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Fatigue fracture of nylon polymers

Part II *Effect of glass-fibre reinforcement*

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The influence of glass fibres on the fatigue crack propagation rates of injection-moulded nylons has been determined. In contrast to previous results for unreinforced nylons, the cracking kinetics are independent of the oscillating load frequency. The fact that the crack growth rate per cycle is constant, when expressed in terms of the time under load, demonstrates that the contribution of creep crack extension is minimized by the glass fibres. Thus a true fatigue process is suggested for the fatigue fracture of the reinforced system, even when the glass fibres are preferentially aligned parallel to the crack growth direction. A complicating factor in characterizing the fatigue resistance of the glass-reinforced nylons is the tremendous influence of fibre orientation on crack growth rate. It is shown that the anisotropy problem can be handled by simply expressing the crack growth rate data in terms of the strain energy release rate rather than the usual stress intensity factor representation. Results for four different glass-filled nylons show that the diverse crack growth rates for cracking parallel versus perpendicular to the glass-fibre axes collapse on to individual strain energy release rate curves. Each single relationship therefore characterizes the fatigue fracture of the filled material and furthermore permits a prediction of the cracking rates for any glass-fibre orientation based upon the expected change in modulus. Finally it is demonstrated that the increased stress dependence of fatigue crack propagation (slope of the Paris plot) in filled nylons can be duplicated in unfilled samples under certain conditions. It is concluded that the fatigue fracture mechanism is matrix dominated in these chopped glass-fibre reinforced materials.

1. Introduction

The first report in this series described the effect of frequency on the fatigue crack propagation rates for unfilled nylon polymers [1]. It was demonstrated that for dry injection-moulded samples, frequencies below 5 Hz are required to avoid the occurrence of significant hysteretic heating at the fatigue crack tip. It was also shown that even under isothermal conditions there is a significant contribution of viscoelastic creep to the fatigue crack growth mechanism. Thus it is not possible to characterize uniquely the fatigue resistance of the unfilled nylons without also taking into account the frequency dependence of the fatigue crack propagation rates. This paper presents results for glass-reinforced nylons with emphasis not only on the influence of cyclic frequency but also on the relationship between glass-fibre orientation and fatigue crack growth rates. Our previous investigation of fatigue fracture in reaction-moulded nylon 6 demonstrated that glass fibres oriented perpendicular to the crack growth direction did retard the fatigue crack [2]. The relatively small effect of the fibre alignment was attributed to the reduced fibre lengths for the milled glasses used in reaction moulding. In addition to an expected increase in glass-fibre length, injection-moulded materials are known to exhibit a more complicated skin–core fibre orientation pattern [3]. Although others have previously investigated the role of fibre alignment on fatigue resistance of reinforced nylons, the results showed little evidence of anisotropy due to the opposing effects of the skin and core structures in the particular mouldings examined [4]. In the present study, an end-gated plaque having a 4:1 length:width ratio was employed in order to orient more highly the glass fibres and observe the role of fibre orientation. Results are presented in terms of the usual stress intensity factor as well as in terms of the strain energy release rate function for cracking parallel versus perpendicular to the glass fibres. Scanning electron microscopy was employed to indicate the extent of fibre alignment and also to provide views of the fatigue fracture and fast fracture regions of the samples.

Finally, this report describes preliminary results for unreinforced nylon 66 which was prepared in a 12.7 mm thick mould. The intent was to determine whether plane strain conditions would greatly modify the fatigue crack propagation rates. A comparison is made between the fatigue fracture behaviour of the glass-fibre reinforced nylon and the unreinforced nylon using the data for the latter under plane strain conditions.

2. Experimental procedure

2.1. Sample preparation

The commercially available nylon resins used in this

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study included two 33% glass-reinforced nylon 66 materials, Zytel 70G33HRL and Zytel FE 5105BK; a 33% glass-filled nylon 6, XPN 1034; and an unreinforced nylon 66, Zytel 122L. For comparison purposes, a 33% glass-reinforced sample of the latter resin was prepared in our laboratory using a twin screw extruder. The glass employed was 1/8 in. ($\sim$ 3.18 mm) chopped fibre, 464AA. All materials were injection moulded into $50.8\ \text{mm} \times 203.2\ \text{mm} \times 3.2\ \text{mm}$ end-gated plaques using standard processing conditions. Following moulding, all plaques were stored in desiccators to maintain their dry as-moulded condition. Samples of Zytel 70G33HRL were moisture conditioned at 50% relative humidity for 6 months to assess the influence of absorbed water on fatigue crack propagation rates at varying frequencies. All other samples were tested in the dry state. The previously reported results for unfilled nylons were also obtained using the 3.2 mm thick plaque. In the present study, additional unreinforced samples were prepared by injection moulding using a thicker plaque having dimensions of $76.2\ \text{mm} \times 127\ \text{mm} \times 12.7\ \text{mm}$.

2.2. Fatigue testing

Compact tension specimens were cut from the plaques according to ASTM E-647 with the orientation of the fatigue crack either parallel or perpendicular to the melt flow direction (see Fig. 1). Fatigue crack propagation measurements were performed as described in the previous report using a video recording system and a separate infrared camera to monitor crack-tip temperatures [1]. Separate grips were required for the thicker samples and, of course, higher loads were needed to achieve the same stress intensity levels as that employed for the 3.2 mm plaques. However, no other changes were made in the fatigue test procedure as the fatigue crack was still visible using the video recording method developed for the thinner plaques. The effect of frequency was investigated over the range 0.1–50.0 Hz using the Zytel 70G33HRL material. All subsequent fatigue crack growth measurements were performed at 5 Hz for the reinforced nylons. Thermography observations demonstrated that crack tip heating did not occur for the filled material at this frequency although significant temperature increases were noted at 50 Hz. For the thicker unfilled nylon 66 plaques, a lower frequency of 0.5 Hz was employed to avoid hysteretic heating at the crack tip.

2.3. Modulus measurements

Modulus measurements were made both parallel and perpendicular to the direction of glass fibre alignment. For this purpose 12.7 mm wide strips were cut from the plaques. The tensile or Young's modulus was determined using an extensometer with a 12.7 mm gauge length at a crosshead speed of $5\ \text{mm}\,\text{min}^{-1}$. Reported values represent an average of six samples.

2.4. Data analysis

Crack propagation data were analysed using an incremental polynomial curve modelling sequence to obtain $\mathrm{d}a/\mathrm{d}N$ values as a function of crack length. The crack growth rate data were subsequently plotted as a function of the oscillating stress intensity factor in the usual Paris equation representation of fatigue results [5], namely

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

The fact that nylon fatigue fracture kinetics follow the Paris equation has been amply demonstrated by the extensive studies of Manson, Hertzberg, and co-workers [6–9] as well as by our earlier reports [1, 2]. In the present study the data for the glass-filled nylons was originally examined using the Paris-type plots; however, an alternative representation of the fatigue crack propagation data was also investigated. This involved plotting the crack growth rate per cycle in terms of the strain energy release rate rather than the stress intensity factor. From basic fracture mechanics principles [10], the strain energy release rate, G, can be calculated from the stress intensity factor, K, and the modulus, E, as follows

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

This expression is strictly true only under plane stress conditions. For plane strain, K^2 is multiplied by an additional term, $(1 - \nu^2)$, where ν is the Poisson's ratio of the material. Under an oscillating loading condition, such as is used in the case of fatigue, we have derived a corresponding expression for the oscillating strain energy release rate which is

$$\Delta G = \frac{(\Delta K)^2}{E}\,\frac{1 - R^2}{1 - 2R + R^2} \tag{3}$$

where R is the load ratio, that is, the minimum load divided by the maximum load. In all of the fatigue experiments described in this report, R was set at 0.1. Thus the expression for ΔG reduces to

$$\Delta G = 1.22\frac{(\Delta K)^2}{E} \tag{4}$$

This expression allows a comparison of the fatigue crack propagation data for cracks growing parallel versus perpendicular to the glass-fibre orientation direction in terms of the energy release rate of the material. All that is required is an independent determination of the modulus of the material in the two orthogonal directions. For the calculations given in this study the Poisson's ratio correction was ignored. By analogy with the Paris equation the crack growth rate per cycle is then given by

$$\frac{\mathrm{d}a}{\mathrm{d}N} = B(\Delta G)^n \tag{5}$$

where B and n are the intercept and slope of the log–log plot of this equation.

2.5. Fractography

The fatigue-fractured samples were examined using an ISI Model DS-130 scanning electron microscope. In addition to defining the extent of glass-fibre orientation, the fracture surface morphology for the stable fatigue crack propagation region was compared to the fast fracture region of the compact tension samples.

3. Results

3.1. Effect of fibre orientation

The orientation of compact tension samples with respect to the injection-moulded plaque is illustrated in Fig. 1. However, it should be emphasized that only one sample was cut from the centre of a given plaque. Therefore, the parallel and perpendicular samples did not come from the very same plaque, but were also from the same exact location in the plaque. In this way any influence of distance from the gate on the glass-fibre orientation was avoided. Parallel samples are so named because the fatigue crack is oriented parallel to the melt flow direction which is also the presumed direction of glass-fibre alignment. Thus, for perpendicular samples the fatigue crack was grown across the direction of fibre alignment. Fig. 2 demonstrates the influence of the glass-fibre orientation on the fatigue crack growth rates for injection-moulded nylon 66. As expected the crack is significantly retarded when the fibres are oriented perpendicular to the growth direction. The fatigue crack grew approximately 15 times faster in the parallel orientation. The data also demonstrate that the sensitivity to stress intensity level (slope of the Paris plot) is increased for both orientations of the glass-reinforced material compared to unreinforced nylon. Furthermore the results in Fig. 2 show the interesting feature that the unfilled and glass-filled data cross over, thus complicating the interpretation of the role of glass fibres. This point will be addressed further in a later section.

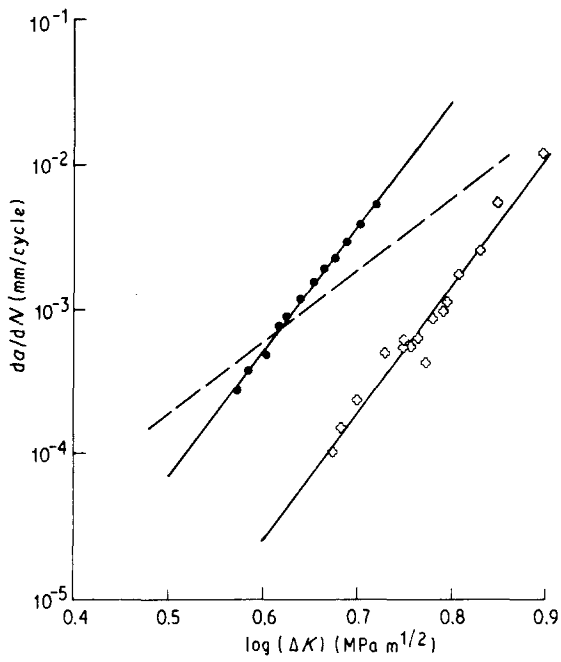

Figure 2 Fatigue crack propagation rates for glass-filled injection-moulded nylon 66 (Zytel 70G33HRL) versus stress intensity factor for crack growth (●) parallel or (◇) perpendicular to the melt flow direction. (– – –) Unfilled nylon 66.

The degree of fibre orientation in the injection-moulded samples is indicated by the micrographs in Fig. 3. In terms of a simple skin–core model the sample cross-section consists of a thick skin, covering approximately 85% of the total sample thickness, and a relatively thin core section representing the remaining 15%. The glass fibres in the skin region are highly aligned parallel to the melt flow direction while in the core they are perpendicular to flow. Thus, these particular plaques are a composite of the two layers with the thicker aligned skin regions dictating the anisotropy in crack propagation kinetics shown in Fig. 2. The fractography results also revealed a clear distinction between the fatigue fracture and the fast fracture regions of the compact tension samples (Fig. 4). In the region of stable fatigue crack growth the glass fibres are debonded from the nylon matrix and extensive ductile tearing of the nylon is also evident. Deformed holes or wells are clearly seen around the individual fibres. The roughness of the fracture surface, particularly evident in Fig. 3a, suggests that the crack may have propagated around fibre bundles or agglomerates of glass fibres. In contrast to the fatigue fracture, the fast fracture produced a surface with very little evidence of matrix deformation and with more definite indications of fibre to matrix adhesion. Although it is

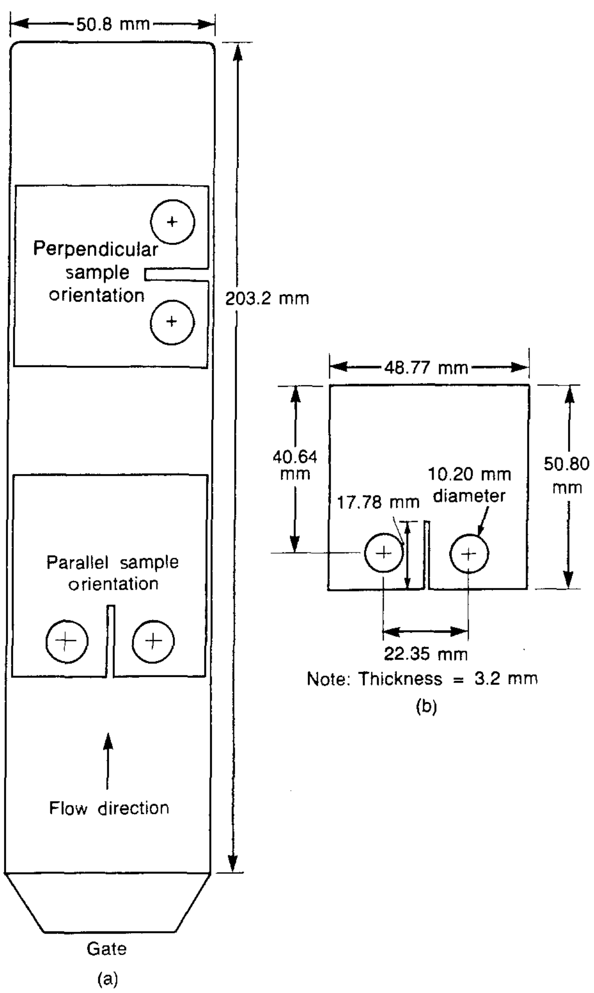

Figure 1 Diagram of injection-moulded plaque showing compact tension sample: (a) orientation and (b) dimensions.

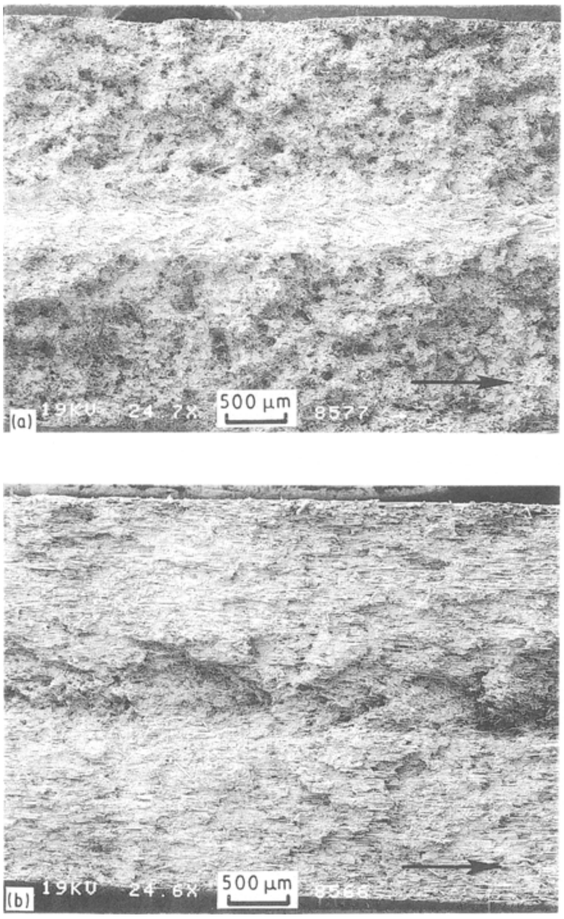

Figure 3 Fracture surfaces of glass-filled injection-moulded nylon 66 showing the extent of glass-fibre alignment for samples with the crack growth (a) perpendicular and (b) parallel to the melt flow direction. × 25.

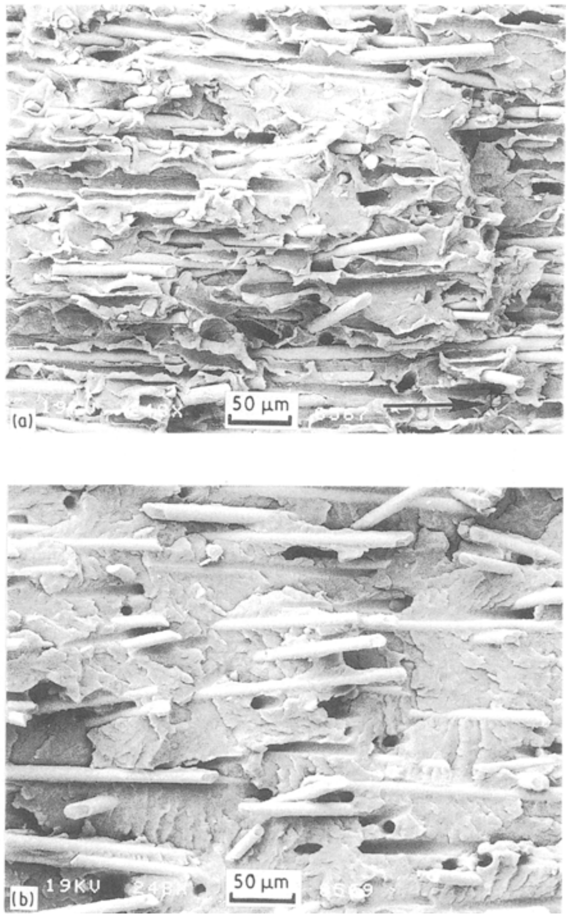

Figure 4 Comparison of (a) fatigue fracture and (b) fast fracture surfaces (× 25) of glass-filled injection-moulded nylon 66 for crack growth parallel to the melt flow direction.

possible to differentiate the fatigue and fast fracture regions of the samples, there is no clear distinction between the two different glass orientations in terms of the degree of fibre pull-out, fibre breakage, or fibre debonding. Obviously the parallel orientation provides an easier path for crack advance by a debonding mechanism without necessitating large jumps out of the crack plane. However, it is not apparent that extensive fibre breakage occurs in one case (perpendicular) and not the other (parallel).

3.2. Effect of frequency

Because an earlier study had demonstrated that the crack growth rates for unreinforced nylon increase rapidly with a decrease in test frequency, it was of interest also to define the frequency dependence for the reinforced material. To maximize any contribution of the matrix, the measurements were made using samples cut in the parallel orientation and data were compared at frequencies of 0.1, 0.2, 0.5, 1.0 and 5.0 Hz where no hysteretic heating occurred. In order to compare the results with the unfilled nylon, the crack propagation rates were taken from the Paris plots at the same stress intensity level used previously [1], namely $\Delta K = 3.98\ \mathrm{MPa\,m^{1/2}}$, or $\log \Delta K = 0.6$. Fig. 5 shows the crack growth rates at each frequency for the glass-filled nylon in terms of the time period of the

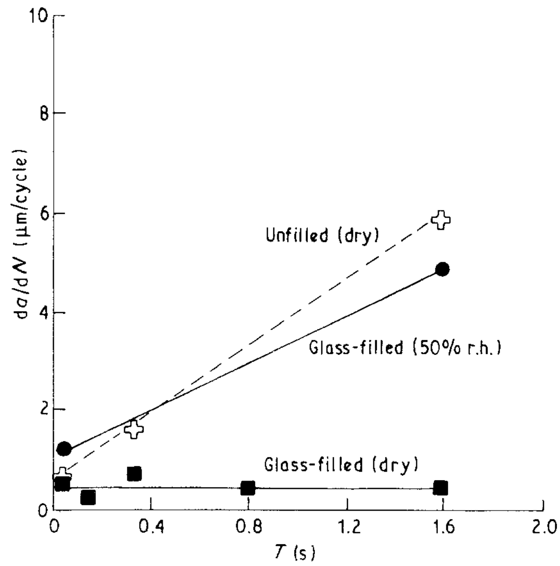

Figure 5 Fatigue crack propagation rates for nylon 66 versus the time period of the oscillating load.

cyclic oscillation. In sharp contrast to the results for the unfilled material the glass-reinforced nylon exhibited no dependence on time under load, in other words no frequency dependence. Following the previously described analysis [1], the slope of zero for the dry glass-reinforced nylon 66 indicates that there is no creep contribution to the fatigue crack growth. Thus the entire amount of crack extension per cycle is attributed to a true fatigue process.

The influence of absorbed moisture was also assessed by equilibrating the glass-reinforced material in a 50% relative humidity environment prior to performing the fatigue test at two different frequencies, 0.1 and 5.0 Hz. The effect of the moisturizing treatment is also shown in Fig. 5. An increase in the crack growth rates as well as in the slope of the line for the moisturized nylon indicates that a significant creep contribution arises due to the plasticizing effect of the water. In fact, the moisturized glass-reinforced nylon 66 and the dry unreinforced material give similar results.

3.3. Strain energy release rate

Although the frequency independence exhibited by the glass-filled nylon simplifies the characterization of the fatigue resistance, the orientation dependence complicates the situation. Obviously for any given fibre-reinforced material a variety of Paris plots may be observed depending on the specific skin–core morphology of the plaque examined and the relationship between the crack growth direction and the fibre axes. To simplify, possibly, the task of characterizing fatigue resistance, the fatigue crack propagation data for cracking either parallel or perpendicular to the predominant fibre orientation direction were replotted in terms of the strain energy release rate. As described earlier in this report, this required only a separate determination of the tensile modulus of the material in order to calculate ΔG in place of ΔK. Table I lists the various moduli for several different glass-filled nylon 6 and nylon 66 samples. Because the terms parallel and perpendicular were defined in relation to the crack growth direction during fatiguing, the same nomenclature is retained here. Thus for parallel samples the load axis is actually perpendicular to the predominant fibre orientation direction whereas the fracture path is still parallel to the glass-fibre orientation direction. Similarly, for the perpendicular samples it is the fracture or crack growth direction that is perpendicular to the glass fibres, whereas the load axis is now parallel to the fibres. Thus it can be understood why the highest moduli are observed for the perpendicular samples and the corresponding parallel samples exhibit moduli which are reduced by 1/3 to 1/2. The latter are still significantly higher than the modulus of the unfilled nylon 66.

TABLE I Tensile moduli of injection-moulded nylons

Sample	Modulus (GPa)	
	Parallel	Perpendicular
Unfilled nylon 66	3.3	3.3
Zytel 70G33HRL (fast fill)	7.1	14.8
Zytel 70G33HRL (slow fill)	7.0	11.6
FE5105 BK	7.3	10.2
GMR system	6.9	11.3
XPN 1034	5.6	9.4

Fig. 6 shows the $\mathrm{d}a/\mathrm{d}N$–ΔG plots calculated from the measured moduli along with the corresponding $\mathrm{d}a/\mathrm{d}N$–ΔK data (from Fig. 2). Both the parallel and the perpendicular data sets collapse on to a single line on the ΔG plot. This is an extremely important finding for several reasons. First, it suggests that in spite of the very real differences in crack propagation rates for different glass orientations under the same loading conditions, equal growth rates can be anticipated on an equal energy input basis. Second, it suggests that there is no fundamental difference in the mechanism for propagating a crack parallel versus perpendicular to the glass-fibre reinforcement. Thus it is difficult to postulate that the mechanism for perpendicular cracking involves primarily fibre breakage, whereas parallel cracking involves mostly matrix fracture. Finally, and of the most practical significance, the results of Fig. 6b indicate that the fatigue resistance of the glass-reinforced nylon can be completely characterized by the $\mathrm{d}a/\mathrm{d}N$–ΔG relationship. This requires the measurement of only a single set of crack propagation data along with a corresponding modulus determination. Once the general $\mathrm{d}a/\mathrm{d}N$ versus ΔG plot has been established, crack propagation data sets for all other orientations can be predicted based solely on the corresponding moduli changes.

Considering the potential value of the results using the ΔG analysis, it was of interest to investigate the generality of the finding by examining a variety of glass-filled systems and moulding conditions. For example, data are shown in Fig. 7 for the same glass-filled system which was injection moulded under a slow fill speed. In spite of the difference in crack growth rates at a given ΔK level, it is again seen that the data sets for cracking parallel and perpendicular to the glass-fibre orientation can be represented by a single line when represented in terms of ΔG. Fig. 8 shows a similar pattern for another commercially available glass-filled nylon 66 material which contains a small amount of carbon black for pigmentation. Although somewhat greater data scatter is noted, owing to the black colour masking the crack tip in the video image, it would be difficult to separate the cracking rates on a ΔG basis.

An additional example was obtained by preparation of a 33% glass-filled nylon 66 in our laboratory using a twin screw extruder. The fatigue crack propagation results for this filled system are given in Fig. 9. As with the commercially available materials, the anisotropic crack growth rates collapse on to a single line using the ΔG analysis. As a final example, the ΔG analysis was applied to a glass-filled nylon 6 material (XPN 1034). The results for this sample (Fig. 10) do not coincide exactly on the ΔG plot; however, the slight offset is within the experimental error expected for the crack propagation data and the modulus measurement.

All of the above examples confirm the generality of the finding that the ΔG analysis allows a simplified method of characterizing the fatigue behaviour of

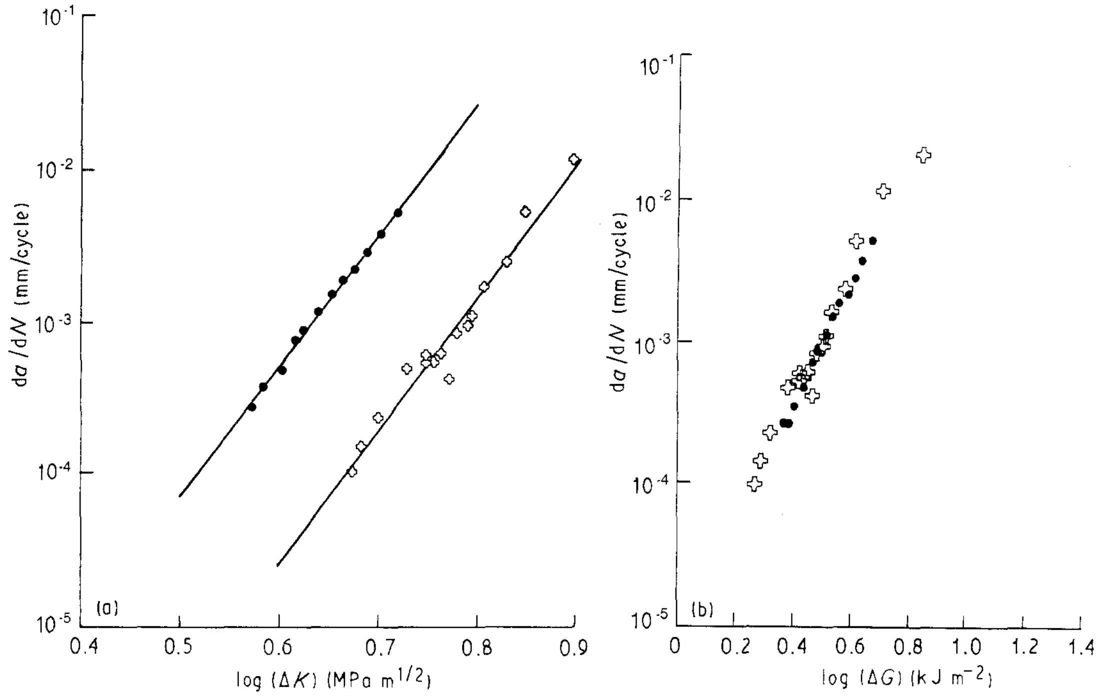

Figure 6 Fatigue crack propagation rates for cracking (●) parallel or (✧) perpendicular to the glass-fibre orientation in glass-filled nylon 66 (Zytel 70G33HRL) as a function of (a) stress intensity factor (ΔK) and (b) strain energy release rate (ΔG).

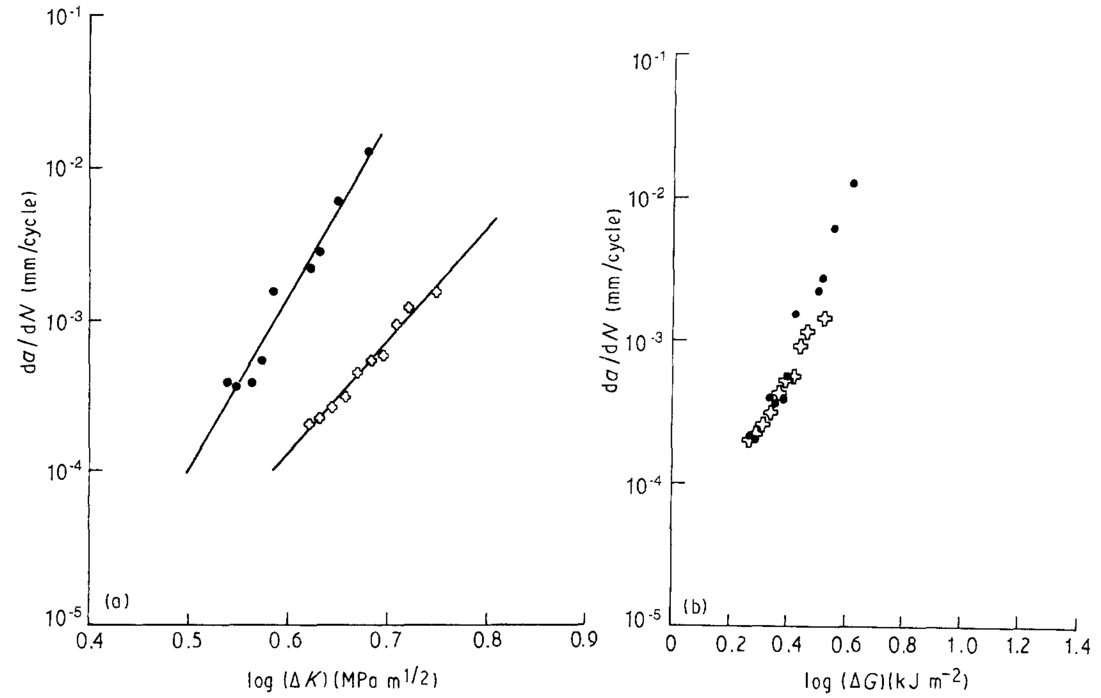

Figure 7 Fatigue crack propagation rates for glass-filled nylon 66, moulded under slow fill speed conditions, as a function of (a) stress intensity factor (ΔK) and (b) strain energy release rate (ΔG). (●) parallel, (✧) perpendicular.

anisotropic glass-filled nylons. This simplified representation in turn permits a straightforward comparison of different glass-filled systems in terms of the magnitude of the crack growth rate at a given ΔG level. Although a composite plot is not shown, another interesting observation is that the crack propagation kinetics for all of the glass-reinforced nylon 66 materials are nearly equivalent when examined on a ΔG basis.

3.4. Unreinforced nylon

In attempting to understand the influence of reinforcing fillers on fatigue fracture behaviour there is a need not only to compare various reinforced systems with each other but also to compare the reinforced system with the unfilled matrix. A review of the earlier crack propagation measurements for nylon 66 with and without glass-fibre reinforcement shows that such a comparison is difficult to interpret. The reason is

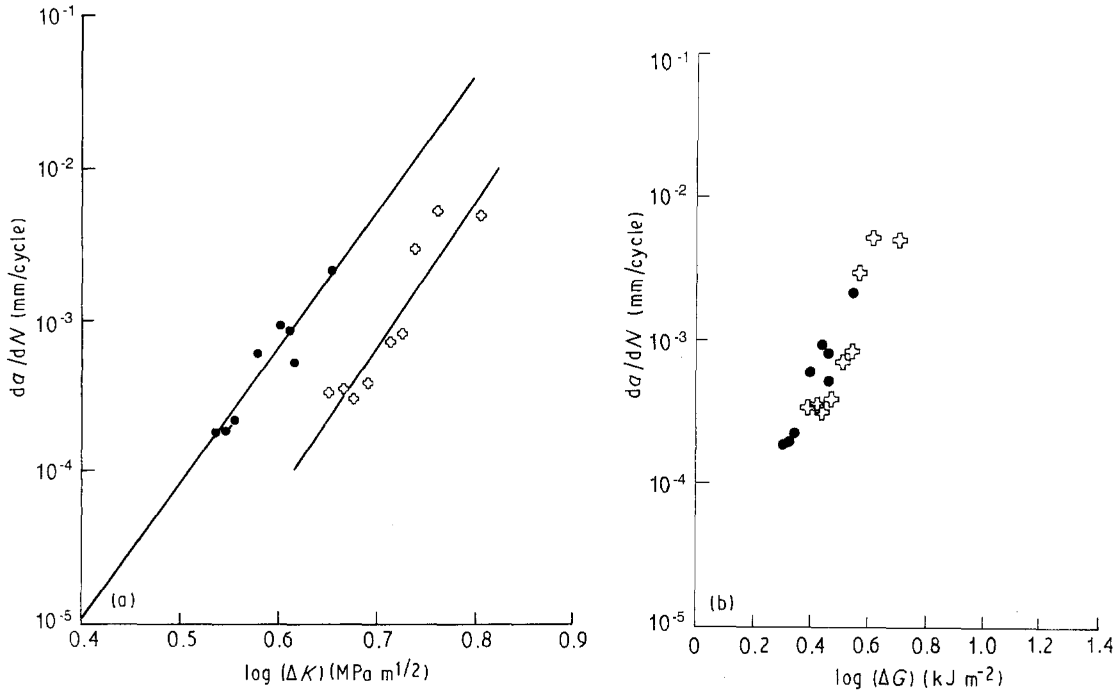

Figure 8 Fatigue crack propagation rates for Zytel FE 5105 glass-filled nylon 66 as a function of (a) stress intensity factor (ΔK) and (b) strain energy release rate (ΔG). (●) parallel, (✧) perpendicular.

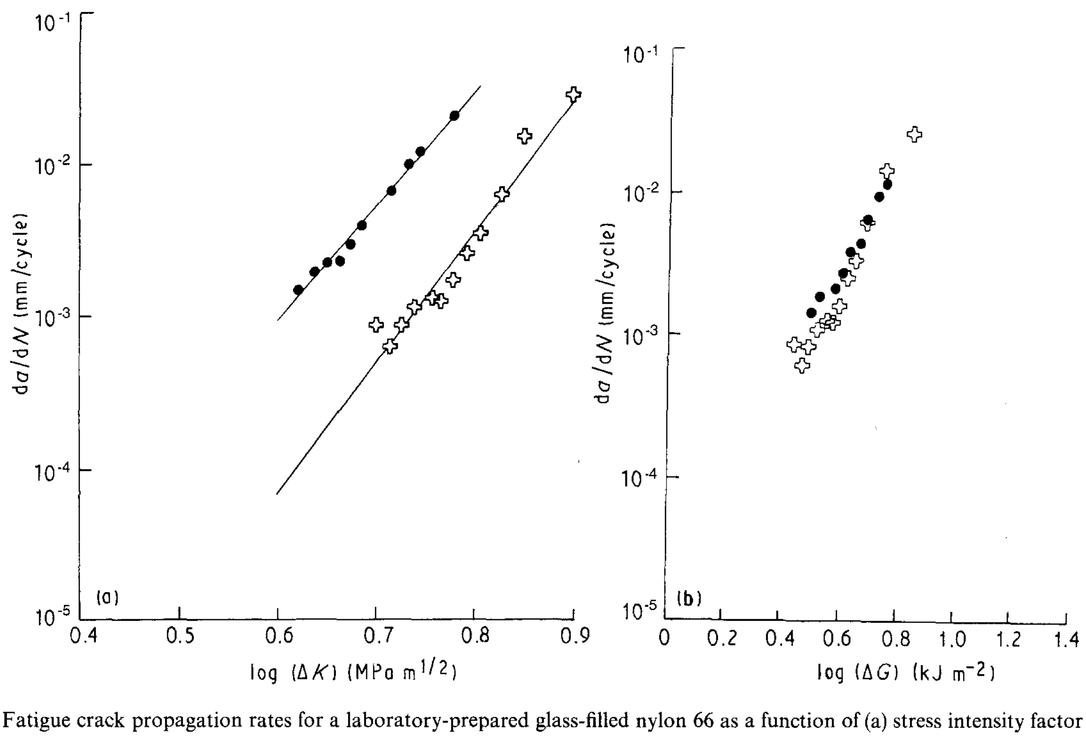

Figure 9 Fatigue crack propagation rates for a laboratory-prepared glass-filled nylon 66 as a function of (a) stress intensity factor (ΔK) and (b) strain energy release rate (ΔG). (●) parallel, (✧) perpendicular.

simply that the dependence of crack growth rate on ΔK is radically different for the two materials. This stress dependence can be quantified by the exponent m in the Paris equation which is given by the slope of the $\mathrm{d}a/\mathrm{d}N$–ΔK plot. For the unfilled nylon, values of m are typically 4–6, whereas the glass-filled materials exhibit values closer to 10. As shown in Fig. 11 the different slopes can result in a situation whereby the unreinforced nylon cracks at a faster rate at low ΔK but cracks at a slower rate at high ΔK. The ΔG analysis does not provide an entirely satisfactory solution to this problem because the difference in slopes of the crack propagation data is not changed by the ΔG calculation.

A second difficulty in the comparison of unfilled and reinforced nylon is that the state of stress at the fatigue crack tip is expected to be quite different in the two materials. Based upon fracture mechanics principles the unfilled nylon, having a lower yield stress, undergoes more of a plane stress fracture while the reinforced nylon is closer to plane strain. It is well known that thicker samples more closely approximate

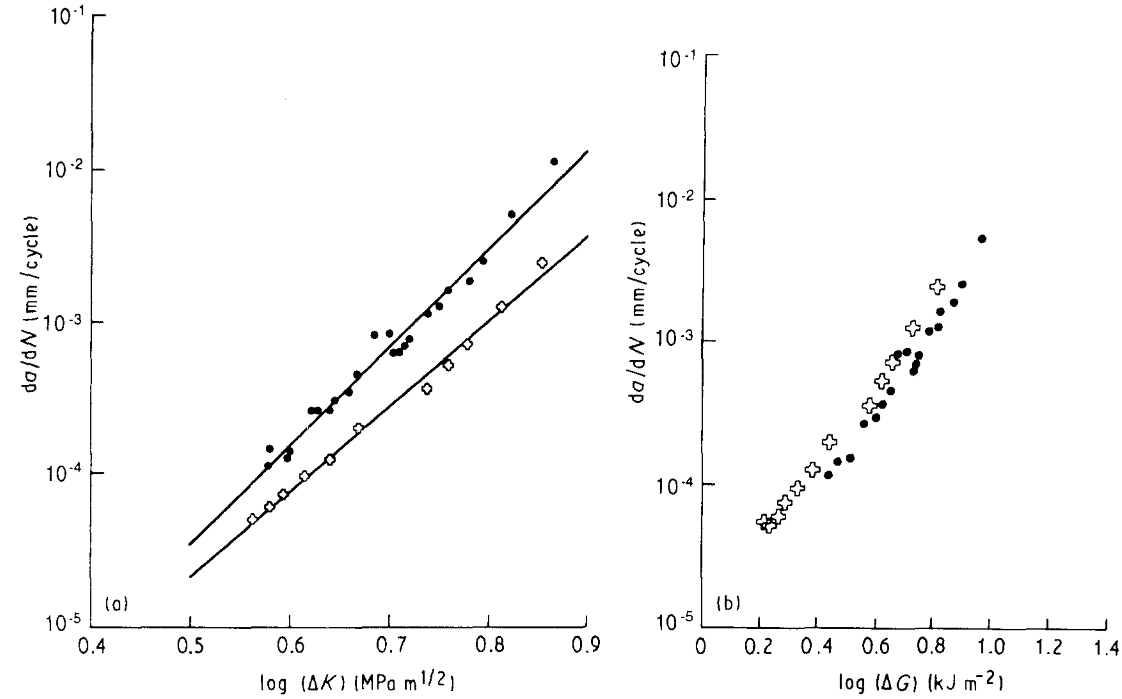

Figure 10 Fatigue crack propagation rates for glass-filled nylon 6 as a function of (a) stress intensity factor (ΔK) and (b) strain energy release rate (ΔG). (●) parallel, (✧) perpendicular.

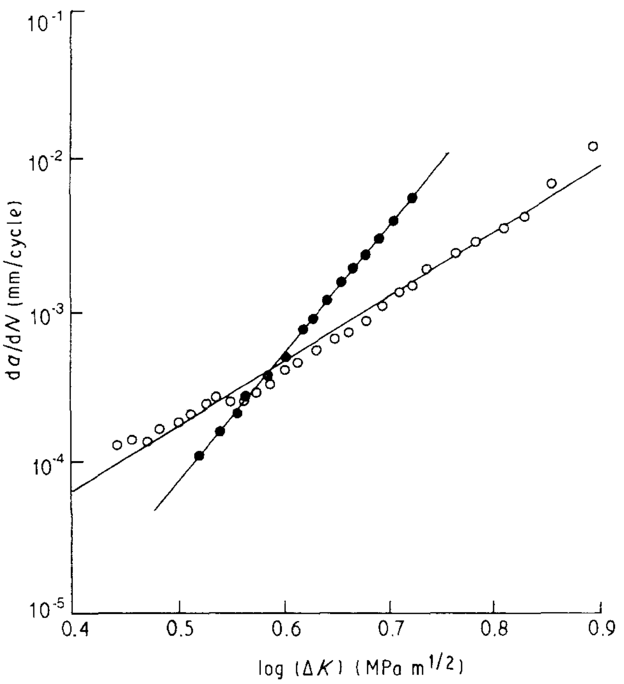

Figure 11 Fatigue crack propagation rates as a function of stress intensity factor (ΔK) for (○) unfilled and (●) glass-filled nylon 66 using 3.2 mm thick plaques.

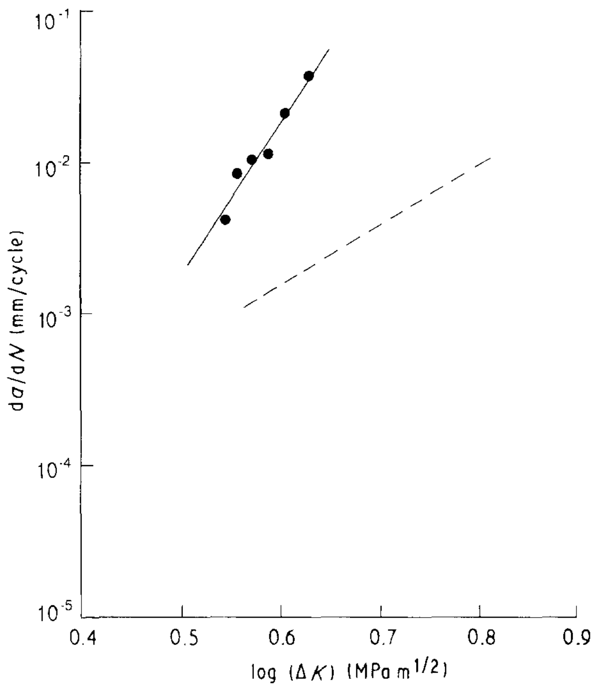

Figure 12 Fatigue crack propagation rates as a function of stress intensity factor (ΔK) for unfilled nylon 66 using a 12.7 mm thick sample. (– – –) Results using a 3.2 mm thick sample at the same frequency.

plane strain conditions and for this reason a variable thickness plaque mould was fabricated to prepare thicker injection-moulded samples. Using this mould it was possible to prepare 12.7 mm thick plaques of the unfilled nylon. Fatigue crack propagation measurements were then conducted using a frequency of 0.5 Hz to avoid hysteretic heating effects. The results are shown in Fig. 12. In addition to observing generally faster crack growth rates under conditions closer to plane strain, the data in Fig. 12 show the unexpected result that the slope, m, of the Paris equation plot is significantly increased for crack propagation in the thicker plaque. For example, a value of $m = 5$ was measured for the thinner plaque whereas a value of 9 was obtained for the data in Fig. 12. Repeated experiments at various frequencies have confirmed the higher slope and the accelerated growth rates for these particular plaques. A more detailed study of the influence of sample thickness and processing history on fatigue fracture will be the topic of a future report.

Of significance to the present study is the observation that the higher slope of the crack propagation data for the thicker unfilled nylon plaque is, in fact, comparable to the slope measured for the glass-filled nylon using the 3.2 mm thick plaques ($m = 8$–10). Most importantly, these results allow a meaningful comparison to be made between the fatigue data for the unreinforced and glass-filled nylons. For example the results shown in Fig. 13, comparing the unfilled and glass-filled materials, indicate that the crack propagation rates are consistently higher in the unfilled nylon 66 even at high ΔK levels. The influence of fibre orientation on crack growth rates also provides a consistent trend when the comparison is made with the data from the thicker plaques. Moreover, using the same data, it is also possible to compare the results in terms of the strain energy release rate concept as shown in Fig. 14. The data for the unfilled nylon 66 fall on the same line as both sets of data for glass-filled nylon 66 (3.2 mm thick plaque). Thus, we are led to the startling conclusion that there is no discernible difference between the reinforced and unreinforced nylons as far as the fatigue crack growth rate at a given level of energy input is concerned. Unfortunately, this simplified view does not hold up upon further scrutiny because it has been determined that the fatigue fracture of the thicker unreinforced nylon plaques still exhibits a frequency dependence. In addition, it has also been determined that the fatigue crack propagation behaviour depends upon the processing history. Thus a truer comparison of the reinforced and unreinforced nylons in terms of strain energy release rate takes on the form shown in Fig. 15. The unreinforced nylon must be represented by a range of possible data sets. From the available results, the glass-reinforced material appears coincident with the worst case condition, i.e. fastest crack growth rates observed, of the unreinforced nylon. However, even more accelerated crack growth rates may be expected under conditions which embrittle the material and, at this time, there is no criterion for selecting a specific data set for such comparisons. Still, the results shown here are very

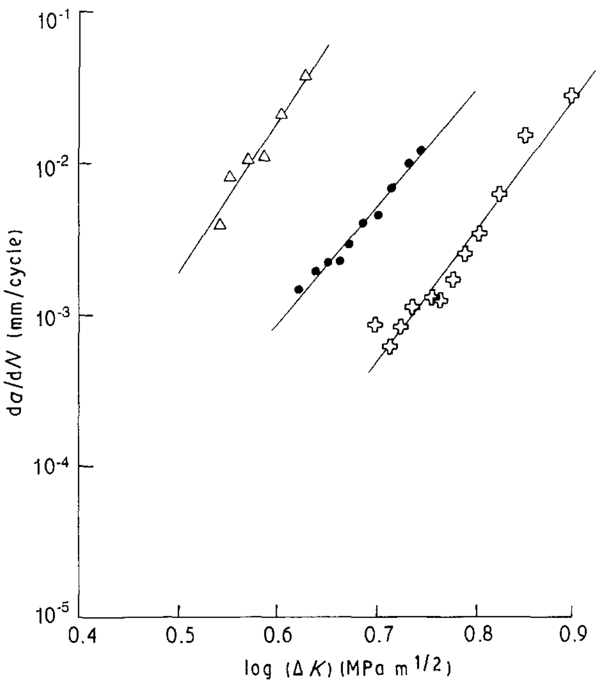

Figure 13 Comparison of fatigue crack propagation rates versus stress intensity factor (ΔK) for (△) unfilled nylon 66 under plane strain conditions (12.7 mm plaque) and for the same nylon 66 with 33% glass fibres, (●) parallel and (✧) perpendicular to the melt flow direction.

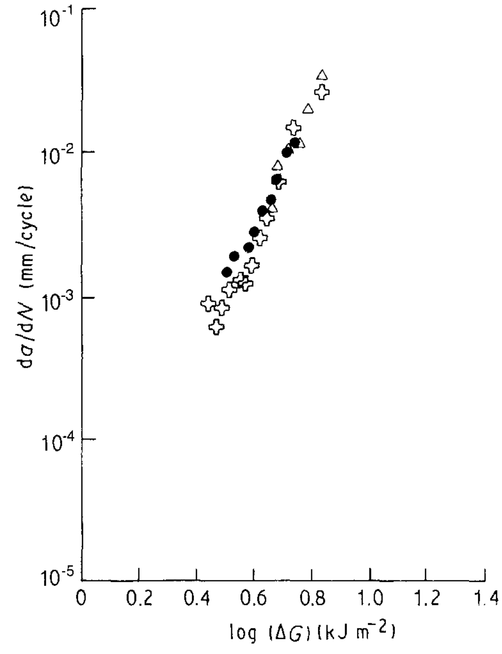

Figure 14 Comparison of fatigue crack propagation rates for (△) unfilled and glass-filled nylon 66 (●) parallel and (✧) perpendicular to the melt flow direction as a function of the strain energy release rate (ΔG).

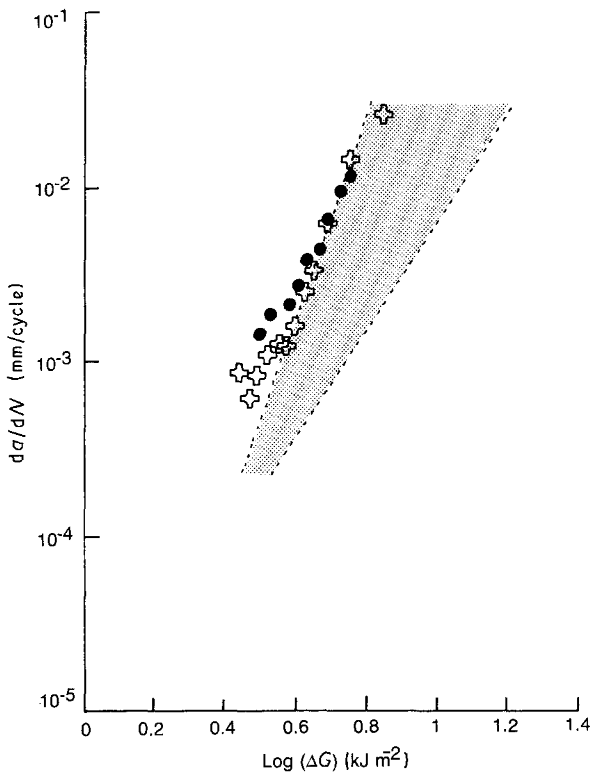

Figure 15 Comparison of the fatigue crack propagation rates for unfilled (shaded area) and glass-filled nylon 66 (●) parallel and (✧) perpendicular to the melt flow direction as a function of the strain energy release rate (ΔG).

interesting because they demonstrate that the reinforcing glass fibres do not necessarily retard the rate of growth of fatigue cracks compared to the unreinforced nylon, especially when the results are expressed in terms of the strain energy release rate. The results also suggest that the reinforcing glass fibres have a dual role in their effect on fatigue crack propagation. First, they place the nylon matrix under plane strain conditions thereby changing the sensitivity to stress and possibly accelerating fatigue crack growth. Second, they provide increased stiffness which, at least under constant load conditions, results in a retardation of the crack growth rate.

4. Discussion

This study and the earlier investigation of the influence of loading frequency on fatigue crack propagation rates for unfilled nylons, demonstrated a major difference between the crack growth mechanisms for unreinforced versus glass-fibre reinforced nylon 66. The unfilled nylon exhibits a strong frequency dependence whereas the glass-filled material showed no effect whatsoever. These results clearly show that viscoelastic creep is involved in the low-frequency fatigue of the unfilled nylon 66 but not for the filled material. For the latter a true fatigue fracture process is indicated with each loading cycle causing the same amount of damage and consequent crack extension. Further time-dependent crack extension is apparently impeded by the well-bonded or unbroken glass fibres. In addition to providing an important clue concerning the fracture mechanism, the frequency independence has a very important practical consequence. It suggests that the use of high frequencies is a viable method to accelerate fatigue testing. This is even more attractive when one recognizes that the onset of significant hysteretic heating is also shifted to higher frequencies for the glass-reinforced nylon.

This study has also demonstrated the dominant role that glass-fibre orientation has on the kinetics of fatigue crack propagation. Obviously the degree of anisotropy will depend upon the skin–core morphology of the injection-moulded plaque. Others have reported very little difference in crack growth rates measured parallel versus perpendicular to the fibre orientation direction for samples taken from 3 in × 6 in (~ 7.62 cm × 15.24 cm) plaques having nearly equal skin and core thicknesses [4]. The use of a 2 in × 8 in (~ 5 cm × 20 cm) plaque in the present study was sufficiently different in length-to-width ratio to produce a thicker oriented skin layer thus providing the observed anisotropy. It is interesting to note that some injection-moulded parts exhibit even thicker oriented skin regions to the point that the core is practically nonexistent. Thus even larger differences in crack growth rates may be expected for such plaques. In spite of the widely different fatigue crack propagation rates for the parallel and perpendicular growth directions, the results of this study strongly suggest that the fracture mechanism is similar for both orientations. This is supported by the similar stress dependencies (slopes of the Paris plots) and most convincingly by the collapse of the different crack propagation data sets on to a single ΔG plot. It is believed that in both cases the fatigue crack advances by a matrix-dominated fibre avoidance mechanism, as has been suggested by others [11]. This is easier to envisage for cracking parallel to the glass fibres. However, even in the perpendicular orientation, the fracture surface is compatible with the fibre avoidance mechanism because the scale of the surface roughness is of the same order as the fibre lengths. The latter were determined to be 100–300 μm in the moulded plaques used in this study which is typical of glass-reinforced materials [12, 13]. Thus, on a local scale, the crack appears to be advancing by moving around bundles or groups of fibres rather than through them. Of course there are indications on the fracture surfaces of glass-fibre breakage also, although it is difficult to quantify. Because of the collapse of the da/dN data on to a single curve in the ΔG representation, and the fracture surface features, it is suggested that fibre breakage is not the rate-controlling mechanism. If it were, then more breakage should have occurred for the perpendicular orientation with presumably a different ΔG relationship.

The strain energy release rate analysis is also of particular significance because it simplifies the seemingly impossible task of characterizing the fatigue fracture resistance of the glass-reinforced nylons. The strong dependence of fatigue crack growth rate on fibre orientation, when expressed in terms of stress intensity level, indicated that a multitude of da/dN data sets could be obtained from any particular sample. However, the ΔG analysis suggests that regardless of the orientation in a particular plaque, a unique master curve can be generated from one set of da/dN data and a modulus determination. The multitude of da/dN versus ΔK relationships can then be calculated from the measured variations in modulus. Similarly, it may also be possible to predict the fatigue behaviour of various reinforced materials from modulus predictions. It would of course be invaluable to test first the validity of the ΔG results through direct measurements of the strain energy release rate during the crack propagation experiment. This is currently being investigated.

The preliminary data for unfilled nylon using very thick plaques provides a link between the fatigue fracture of the unreinforced and glass-filled systems. Based upon the frequency effects alone, one might not expect that a simple or straightforward relationship could exist between the fatigue fracture of filled and unfilled nylon 66. The strain energy release rate analysis results are therefore surprising, not only in bringing together the data for different glass-fibre orientations, but also in demonstrating that there can be very little difference in the filled versus unfilled nylon in terms of the relationship between crack growth rate and the calculated strain energy release rate. A major reason for finding such a relationship is, of course, the desire to investigate the fatigue fracture process of the unfilled nylon under plane strain conditions. Not only were the crack growth rates increased at all ΔK levels for the thicker plaque, but the slope of the Paris equation plot was also doubled. Based upon available criteria, using the yield stress and fracture toughness of nylon 66 [8], the thickness required to achieve plane strain is 9 mm. Thus the 12.7 mm thick plaque should be well above the needed thickness and further increases should produce no effect. However, recent results in our laboratory have demonstrated that a unique relationship does not exist between the sample thickness and the Paris plot slope. Therefore it appears that it is not simply a matter of whether or not plane strain conditions exist at the crack tip, but also a question of to what extent material variables also restrict shear yielding in the nylon matrix. The latter can be influenced by thermal history and crystalline morphology as well as thickness. At the present time we must conclude that a unique da/dN–ΔK relationship does not exist for unfilled nylon, even under plane strain conditions. Moreover it is not presently clear a priori how to prepare a sample of unreinforced nylon which represents a true control (i.e. duplicates the local conditions of restricted yielding) for the reinforced nylon. Admittedly the wish to achieve this goal may have been an oversimplification of the fatigue fracture process. Still, the results presented here suggest the need for similar measurements in other materials, for example in polymers which exhibit no frequency dependence in the unfilled condition and which are less dependent on thermal history or processing conditions.

As a final point we wish to note that a somewhat puzzling feature arises from the comparison of fatigue results with the fracture surfaces. The lack of a frequency sensitivity would seem to imply that extensive matrix deformation is not involved in the fatigue fracture process for the glass-filled material. Similarly, this extensive ductile drawing around the glass fibres is perhaps not expected for a plane strain fracture process. Although explanations can be proposed for this apparent contradiction, more detailed information concerning the sequence of events during fatigue fracture is clearly needed.

5. Conclusions

1. A true fatigue process (frequency independent) is observed for glass-filled nylon.

2. Glass-fibre orientation strongly influences the fatigue crack propagation rates under constant ΔK conditions; however, no distinction can be made between crack growth rates parallel versus perpendicular to the fibre axes in terms of strain energy release rates.

3. Under certain preparation conditions the fatigue crack propagation rates for unreinforced injection-moulded nylon are identical to those observed in glass-fibre reinforced nylon when expressed in terms of strain energy release rate.

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