Temperature and Frequency Effects on Fatigue Crack Growth in Acrylonitrile–Butadiene–Styrene (ABS)

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SYNOPSIS

Fatigue crack growth (FCG) in a commercial-grade acrylonitrile–butadiene–styrene (ABS) over the temperature and frequency ranges of 10–70°C and 0.01–10 Hz was studied. A model for the effects of temperature and frequency on the FCG rate was refined. The refined model is shown to accurately predict FCG rates in ABS. Three different types of fatigue fracture surfaces have been found. The first type is characterized by discontinuous growth bands; the second, by a rather smooth surface; and the last, by a rough surface relative to the second. The transition between the first and second types was found to be dependent on temperature and frequency as well, whereas the transition between the second and last types was found to be only dependent on temperature. These findings are discussed in relation to crazing. The apparent activation energy (ΔH_{th}) was evaluated for both the first and second types to be 19.22 kJ/mol. © 1995 John Wiley & Sons, Inc.

INTRODUCTION

Structural polymers are often found to be subject to cyclic loading rather than to static loading. Hence, the lifespans of structural polymers largely depend on fatigue crack growth (FCG).[1] Major factors affecting the FCG are known to include temperature and the frequency of loading. In general, the FCG rates increase as the temperature increases while they decrease as the frequency increases. For example, FCG rates in polystyrene (PS),[2] poly(vinyl chloride) (PVC),[3] unplasticised poly(vinyl chloride) (uPVC),[4] acrylonitrile–butadiene–styrene (ABS),[5] poly(methyl methacrylate) (PMMA),[6] and polysulfone (PSF)[7] all increase with increasing temperature at a given stress intensity factor range, ΔK, although some polymers, such as polycarbonate (PC),[8] show a somewhat anomalous response in FCG rates to temperature. FCG rates, on the other hand, in PS,[7] poly(phenylene oxide) (PPO)/high-impact polystyrene (HIPS) blend,[7] PVC,[3] uPVC,[9,10] and PMMA[6] all decrease with increasing frequency although exceptions have been reported.[6] One of the reasons for the exceptions is that hysteretic heating at high frequencies softens material and, hence, leads to a higher degree of chain mobility, thus increasing the FCG rates.[6] As such, it has been recognized that there is a general equivalence between temperature and frequency. In other words, increasing the frequency has the equivalent effect on the FCG rates of decreasing the temperature. To quantify such a relationship between the temperature and the frequency, recently, Kim and Wang[9] proposed a model for the FCG rate, da/dN, following an attempt by Michel and Manson[6,11,12]:

$$\frac{da}{dN} = \left(\frac{f}{f_r}\right)^{-nm} \left(B \exp\left[-\frac{\Delta H_{th} - \gamma \log \Delta K}{RT}\right]\right)_r \quad (1)$$

where nm, γ, and B are constants; f, the frequency of loading; ΔH_{th}, the apparent activation energy independent of ΔK or the apparent activation energy at unit ΔK; R, the gas constant (8.31 J/mol K); and T, the absolute temperature and the subscript, r, denotes the reference.

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Journal of Applied Polymer Science, Vol. 57, 811–817 (1995)

The model may be refined as follows: Since eq. (1) has been developed for the region governed by the Paris power law

$$\frac{da}{dN} = A\Delta K^m \qquad (2)$$

where A is a constant, it can be equated to eq. (2) after taking logs on both equations. Then, the following relations are obtained:

$$m = \frac{\gamma_r}{RT \ln 10} \qquad (3)$$

and

$$\log A = \log f^{-nm} + \log C - \frac{\Delta H_{th}}{RT \ln 10} \qquad (4)$$

where C is B_r / f_r^{-nm} It should be noted that the constant B in eq. (1) is dependent on a reference frequency. However, the constant C here is independent of frequency and temperature as well. Also, eq. (3) indicates that the γ_r is independent of frequency and temperature. Hence, the subscript r in eq. (1) is allowed to be removed and eq. (1) becomes

$$\frac{da}{dN} = f^{-nm} C \exp\left[-\frac{\Delta H_{th} - \gamma \log \Delta K}{RT} \right] \qquad (5)$$

This equation expresses the combined effects of frequency and temperature on the FCG rate.

This article demonstrates the applicability of eq. (5) to ABS, which is a two-phase polymer, and investigates its FCG when subjected to variations of temperature and frequency. Also, results of a fractographic examination of FCG in ABS are described and discussed in relation to crazing.

EXPERIMENT

Single-edge-notched (SEN) specimens for fatigue tests 70 × 210 mm^2 were cut from an extruded sheet (3 mm thick) of commercial ABS with an approximate molecular weight average of 1.2×10^5. The glass transition temperature of the ABS, 115°C, was obtained from a Rigaku Thermoflex 1500 thermal analyzer with a heating rate of 10°C/min. The tensile strength of the material was determined at 23°C to be 46 MPa. FCG was monitored by a computerized data acquisition system using a conductive surface grid (1 mm spacing between grid lines) printed on a specimen interfaced with an MTS closed-loop servo hydraulic fatigue testing system (Model 810.03). The principles of this data acquisition system are given elsewhere.[13] FCG data were collected at crack lengths approximately between 10 and 35 mm. A temperature chamber with an accuracy of ±1°C was used to control fatigue test temperatures: Subambient temperatures were controlled in a flowing nitrogen gas environment. The frequency range employed was between 0.01 and 10 Hz with a sinusoidal wave form and the tests were made at a stress ratio of 0.1. A scanning electron microscope (JEOL JSM-840) was used for fractography.

RESULTS AND DISCUSSION

Fatigue Crack Growth Data

Figure 1(a)–(d) shows the effect of frequency on FCG rates at different temperatures. Data of macroscopic FCG rates associated with discontinuous growth (DG) bands are included in Figure 1. The FCG rates obtained at 70°C (0.1–10 Hz), at 50°C (0.01–10 Hz), at 30°C (0.1–10 Hz), and 10°C (0.1–10 Hz) are given in Figures 1(a)–(d), respectively. These results show that FCG rates decrease with increasing frequency at all temperatures. It is seen that the frequency effect on FCG rates at 10°C is not as significant as that at higher temperatures, although the FCG rates appear to be affected by both temperature and frequency. The Paris power law constants obtained from experiments are listed in Table I.

Scanning Electron Microscopy (SEM)

The fracture surfaces of SEN specimens were examined using SEM. The three typical features at $\Delta K = 1$ MPa$\sqrt{m}$ are given in Figure 2. The first [Fig. 2(a)] is characterized by DG bands; the second [Fig. 2(b)], by a rather smooth surface; and the last [Fig. 2(c)], by a rough surface relative to the second. Test conditions for the different features of fracture surface are listed in Table II.

The DG bands were found at 70°C, 0.1 Hz, between ΔK = 0.77 and 1.69 MPa$\sqrt{m}$, and at 50°C, 0.01 Hz, between ΔK = 0.83 and 1.32 MPa$\sqrt{m}$, but found to be absent at higher ΔKs. Kim et al.[5] found the DG bands for the same grade ABS to occur at 80°C, 5 Hz, between ΔK = 0.52 and 1.28 MPa$\sqrt{m}$. The existence of the DG bands appears to be affected

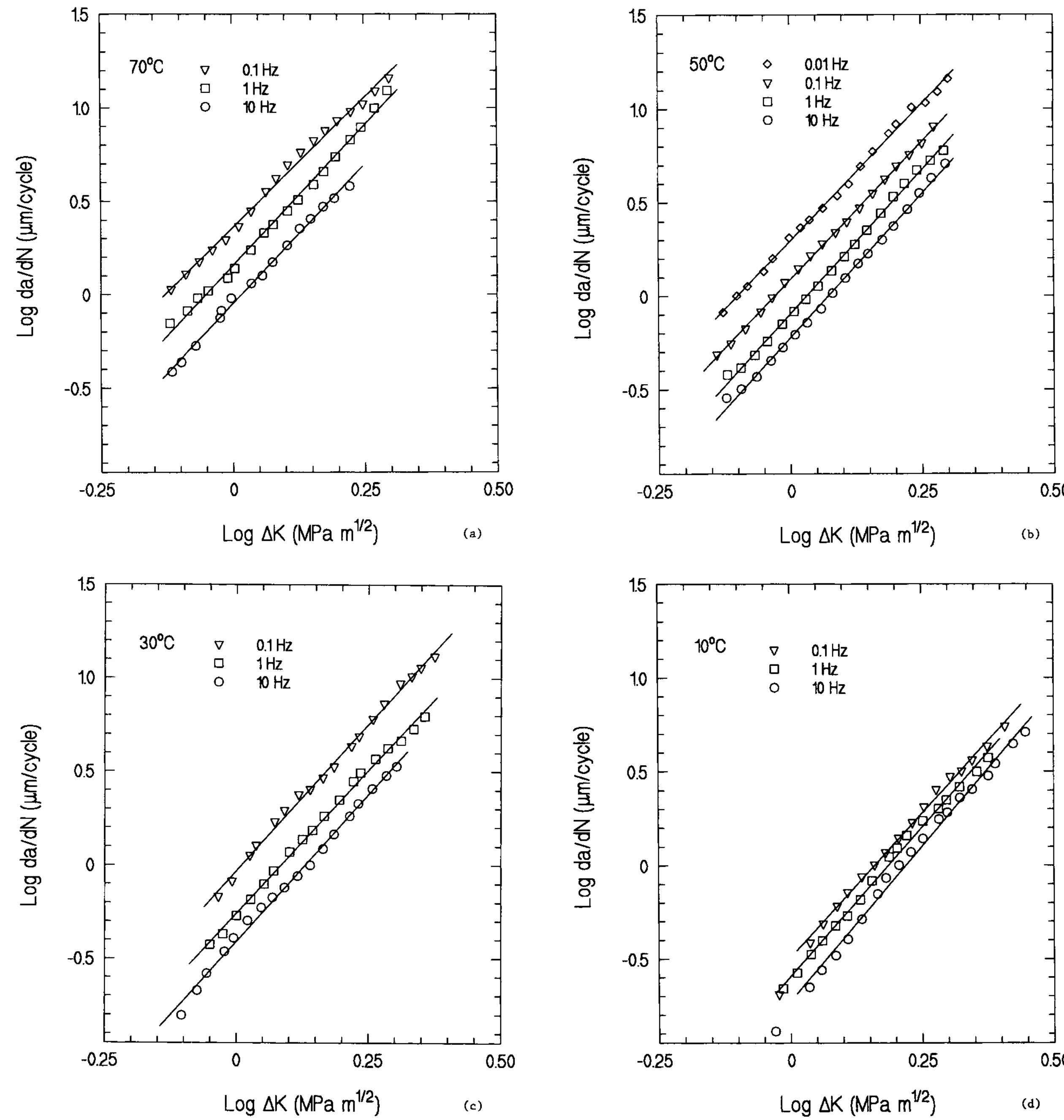

Figure 1 FCG rates of ABS at different frequencies, tested at (a) 70°C, (b) 50°C, (c) 30°C, and (d) 10°C.

by both temperature and frequency, since, for a given ΔK, transitions took place from normal FCG to DG at lower frequencies (lower crack growth speed) [see Fig. 1(a) and (b)] or/and at higher temperatures. In regard to the existence of DG bands, Döll[14] explained it in terms of the fibrils of craze and concluded that "the process of fibril coalescence" could be the fundamental process giving rise to the DG growth and that the growth of "superfibrils" (due to the coalescence) would only occur if the time involved in crack growth was sufficiently high. Our finding of DG bands at low frequencies is in agreement with this conclusion. Also, the finding of DG bands at high temperatures leads to a speculation that "the process of fibril coalescence" would be easier if the temperature is sufficiently high. Results

Table I The Paris Power Law Constants *A* and *m* Obtained from Experimental Results (da/dN in μm/cycle, ΔK in MPa$\sqrt{m}$)

Frequency (Hz)	Temperature (°C)	*A*	*m*	Standard Dev.[a]
0.01	50	2.301	2.94	0.0195
0.1	30	0.934	3.13	0.0240
	50	1.583	2.79	0.0207
	70	2.280	2.79	0.0266
1	30	0.552	3.05	0.0224
	50	0.990	3.06	0.0153
	70	1.422	3.01	0.0279
10	30	0.390	3.14	0.0282
	50	0.598	3.07	0.0200
	70	0.890	2.98	0.0209

[a] Standard deviation of da/dN from the least-square lines.

from the published literature,[15] however, report that the formation of DG bands in some polymers such as PS, PC, and PSF requires high frequency (100 Hz).

As indicated in Table II, a transition between the second [Fig. 2(b)] and last [Fig. 2(c)] types occurs between 30 and 10°C irrespectively of frequency and, thus, it seems to be due solely to temperature. A similar transitional behavior of the same-grade ABS affected by temperature at a frequency of 5 Hz is reported to occur between 30 and 19°C.[5] This transitional behavior was explained in terms of craze length at the crack tip and spacing between crazes.[5] In regard to the craze length, Döll and Könczö reported that the craze length at the crack tip of PMMA is independent of frequency (0.4–50 Hz) at a given ΔK. Therefore, the independence of the transitional behavior on frequency appears to be due to the independence of craze length on frequency.

Analysis of Fatigue Crack Growth Data

There are four unknowns in eq. (5) including ΔH_{th}, γ, nm, and C. To determine ΔH_{th}, the values of the Paris constant A (see Table I) are plotted against $1/T$ in accordance with eq. (4) as shown in Figure 3. The mean value of ΔH_{th} for different frequencies in the temperature range 30–70°C was 19.22 kJ/mol. The slopes with this value fit data very well for all frequencies (30–70°C). Also, this value is in agreement with that (19.63 kJ/mol) for the same-grade ABS tested at 5 Hz in Ref. 5. Thus, it appears that ΔH_{th} is constant independent of frequency and temperature. It is noteworthy though that Cheng et al.[6] evaluated the apparent energy for PMMA not to be constant, but, rather, to decrease as frequency increases. This, however, is the case where the hys-

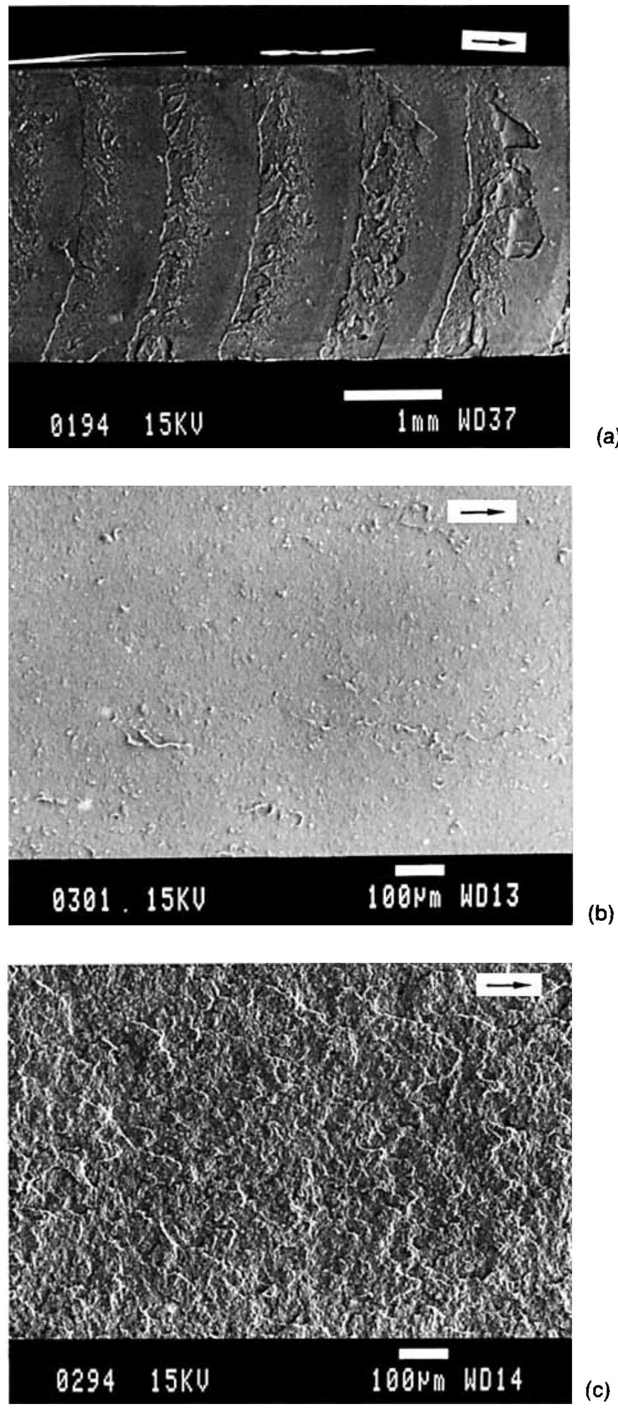

Figure 2 SEM fractographs of ABS taken at $\Delta K = 1$ MPa$\sqrt{m}$: (a) 70°C, 0.1 Hz; (b) 70°C, 1 Hz; (c) 10°C, 10 Hz. The arrow indicates crack growth direction.

Table II Fracture Surface Features at ΔK = 1 MPa$\sqrt{m}$ for Different Test Conditions

Fracture Surface	Temperature (°C)	Frequency (Hz)
DG bands	70	0.1
	50	0.01
Smooth	70	1
	70	10
	50	0.1
	50	1
	50	10
	30	0.1
	30	1
	30	10
Rough	10	0.1
	10	1
	10	10

teretic heating effect cannot be ruled out since frequencies employed in their tests include a high frequency of 100 Hz.

Although, for FCG at 10°C, the ΔH_{th} was not determined because of the scarcity of the data below 10°C, it is noted that data points at this

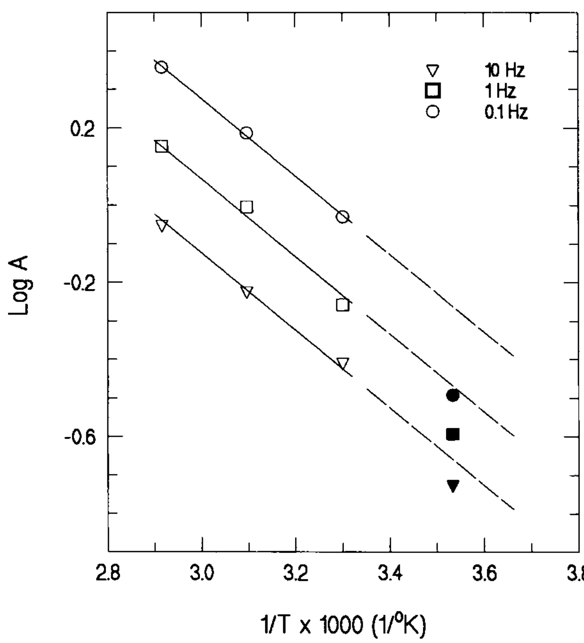

Figure 3 A plot of the Paris power law constant, A, as a function of $1/T$ at different frequencies. Data points at 10°C distinguished by filled symbols were not included in the regression analysis. Standard deviations of Log A from the regression lines were calculated to be 0.032, 0.027, and 0.012 for 0.1, 1, and 10 Hz, respectively.

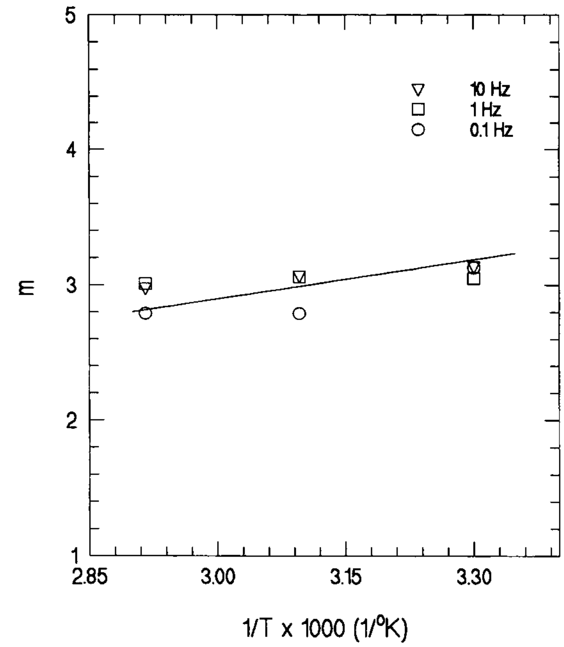

Figure 4 A plot of the Paris power law constant, m, as a function of $1/T$ at different frequencies.

temperature deviates noticeably from the least-square lines for the higher-temperature range, indicating that the transition is occurring as shown in Table II. The γ in eq. (5), which is slope $\times R \ln 10$ in a plot of m as a function of $1/T$, was

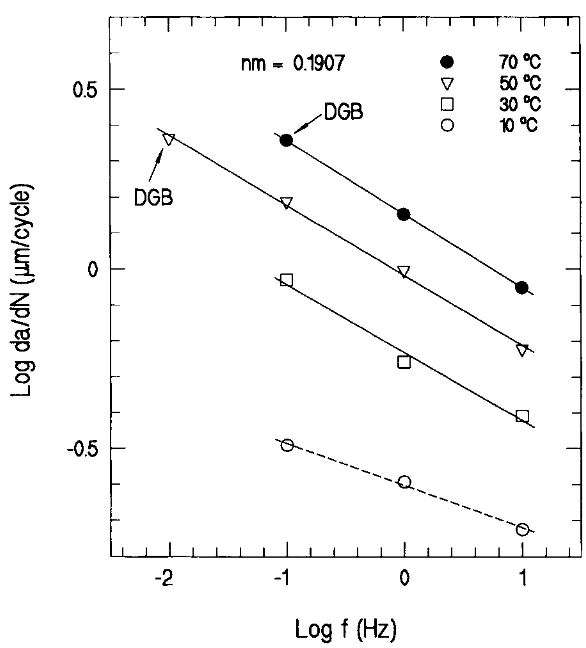

Figure 5 FCG rates as a function of frequency at different temperatures for ΔK = 1.00 MPa$\sqrt{m}$.

found in accordance with eq. (3) to be 18.439 (see Fig. 4).

To determine the values of nm in eq. (5), FCG rates as a function of frequency at different temperatures can be plotted as shown in Figure 5 for $\Delta K = 1$ MPa$\sqrt{m}$. According to eq. (5), nm is a slope in a plot of da/dN as a function of frequency on log scales for a given temperature and ΔK. The mean value of nm for temperatures 70, 50, and 30°C, at ΔK = 1.00, 1.25, and 1.60 MPa$\sqrt{m}$, was 0.19 (but 0.11 for the temperature of 10°C). Finally, the C in eq. (5), which can be determined from the ordinate intercept ($\log f^{-nm} + \log C$) in Figure 3 [see eq. (4)], was 1215. Then, the slopes (nm) may be plotted in Figure 5 in accordance with eq. (5). The slopes appear to fit the data very well including those with DG bands. This indicates that the obtained value of nm is independent of ΔK and temperature. Also, the transition between the normal FCG and the FCG associated (macroscopically) with DCB bands does not appear to affect the apparent activation energy, ΔH_{th}, and constant, nm.

Using eq. (5) with the obtained values in the above, da/dNs were predicted and compared with experimental data as shown in Figure 6. The predicted Paris constants A and m are listed in Table III. It is seen that there are good agreements between the predictions and the experimental data.

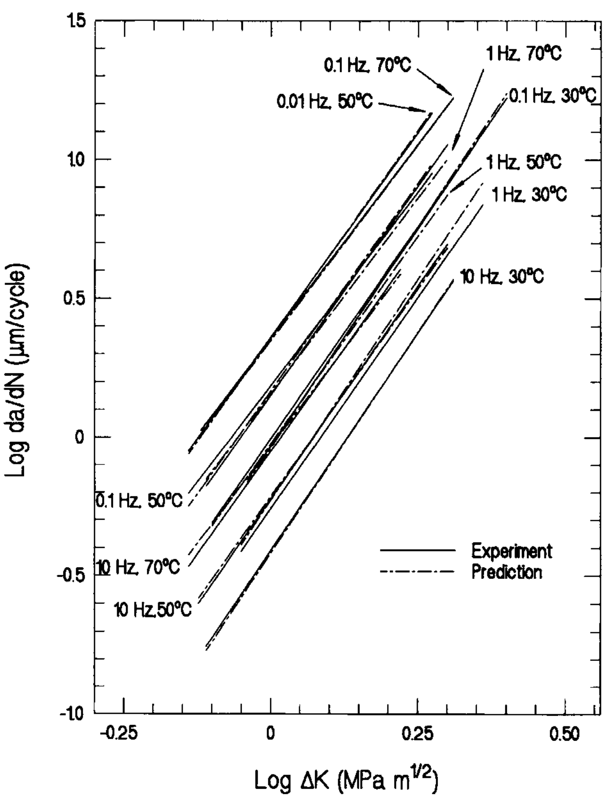

Figure 6 Comparison of predicted FCG rates based on eq. (5) with experimental results.

Table III The Paris Power Law Constants A and m Predicted by Eq. (5) (da/dN in μm/cycle, ΔK in MPa$\sqrt{m}$)

Frequency (Hz)	Temperature (°C)	A	m
0.01	50	2.284	2.99
0.1	30	0.918	3.19
	50	1.472	2.99
	70	2.234	2.82
1	30	0.918	3.19
	50	0.949	2.99
	70	1.440	2.82
10	30	0.381	3.19
	50	0.612	2.99
	70	0.928	2.82

CONCLUSIONS

A refined model for effects of temperature and frequency on FCG rate has shown to accurately predict FCG rates in ABS at various temperatures and frequencies. Three different types in fracture surfaces have been found in the range of temperatures between 10 and 70°C and frequencies between 0.01 to 10 Hz. The first type was characterized by DG bands; the second, by a rather smooth surface; and the last, by a rough surface relative to the second. The apparent activation energy has been evaluated for both the first and second types to be 19.22 kJ/mol independent of temperature and frequency.

The authors wish to thank the Electron Microscope Unit for facilitating the microscopy and Mr. R. Lyons of Sydney University for the molecular weight measurement of ABS.

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Received September 24, 1993
Accepted February 19, 1995