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Fatigue crack propagation in polypropylene reinforced with short glass fibres

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Abstract

Fatigue crack propagation (FCP) behaviour of polypropylene composites reinforced with short glass fibres has been investigated as a function of fibre content and frequency of the sinusoidal applied load. The FCP resistance of the composites was found to improve as the fibre weight fraction increased. Results for all composites showed a dramatic decrease in the crack growth rate per cycle as a result of increasing frequency, at any given crack length. A further analysis of the data indicated that crack propagation was governed by viscoelastic creep which produced, at the lower frequencies, a crack speed approximately independent of frequency. However, it was recognized that at the highest frequency hysteretic heating at the crack tip induced a higher crack speed, associated with non-isothermal creep processes.

Keywords: A. Short-fibre composites; B. Mechanical properties; B. Fatigue; Glass fibres polypropylene matrix

1. Introduction

The fatigue properties of polymer-matrix composites are of paramount importance for many intended applications where components are subjected to load and environmental histories which vary in time over the period of service [1]. In particular, the fatigue behaviour of advanced continuous-fibre composites have received great attention during the past 40 years as a result of the strong focus on applications in the aerospace field. Recently, efforts to reduce the weight of automobiles by the increased use of plastics and their composites, have led to a growing penetration of short-fibre-reinforced injection-moulded thermoplastics into fatigue-sensitive applications [2,3]. In general, short-fibre/polymer-matrix composites are much less resistant to fatigue damage than the corresponding continuous-fibre-reinforced materials, mainly because the weak matrix has to sustain a greater proportion of the cyclic load [4]. Fatigue damage is generally associated with the initiation and propagation of cracks in the matrix and/or the destruction of bonding at the polymer/matrix interface. Final failure of discontinuous-fibre-reinforced engineering thermoplastics under alternating loading mainly occurs by fatigue-crack propagation (FCP) [5]. Most of the past work on the FCP behaviour of injection-moulded short-fibre-reinforced plastics (SFRPs) has been performed on polyamides [6–13], polypropylene [14–17], polyethylene [18] poly(butyleneterephthalate) [19], and poly(ether ether ketone) [20–22] systems, reinforced with either glass or carbon fibres. In spite of the inhomogeneous structure due to the discontinuities introduced by the presence of the short fibres, fatigue-crack propagation in SFRPs is generally found to follow the Paris crack-propagation equation [23]:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = A\Delta K^m \quad (1)$$

where $\frac{\mathrm{d}a}{\mathrm{d}N}$ is the crack growth rate per cycle, and ΔK is the difference between the maximum and minimum Mode I, or opening mode, stress intensity factors in the fatigue cycle. Among the various parameters affecting the FCP behaviour (i.e. A and m values of the Paris equation), material variables, frequency and wave form of the alternating load, temperature, environment, stress ratio and mean load, are of primary importance [5].

In a load-controlled fatigue test, a polymeric material may undergo either mechanical or thermal failure, depending mainly on the test frequency and the sample geometry. Consequently, it is of primary importance to

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examine how the FCP resistance of engineering polymers varies as a function of test frequency. In the range from 0.1 to 100 Hz the FCP rate per cycle of several polymers such as, poly(methyl methacrylate) [24], polystyrene [25], poly(vinyl chloride) [26], poly(phenylene oxide)/high-impact polystyrene blend [25], nylon-6 and nylon-6,6 [27] was found to decrease with increasing frequency. Other polymers such as polycarbonate [28], poly(vinylidene fluoride) [25] showed no apparent sensitivity of FCP rate to test frequency. Interestingly enough, for both plain and rubber-toughened epoxies Hwang et al. [29] found a decreasing fatigue resistance with increasing cyclic frequency. A slight increase of the FCP rate as the frequency is reduced was observed in polycarbonate by Arad and co-workers [30]. The reasons for these differences are not clear at this time, even if a major role is generally attributed to the different time-under-load conditions related to the test frequency. Very limited experimental work exists on the effects of the loading frequency on the FCP behaviour of SFRPs [9,17,31] and, despite the great practical interest, no data are available on the effects of the cyclic testing conditions (e.g. frequency, wave form, mean stress level) for glass-fibre-reinforced polypropylene.

The aim of the present study is to investigate how the fatigue-crack propagation behaviour of short-glass/fibre polypropylene composites is affected by the test frequency and the amount of reinforcing fibres.

2. Experimental

The materials used in the present investigation were short-glass-fibre-reinforced polypropylene composites manufactured and supplied by Montell Polyolefins S.p.A. (Ferrara, Italy) as injection-moulded square plaques of 127×127×2.7 mm. The matrix was a commercial-grade polypropylene with a melt flow index equal to 3.5 dg/l. The reinforcing fibres were of the E-glass type with a diameter of 14 microns and an initial average length of 4.5 mm and were added in three different percentages of 10, 20 and 30 wt%. After compounding and injection moulding, the manufacturer evaluated a fibre length range in the moulded plaques of about 0.5–0.7 mm. All test pieces were cut with the same orientation with respect to the mould-fill direction, as depicted in Fig. 1.

A Mettler DSC 30 differential scanning calorimeter was used to detect the melting temperature, T_m, and the crystallinity content of the matrix by integrating the normalized area of the endothermal peak and rating the heat involved to the reference value of the 100% crystalline polymer (165 J/g) [32]. The conditions for DSC measurements were as follows: specimen weight: about 20 mg; temperature interval: 0 to 230°C; heating rate: 10°C/min; nitrogen flux: 100 ml/min.

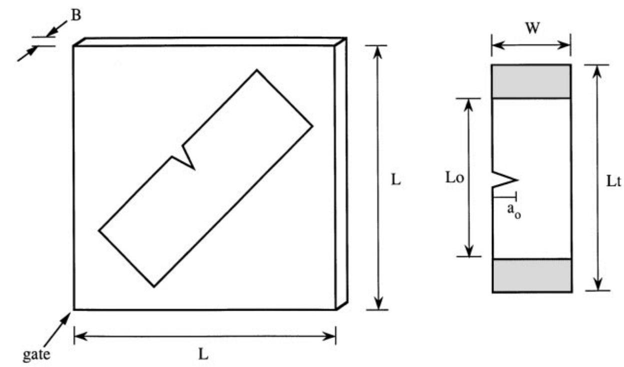

Fig. 1. Position from which test pieces were cut from polypropylene/glass injection moulded plaques, and shape and size of SENT specimens. Dimensions are: $L=127$ mm, $B=2.7$ mm, $L_t=120$ mm, $L_o=62$ mm, $W=27$ mm, $a_0=3$ mm.

Dynamic mechanical tests were conducted in bending mode by a dynamic mechanical thermal analyzer (DMTA, model MKII, by Polymer Laboratories) under the following conditions: specimens dimensions: 60 mm×10 mm×2.7 mm; temperature interval: −50 to 130°C; heating rate: 0.5°C/min; peak-to-peak displacement 64 μm; frequencies: 0.1, 1, 10 Hz.

Monotonic uniaxial tensile tests were performed on rectangular unnotched specimens of 27 mm×120 mm×2.7 mm in an Instron 4502 tensile tester equipped with a 10 kN load cell and a strain-gauge extensometer (Instron, model 2620). All measurements were performed at room temperature, at a cross-head speed of 1 mm/min on at least five specimens.

Fatigue-crack propagation experiments were conducted on single-edge notched tension (SENT) specimens whose dimensions and position in the original injection-moulded square plaques are reported in Fig. 1. Specimens dimensions were chosen in accordance to the ISO/TC 61/SC 2/WG 7 N5 recommendations. An initial crack of length a_0 was made by means of a razor blade. All fatigue test were performed at room temperature by a closed loop servohydraulic MTS Mini Bionix testing machine under tension-tension sinusoidal load control. The cyclic frequencies were 0.1, 1, and 10 Hz, the mean load was 1200 N and the minimum to maximum load ratio was 0.4. Signals from the load cell and the LVDT channels were recorded and analyzed in order to determine the load/displacement hysteresis loops during FCP experiments. With the aid of a video-camera, a video-recorder, and an image analyser system, the crack length, a, was measured as a function of the number of cycles, N. For each experimental situation, at least three specimens were tested and an average crack-propagation rate was obtained as the derivative of the best-fit third-order polynomial curve. The stress-intensity factor, K, at the crack tip was evaluated on the basis of the linear elastic fracture mechanics approach which is often used also to describe fracture and fatigue behaviour of non-linear and heterogeneous materials [5]. The specific equation for the stress intensity factor amplitude, ΔK, for SENT specimens is [33]:

$$\Delta K = \frac{\Delta P}{BW}\sqrt{a}\left[1.99 - 0.41\frac{a}{W} + 18.7\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4\right] \quad (2)$$

were ΔP is the difference between the maximum and the minimum applied loads, B is the thickness, and W the width of the specimens.

The surface temperature of the SENT specimens in the crack-tip region during fatigue-crack propagation was monitored with an infrared sensing thermography camera (Hughes thermal video system TVS-300 Series).

3. Results and discussion

3.1. Material properties

The monotonic stress/strain curves obtained in uniaxial tension are shown in Fig. 2. As the amount of fibres increases the elongation at break decreases and, as reported in Table 1, both tensile modulus and strength increase. From the same table it can be seen that, as indicated by the DSC measurements, the fibres content does not appreciably affect the melting temperature and crystallinity content of the composites. On the other hand, the dynamic mechanical properties of the materials under investigation were markedly influenced by the fibre weight fraction: in particular, the higher the fibre weight fraction the lower the loss tangent. Moreover the dissipation behaviour of the composite systems strongly depends on the test frequency, with lower loss-tangent values at higher frequencies.

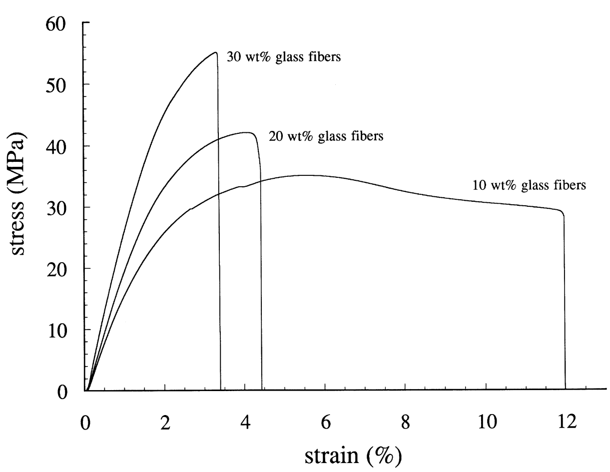

Fig. 2. Stress/strain curves of the short-glass-fibre-reinforced polypropylene composites used in the present study.

3.2. Fatigue crack propagation (FCP) data

In Fig. 3(a) is reported a characteristic curve of the crack extension, a, vs. the number of fatigue cycles, N. In Fig. 3(b) the corresponding curve of the crack propagation rate per cycle, da/dN, vs. the stress intensity factor amplitude, ΔK, can be observed. In the early stage of the fatigue test (region I of Fig. 3), the slope of the curve decreases as the crack extension increases. As already reported by Karger-Kocsis and co-workers [15,16] for both unreinforced and short-glass-fibre-reinforced polypropylene, the high crack-propagation rate at the beginning of the test is related to the sharpness of the notch tip created by the razor blade. In the course of fatigue cycling the notch undergoes blunting and the FCP rate decrease (deceleration) until a minimum value is reached. This lower value of the FCP rate has been associated [16] to the development of a critical damage zone and/or critical damage density which corresponds to the onset of a stable FCP acceleration (region II of Fig. 3) which is followed by crack instability and complete fracture (region III of Fig. 3). Range II (stable FCP acceleration) can be described by the Paris power law [cf. Eq. (1)]. A least-squares linear regression were first performed on the experimental results for all specimens and the values located outside the 95% confidence bands were then eliminated. In Fig. 4 the resulting Paris plots are reported for all of the materials under investigation at various frequencies.

3.3. Effect of fibre content

By comparing the FCP curves of Fig. 4 obtained at the same frequency, it can be seen that an increase of the

Table 1
Some properties of the composites used in the present study

Fibre weight fraction (wt%)	Tensile modulus E (MPa)	Tensile yield strength σ_y (MPa)	Melting temperature T_m (°C)	Crystallinity content X_c (%)	Storage modulus at 25°C E' (MPa)			Loss tangent at 25°C tan δ		
					0.1 Hz	1 Hz	10 Hz	0.1 Hz	1 Hz	10 Hz
10	2910 ± 50	35.1 ± 0.1	174	62.4	2880	3090	3270	0.070	0.048	0.040
20	3620 ± 150	42.1 ± 0.2	171	64.8	3880	4090	4290	0.053	0.038	0.032
30	5520 ± 30	53.1 ± 1.4	173	62.8	5440	5740	5960	0.045	0.032	0.027

fibre weight fraction is connected with an improved resistance to fatigue crack propagation, i.e. lower FCP rates. A similar effect has been reported by many authors for a number of short-glass or carbon-fibre-reinforced polymers like polypropylene [14–16], polyamides (either nylon-6 or nylon-6,6) [6–8], poly(butyleneterephthalate [19], and poly(ether ether ketone) [20,21]. Studying the influence of short-fibre orientation on the FCP rates of injection-moulded nylons, Wyzgoski and Novak showed that the use of a strain-energy release rate model provided a superior representation of the results since it led to a generalized plot for different glass-fibre orientation directions [9,13]. The strain-energy release rate, G, can be calculated from the stress-intensity factor, K, and the modulus, E, as follows [34];

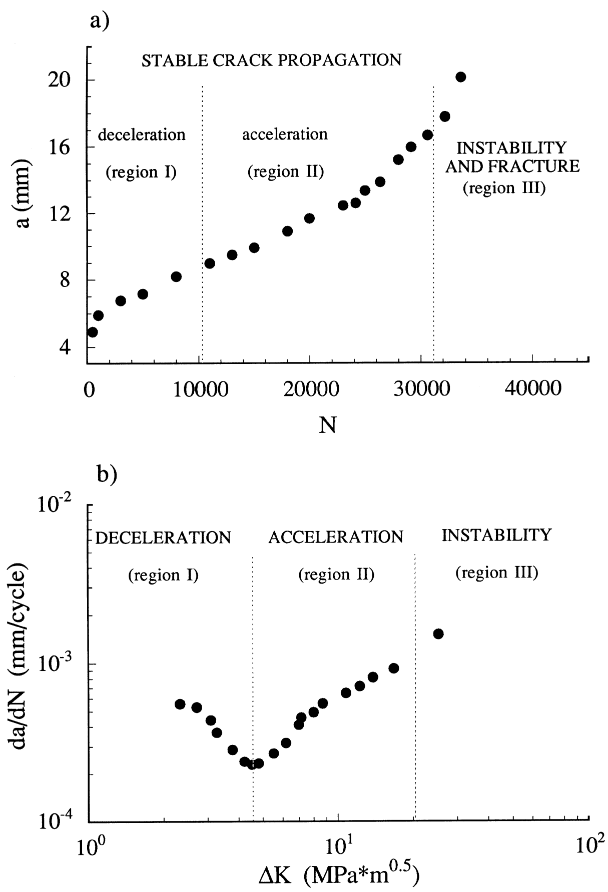

Fig. 3. Characteristic (a) crack extension, a, vs. number of fatigue cycles, N, and (b) crack propagation rate per cycle, $\mathrm{d}a/\mathrm{d}N$, vs. stress intensity factor amplitude, ΔK, curves for the short glass fibre reinforced polypropylene composites.

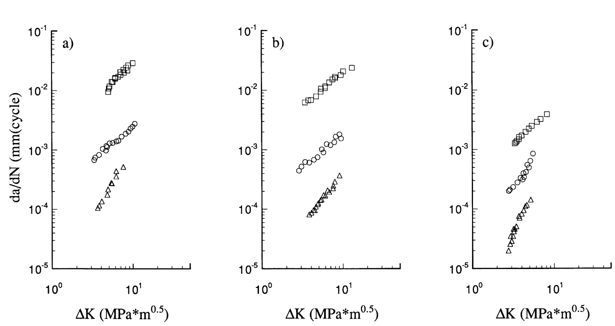

Fig. 4. Paris plots (stable crack acceleration region) at (□) 0.1 Hz, (○) 1 Hz, and (△) 10 Hz for composites reinforced with (a) 10 wt%, (b) 20 wt%, and (c) 30 wt% of short glass fibres.

$$G = \frac{K^2}{E} \tag{3}$$

Under an oscillating loading condition, such as is generally used in fatigue tests, Wyzgoski and Novak derived a corresponding expression for the oscillating strain-energy release rate, which is [9]:

$$\Delta G = \left(\frac{1+R}{1-R}\right)\frac{\Delta K^2}{E} \tag{4}$$

where R is ratio of the minimum to the maximum loads. In our case R was set at 0.4 and consequently expression (4) reduces to:

$$\Delta G \cong 2.33\frac{\Delta K^2}{E} \tag{5}$$

Strictly speaking, under plane-strain condition, this expression should also be multiplied by the term $(1-\nu^2)$ where ν is the Poisson's ratio. However, values for ν were not available for the composites under investigation and this correction was therefore ignored. By analogy with the Paris equation, the crack-growth rate is then given by:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = B\Delta G^n \tag{6}$$

From Eqs. (5) and (6), with the tensile-modulus data of Table 1, the curves of FCP rate vs. the strain-energy release amplitude were obtained for all of the composites under investigation in the present study at various frequencies (see Fig. 5). It is interesting to observe that, for any given frequency, the data sets for various fibre weight fractions collapse onto an individual curve. In other words, through the strain-energy release rate approach one can obtain FCP 'master curves' whose constants B and n [of Eq. (6)] are independent from the glass fibre content. This can be explained by supposing that the failure in the composites probably occurs by a similar mechanism, being the failure of fibres in the moulded plaques of comparable aspect ratio (equal to about 40–50).

3.4. Effect of frequency

From Figs. 4 and 5 it clearly emerges how the FCP resistance of the various polypropylene composites varies as a function of the test frequency, for all of the fibre weight fractions. In particular, the higher the frequency the lower the FCP rate at any fixed ΔK or ΔG value. The magnitude of this effect can be estimated from the values of the coefficients of Eq. (1), reported in Table 2. Coefficients A and m are obtained from the least-squares regression of the data of Fig. 4, and represent the intercept and slope of the log–log plot of Eq. (1), respectively. Coefficient A falls markedly as the test frequency increases. It is worth noting that the slope of the Paris plots (m coefficient) is only slightly affected by the test frequency. In order better to quantify the frequency effect on the FCP behaviour of different materials, Hertzberg and Manson introduced a frequency sensitivity factor (FSF) defined as the multiple by which the FCP rate changes per decade of test frequency. This factor is computed from the linear and parallel portions of the FCP plots (see p. 85 of Ref. [5]). In the above reference the authors listed the FSF values for several unfilled polymers, the highest of them being 2.5–3.3, which is the FSF range for the unfilled poly(methyl methacrylate). The very high sensitivity to the test frequency displayed by the short-glass-fibre-reinforced polypropylene composites used in the present study is confirmed by the exceptionally elevated values of the FSF (up to 10.8) reported in Table 3.

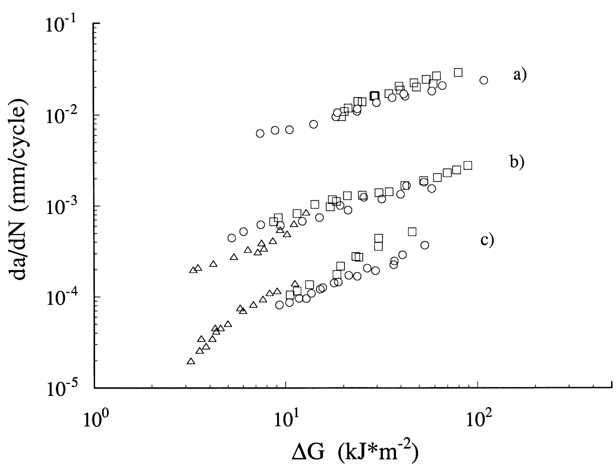

Fig. 5. Fatigue crack propagation rate vs. strain energy release rate curves at (a) 0.1 Hz, (b) 1 Hz, and (c) 10 Hz for composites reinforced with (□) 10 wt%, (○) 20 wt%, and (△) 30 wt% of short glass fibres.

Table 2
A and m coefficients of the Paris equation

Fibre weight fraction (wt%)		Test frequency (Hz)		
		0.1	1	10
10	A (mm/cycle)(MPa$\sqrt{m}$)$^{-m}$	1.89×10^{-3}	1.93×10^{-4}	3.25×10^{-6}
	m	1.40	2.10	2.58
20	A (mm/cycle)(MPa$\sqrt{m}$)$^{-m}$	1.59×10^{-3}	1.44×10^{-4}	8.40×10^{-6}
	m	1.09	1.10	1.68
30	A (mm/cycle)(MPa$\sqrt{m}$)$^{-m}$	2.92×10^{-4}	1.59×10^{-5}	5.34×10^{-7}
	m	1.25	2.21	3.67

As firstly suggested by Hertzberg et al. [25], and more recently by Wyzgoski et al. [27] the fatigue crack growth can be considered to be composed of two components: one is due to a true fatigue process which induces a certain amount of damage and consequent crack extension, while the other is the crack growth due to viscoelastic creep which is proportional to the time under load. From a mathematical point of view this concept can be expressed as:

$$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\text{total}} = \left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\text{fatigue}} + \left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\text{creep}} \quad (7)$$

or equivalently [27]:

$$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\text{total}} = \left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\text{fatigue}} + \left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)_{\text{creep}} \frac{\mathrm{d}t}{\mathrm{d}N} \quad (8)$$

where $\frac{\mathrm{d}t}{\mathrm{d}N}$ is the time period, P, of the cyclic oscillation, which is also equal to the inverse of the frequency ($P = 1/\nu$). This dependence is illustrated in Fig. 6 where the crack growth rate per cycle is expressed at a fixed level of ΔK as a function of the time period. The lowest possible ΔK value of 3.5 MPa$\sqrt{m}$ was chosen in order to minimize crack-tip heating effects. According to Eq. (8), the intercepts of the linear regressions of the data in Fig. 6 represent the crack-growth rate contribution due to true fatigue while the slopes represent crack speed due to the contribution of the viscoelastic creep. The intercepts of the lines are in any case lower than 0.08 μm/cycle while the slopes are equal to 0.687, 0.626, and 0.134 μm/s for composites reinforced with 10 wt%, 20 wt% and 30 wt% of fibre, respectively. This implies that at low frequencies the true fatigue contribution is much lower than the crack growth associated to the creep process. This phenomenon is particularly

Table 3
Frequency sensitivity factor (FSF) evaluated at $\Delta K = 3.5$ MPa$\sqrt{m}$

Fibre weight fraction (wt%)	FSF	
	0.1–1 Hz	1–10 Hz
10	8.9	9.3
20	10.8	8.3
30	5.5	4.8

pronounced for composites with low fibre weight fraction at low test frequencies, i.e. at high time periods. For example, in specimens reinforced with 10 wt% of glass fibres and tested at 0.1 Hz the crack growth rate due to viscoelastic creep resulted about 140 times higher than the fatigue contribution. In view of the above considerations, it is interesting to re-examine the FCP data by considering the crack growth speed, da/dt, as a function of the mean strain energy release rate, G_{mean}, applied to the specimen (see Fig. 7). The experimental points can be reasonably well fitted by a Paris-like equation [35] in the form:

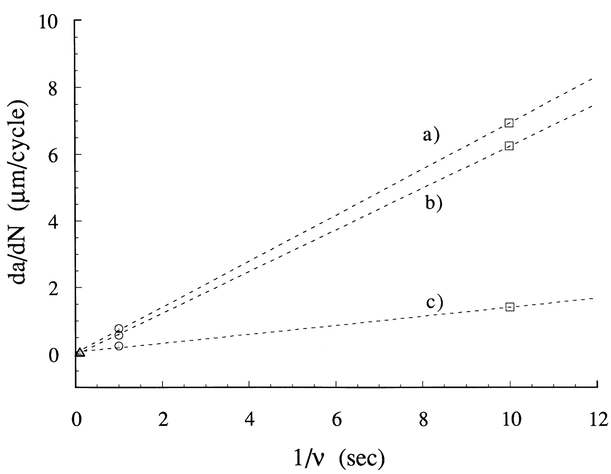

Fig. 6. Fatigue crack propagation rate evaluated at a constant ΔK value of $3.5\,\mathrm{MPa}\sqrt{m}$ vs. the fatigue time period ($1/\nu$) at (□) 0.1 Hz, (○) 1 Hz, and (△) 10 Hz for composites reinforced with (a) 10 wt%, (b) 20 wt%, and (c) 30 wt% of short glass fibres.

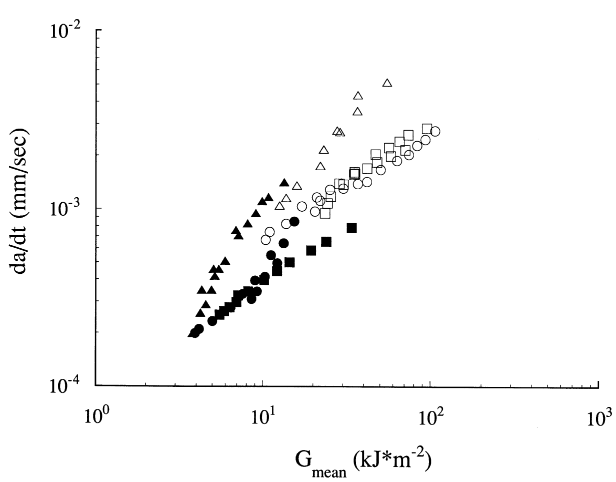

Fig. 7. Crack propagation speed, da/dt, as a function of the average strain energy release rate, G_{mean}, for composites reinforced with 10 wt% of short glass fibres, tested at (□) 0.1 Hz, (○) 1 Hz, and (△) 10 Hz, and for composites reinforced with 30 wt% of short glass fibres, tested at (■) 0.1 Hz, (●) 1 Hz, and (▲) 10 Hz.

$$\frac{\mathrm{d}a}{\mathrm{d}t} = CG^{p}_{mean} \quad (9)$$

which is usually employed to predict crack growth speed under static loads. Fig. 7 indicates that the crack growth speed is reduced with increasing fibre content. The fibre effect could be explained by considering that the creep contribution is lower as the material compliance is reduced by the fibre presence. At low frequencies (0.1–1 Hz) the crack speed is almost independent from the test frequency itself, thus confirming the major role played by the viscoelastic creep. When the test frequency is enhanced to 10 Hz, the creep crack propagation increases probably due to the matrix softening related to hysteretic heating.

3.5. Hysteretic heating

Typical load–displacements loops are reported in Fig. 8 for a composite with a fibre content equal to 10 wt% during an FCP test performed at 0.1 Hz. It can be observed that as the fatigue experiment proceeds the hysteresis loops shift to higher displacement values and their average slope is reduced, as a result of both reduced specimens compliance due to the crack propagation and matrix softening due to temperature increase. Evaluation of the energy dissipated during each load–displacement cycle (area of the hysteresis loop) allows the evaluation of the power dissipated during FCP as reported in Fig. 9. The dissipated power is practically constant during the testing time and increases in correspondence to the fracture instability (see Fig. 3). As expected, it is found that the power dissipated in the samples during the stable crack propagation is a linear function of the test frequency, and at a given frequency it decreases as the fibre content is increased. Either in neat or reinforced polymeric materials much of the energy consumed by irreversible

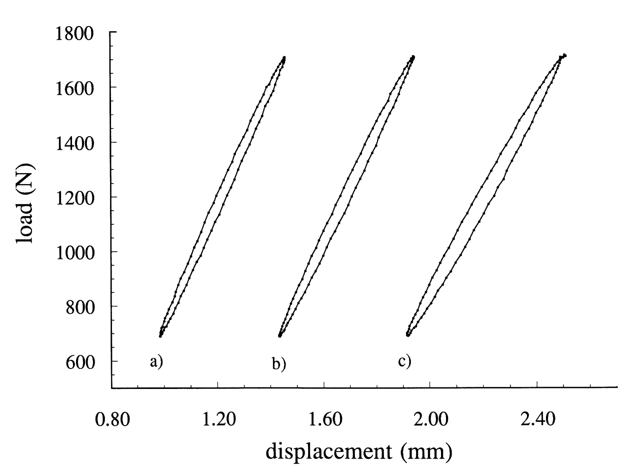

Fig. 8. Load–displacement hysteresis cycles for composite SENT specimens reinforced with 10 wt% of short glass fibres, tested at 0.1 Hz after (a) 240 cycles, (b) 690 cycles, and (c) 870 cycles.

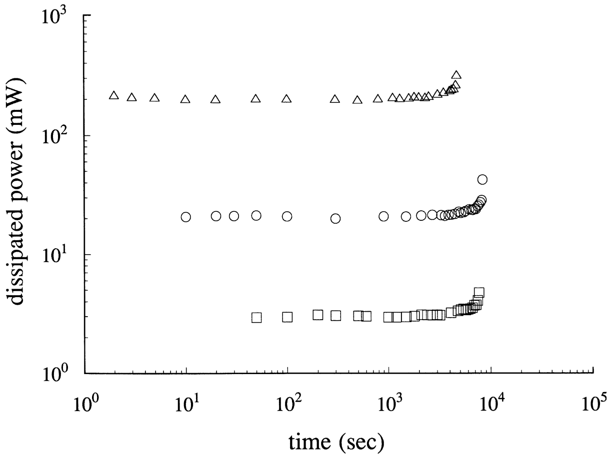

Fig. 9. Power dissipated in composite SENT specimen reinforced with 10 wt% of short glass fibres during the fatigue crack propagation at (□) 0.1 Hz, (○) 1 Hz, and (△) 10 Hz.

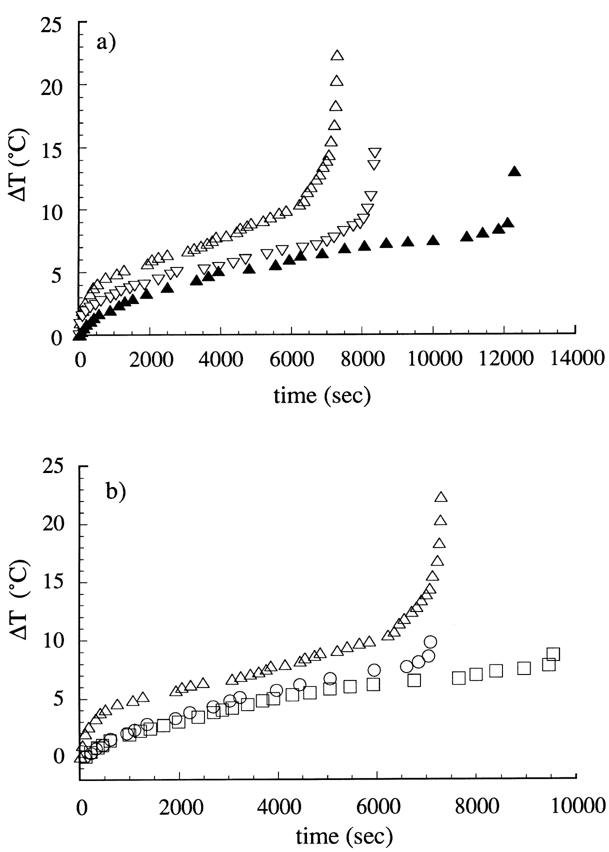

Fig. 10. Temperature increase at the crack tip during the FCP experiments for (a) specimens reinforced with (△) 10 wt%, (▽) 20 wt% and (▲) 30 wt% of short glass fibres tested at a frequency of 10 Hz and (b) specimens reinforced with 10 wt% of short glass fibres tested at (□) 0.1 Hz, (○) 1 Hz, and (△) 10 Hz.

processes during the FCP is converted into heat [5,36–38] In a notched specimen the temperature increase is mainly localized in a region close to the crack tip. However, direct measurements of the temperature rise at the crack tip during fatigue propagation are quite rare [5,27,39]. In the present study the surface temperature of the specimens in the region near the crack tip has been evaluated during the fatigue propagation by infrared thermography and the results are reported in Fig. 10. The hysteretic heating leads to an increase of the crack tip temperature with a trend which is quit rapid during the initial stages, steadily increasing during the stable FCP propagation, and abruptly increasing in the finale part when the specimen is approaching fracture instability. As it clearly emerges from Fig. 10(a), the level of hysteretic heating is markedly affected by the fibre content: in particular, the higher the fibre weight fraction the lower the temperature reached at the crack tip. Another parameter which is strongly effecting the temperature rise is the test frequency. As reported in Fig. 10(b), the level of temperature increase is growing when the frequency is increasing.

In view of the above considerations we can now better understand the crack speed curves reported in Fig. 7. In particular, it is interesting to observe that at low test frequencies (0.1 and 1 Hz), when the temperature increase is similar [see Fig. 10(b)], the crack speed at a given value of the mean strain energy release rate is almost the same. At higher frequency (10 Hz) the temperature at the crack tip increases to a greater extent leading to an higher crack speed due to enhanced creep effect.

4. Conclusions

The growth of cracks in short glass fibre reinforced polypropylene composite specimens due to cyclic sinusoidal loading has been studied for various fibre weight fractions and test frequencies by using the linear fracture mechanics approach.

It was found that, at a fixed stress intensity factor amplitude (ΔK), the fatigue crack propagation (FCP) rate per cycle (da/dN) is reduced when the fibre content is increased. A normalization of the fatigue crack propagation data can be achieved if the propagation rate per cycle is reported as a function of the strain energy release rate amplitude (ΔG). When the effects of the loading frequency were investigated, it was found that the higher the frequency the lower the FCP rate at any fixed ΔK or ΔG value. A further data analysis indicated that the mechanism of crack growth is primarily based on viscoelastic creep crack growth.

The crack speed (da/dt) as a function of the mean strain energy release rate resulted approximately independent from the frequency at 0.1 and 1 Hz. At higher frequency (10 Hz) an higher crack speed was found, associated with non-isothermal creep processes, as pointed out by measurements carried out by an infrared video camera.

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