteretic heating may be more effective during the upper part of the fatigue cycle and at higher levels of ΔK when the crack is more fully open. In any case, due to the similarity of Equations 2 and 4 it is difficult to obtain conclusive evidence for the contribution to frictional heating just by looking at the test-parameter dependence. However, an examination of the material characteristics D'' and μ may provide a clue.

Dynamic mechanical tests on the neat matrix materials and several of the composites revealed noticeable differences in the magnitude and temperature dependence of the dynamic loss compliance, D'' (Fig. 5). While the lower ductility together with the lower values in D'' of dry N66(A) compared with N66(B) containing 1.7% H_2O may help to explain the lower crack tip temperatures measured in the composite with the former matrix (Fig. 4), it is particularly the comparison between the N66 and PS systems of Series B that is of interest with regard to frictional heating. Specifically of importance are (i) the higher values in D'' of neat N66(B) compared with neat PS(B) (Fig. 5a), (ii) the stronger increase in D'' in N66-16G(B-T) just above room temperature (Fig. 5b) which implies a higher tendency for auto-accelerated hysteretic heating, and (iii) the significantly higher degree of plastic deformation and matrix yielding visible on the fracture surface of the N66 composite as compared to the more brittle fracture surface appearance of the PS composite [10].

Although neat nylon 66 does have a somewhat higher thermal conductivity than neat PS [20] (a difference which is decreased at least to some degree by the addition of glass fibres), all of the above factors would imply a higher tendency for crack tip heating in N66-166(B-T) if hysteretic heating were the dominant mechanism. Hence it is concluded that the higher crack tip temperatures in the PS composite shown in Fig. 4 are a result of a greater contribution of frictional heating in this system. Consistent with this conclusion and with Equation 4 are the generally higher values in the coefficient of friction reported in the literature for PS ($\mu_{PS} \approx 0.4$ to 0.5; $\mu_{N66} \approx 0.25$ to 0.3 [21]), as well as the generally superior wear properties of nylon 66 [22]. To further strengthen the argument, temperature profiles recorded for PS-18G(B-T) along the crack plane are shown in Fig. 6. In good agreement with the concept of frictional heating and crack-surface interference, the maximum temperature rise is seen to occur at a distance well behind the visible damage-zone tip, in a region separated to a large extent by the advancing crack.

5. Conclusions

Crack tip heating in fatigue-loaded short-fibre reinforced plastics occurs by a combination of hysteretic heating and frictional heating. At a given level of ΔK,

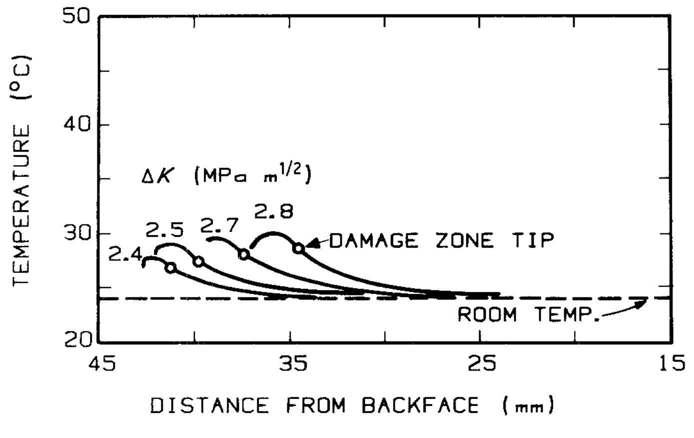

Figure 6 Temperature profiles recorded along the crack plane for several ΔK conditions and plotted as a function of the distance from the specimen backface. PS-18G (B-T), $R = 0.1, f = 10$ Hz.

the *relative* contribution of frictional heating will be favoured by (i) poor interfacial adhesion which increases the crack-tip damage zone and maximizes interfacial friction, (ii) fibre orientation distributions more perpendicular to the crack plane which enhance fracture surface roughness and crack closure effects and simultaneously increase fracture surface friction, and (iii) brittle matrices with little tendency for plastic and viscoelastic energy dissipation. Similar to the case of localized hysteretic heating [6], frictional heating may be beneficial to the FCP resistance of sf-composites in that it dissipates additional energy and effectively blunts the crack, due to a decrease in the crack tip damage initiation stress and the simultaneous increase in the size of the crack tip damage zone.

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