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A computerized data acquisition system for fatigue crack growth studies in polymers

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A new method for automatic fatigue crack growth measurement in polymers using electrical conductive surface grids and a micro-computer is developed. The grid pattern is made from a graphite ink and transferred to the specimen surface using a screen printing technique. The computer scans each bar individually and counts the elapsed fatigue cycles using a simple interface. Experimental results for crack length and elapsed cycles are produced in a form suitable for further computer analysis to establish the Paris power law for fatigue crack growth. The usefulness and accuracy of this computerized automatic method are compared to the conventional optical method. Fatigue crack growth results are obtained for several polymers using this computerized technique.

1. Introduction

The study of fatigue crack growth in polymeric materials requires the measurement of crack length (a) as a function of elapsed cycles (N). Such data are normally used to determine the relationship between fatigue crack growth rate ($\mathrm{d}a/\mathrm{d}N$) and the applied stress intensity factor range (ΔK). This is usually expressed in terms of the well-known Paris power law equation [1]:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \alpha(\Delta K)^{\beta} \qquad (1)$$

where α and β are constants.

The conventional method for monitoring crack growth is to use a travelling microscope to make periodic measurements of both a and N. The major disadvantage for this method is the need for constant attention by the experimenter thus limiting test time to normal working hours. Testing must be interrupted each night and started the following day. The rest period between stops and starts may affect fatigue crack growth results and greatly increase the time required to complete a test. There is, therefore, a need for an automatic crack monitoring system for fatigue crack propagation studies in polymers.

Many automatic crack length measurement techniques have been developed for metals (e.g. [2, 3]). These include electrical potential difference methods, compliance technique, ultrasonics, acoustic emissions and conductive surface foils or grids. However, polymers are nonconductors and not all of these methods are directly applicable. The most promising one seems to be the use of conductive surface grids printed on to specimen surfaces. This technique is both simple to operate and relatively inexpensive to implement particularly when the conductive grids are printed using a screen printing process [4, 5] instead of the more expensive vapour deposition method [6]. Passage of the crack through each bar causes step changes in the voltage output which can be recorded in an X–Y recorder. Knowing the distance between each bar and the test frequency, an a–N plot can be constructed and then used to determine Equation 1. As pointed out by Mai and Kerr [4, 5] this is not a completely automatic method since one needs to calculate both a and N from the output of the recorder. Also, if there are any defect bars in the grid after they are printed these must be noted. Otherwise, this will cause inaccuracies in crack length measurements. To overcome these

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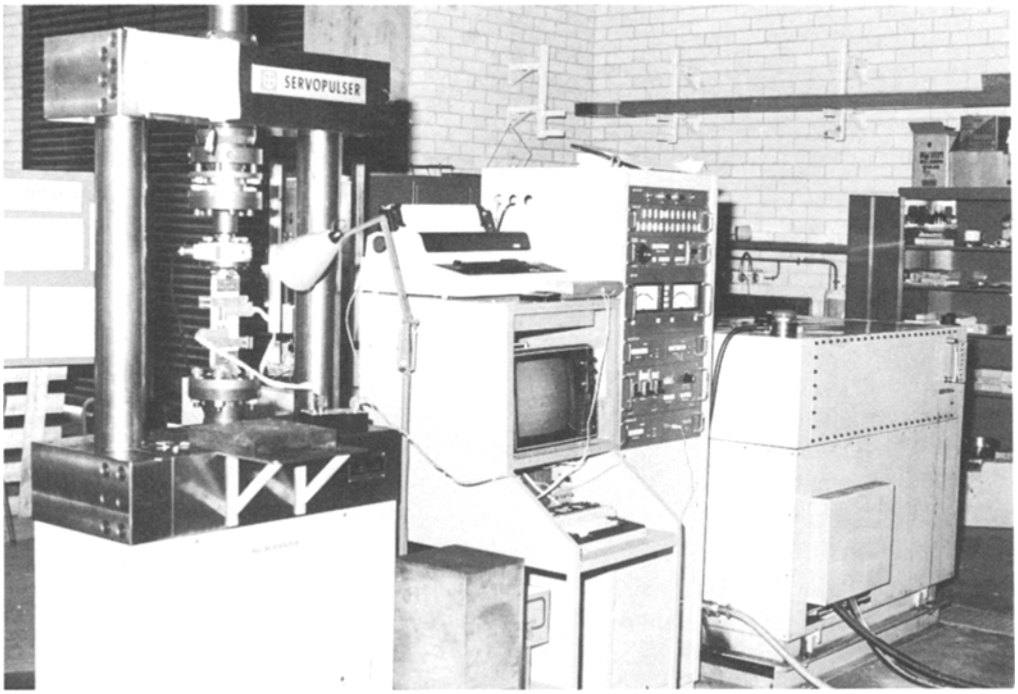

Figure 1 General view of hardware of the computerized crack monitoring system.

problems we have recently developed a computerized automatic crack monitoring system based on screen printed conductive surface grids for fatigue crack growth studies in polymers. Details of the computerized technique are given in this paper.

2. The computerized automatic crack length monitoring system

2.1. Principle of operation

Fig. 1 shows a general view of the hardware of the computerized data acquisition system. A corresponding block diagram is also given in Fig. 2 showing how the system works. The interface between the specimen and the microcomputer is both simple and low in cost. To scan a grid with a pattern given in Fig. 3 the bars were grouped in blocks of eight, each block forming one column of a matrix as shown in Fig. 4. A bar was considered broken if its resistance was above a certain preset value. This approach enabled defective bars to be detected before testing so that due allowance could be made in subsequent crack length measurements during fatigue.

Scanning was performed by initially resetting the decade counter so that A0 was set at 5 V and A1 to A9 at 0 V (see Fig. 4). Outputs D0 to D7 referred to the block of bars addressed by A0. Each output would be 0 V if the corresponding bar was unbroken and 5 V if the bar was broken. Gates G0 to G7 switched from 0 V to 5 V when their input voltage dropped below 2.3 V. Each bar ($R_b \simeq 14\,k\Omega$), diode and reference resistance (R_r) formed a voltage divider the output of which would be initially close to 5 V since R_r was set at approximately $15 R_b$ (i.e. $210\,k\Omega$). As the crack passed through the bar, R_b increased and the divider voltage dropped until R_b was $0.83 R_r$. At this time the gate switched from 0 to 5 V indicating a broken bar. Scanning of successive blocks in the grid was performed by applying a pulse from the microcomputer to the clock input of the decade counter. Although only 32 bars were scanned in this work the system would be capable of scanning up to 80 bars with ten pulses.

2.2. Implementation of the system

The computerized method was implemented in five parts: (1) the conductive surface grid, (2) the contact circuit, (3) the interface circuit, (4) a micro-computer, and (5) control programs. Details of these individual parts are given below.

2.2.1. Conductive surface grids

The grid pattern shown in Fig. 3 was printed on the specimen surface using the screen printing

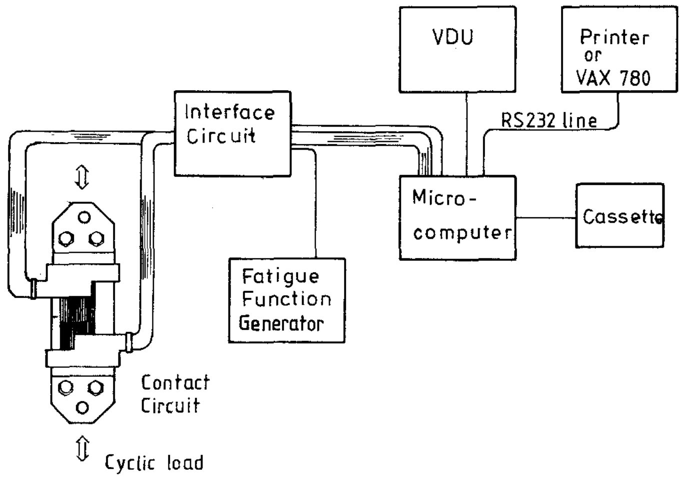

Figure 2 Block diagrams for the crack monitoring system shown in Fig. 1.

technique and conductive ink as described previously [4, 5]. Bars were divided into four blocks of eight giving 32 bars approximately 0.12 mm wide at 1 mm spacing. This allowed crack lengths to be measured from 12 mm to 44 mm on a 75 mm × 200 mm single edge notched (SEN) specimen. Screen printing is a common technique in both industry and the arts which allows thick films of ink to be deposited in complex patterns. This technique is inexpensive and simple to use.

The choice of a suitable ink is important for satisfactory operation of the method. A good ink must have thickness and flow characteristis appropriate for screen printing. For example, particle size must be fine enough to prevent blockages in the screen and the ink solvent must be compatible with the polymeric material. Most importantly, the conductive ink must have similar mechanical characteristics to match those of the polymeric specimen, The bar must break at the passage of the crack tip. Thus, the ink should not be so ductile as

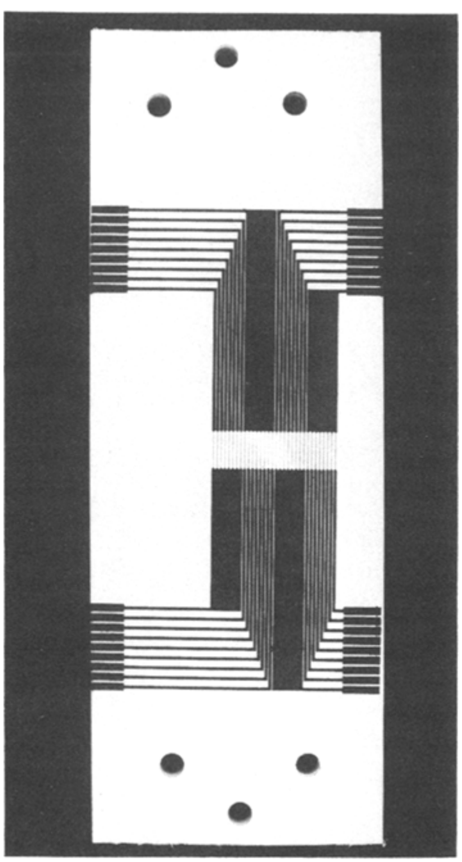

Figure 3 Grid pattern printed on a SEN specimen surface by the screen printing process.

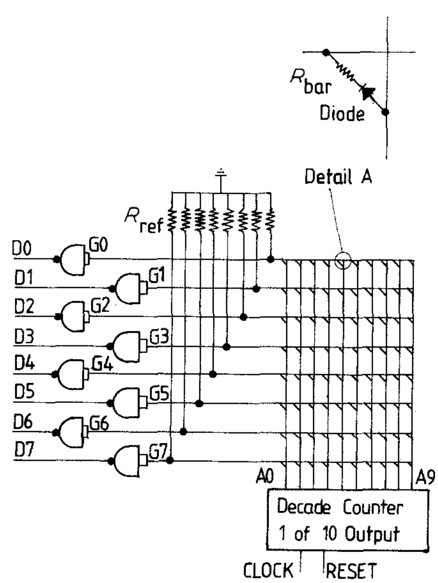

Figure 4 Operation principle for scanning the grid in Fig. 3.

to bridge the crack faces nor should it be so brittle as to break prematurely.

The conductive ink eventually chosen for this work was Electrodag 423SS purchased from Acheson Colloids (USA). It was specifically designed for screen printing on plastics and contained finely divided graphite powders dispersed in a vinyl resin binder and a butyl cellulose acetate solvent. The ink was found to give a very good print quality on polyvinyl chloride (PVC), high impact polystyrene (HIPS) and acrylonitrile-butadiene-styrene (ABS). A conductive bar was observed to break with a travelling microscope just as the computer registered a break. This means that the data acquisition system developed with this ink is suitable for fatigue crack growth studies in these polymers. However, application of the ink to a brittle polymer, polymethylmethacrylate (PMMA), was found to be unsuitable. The vinyl binder was too ductile so that the grid lines across the crack faces for up to 0.5 mm after passage of the crack front. A new ink with a more brittle binder such as acrylics or resins should be developed for brittle polymers like PMMA and polystyrene (PS).

2.2.2. Contact circuit

The contact circuit shown in Fig. 5 uses 2.54 mm printed circuit board edge connectors cut in half to connect each bar via a diode to a data line and also to connect each block line to an address line (A1 or Ar). These were then routed to the edge of the circuit board to allow a cable and edge connector to join the contact circuit to the interface circuit. The contact circuits were held in place on the specimen by simple clamps, (see Fig. 1).

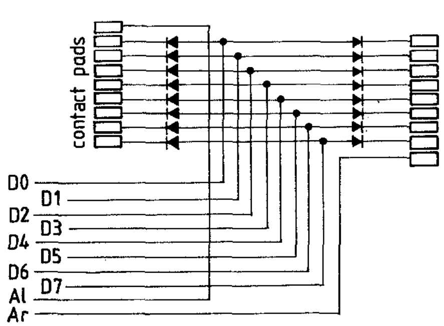

Figure 5 Contact circuit connecting grid to the interface circuit.

2.2.3. Interface circuit

The interface circuit given in Fig. 6 connects the contact circuit to the micro-computer parallel port and provides circuitry to scan the bars as well as to accept an input from the fatigue servo-pulser to allow the computer to count the number of elapsed cycles.

The reset line was not part of the parallel port but was simply a square line using a separate output signal available on the micro-computer to reset the decade counter IC1 before scanning.

Scanning of the grid involved ten successive inputs from the port by the computer. Each input caused the ready line to go from 5 to 0 V and back to 5 V after the input was complete. The rising edge of this ready line signal incremented the decade counter to the next block ready for further scanning of this block.

A signal from the servo-pulser provided a 10 V pulse for each cylcle. This pulse was shortened to approximately 0.3 msec and connected to the strobe line of the port. Each pulse generated an interrupted signal on the micro-computer.

The integrated circuits IC1, IC3, and IC4 used for scanning were complementary metal oxide silicon (CMOS) type which drew very low currents. This was necessary owing to the high resistance of the reference and bar resistors.

2.2.4. Micro-computer

The micro-computer used was a Microbee IC, a small personal computer, using a Z80 CPU, 32 K of random access memory (RAM), 16 K basic in read only memory (ROM), 8 bit parallel port, a RS 232 serial port and a cassette interface.

2.2.5. Control programs

Two control programs were written for the automated data acquisition system. The first program was a machine language routine which performed two functions: to scan the grid and to count the number of elapsed cycles. This is shown in the flow diagram of Fig. 7. It was necessary to impose a time delay between each input while scanning in order to allow for the slow response of the interface. However, scanning rates of up to 100 Hz were possible.

The second program was written in basic language and was used for operator inputs and outputting results. Inputs could include specimen identification, sizes and dimensions, crack length to first bar, frequency, maximum and minimum

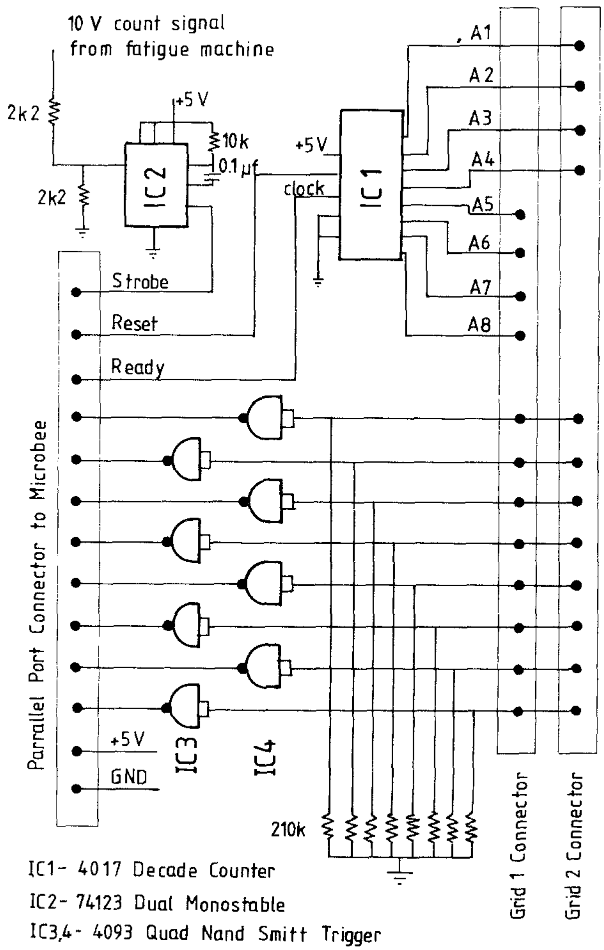

Figure 6 Interface circuit diagram.

loads as well as temperature. Experimental (a, N) results could be displayed on the video display unit, fed to a line printer, saved in a cassette tape for later transfer or sent via a RS 232 port to the VAX computer for further analysis.

3. Some experimental results

As discussed in Section 2.2 this automated crack length measurement technique using the particular Electrodag 423SS conductive ink was only suitable for PVC, HIPS and ABS but was inappropriate for PMMA. Fatigue experiments using SEN specimens were conducted on these few polymers for which the technique was applicable in a servo-pulser. The stress ratio ($= K_{min}/K_{max}$) was close to zero, and unless otherwise stated the temperature was approximately 23° C. The crack lengths were measured both by optical means using a travelling microscope and by the electrical conductive surface grid using computer scanning. As an example, Fig. 8 shows the a–N results for ABS obtained from both methods and the agreement is remarkably good. These results give good confidence to the computerized data acquisition system for fatigue crack growth measurements in polymers. Fatigue crack propagation rates (da/dN) were determined from the slopes of the a–N curves such as those shown in Fig. 8 using a piecewise second order polynominal fit to sets of seven successive data points by the least square method [7]. Equation 1 could then be established by plotting log (da/dN) against log ΔK. Programs for calculating da/dN and ΔK as well as for the Paris plot were written for the VAX computer. Fig. 9 gives the fatigue crack growth results for a pipe grade uPVC plotted according to Equation 1. The experimental data were obtained from four separate fatigue tests and they almost all fell within the ± 90% confidence limits of the mean line. Thus, data reproducibility is good. The usefulness of the computerized crack monitoring system can also be seen from Fig. 10 in which fatigue crack growth data for ABS are plotted. In

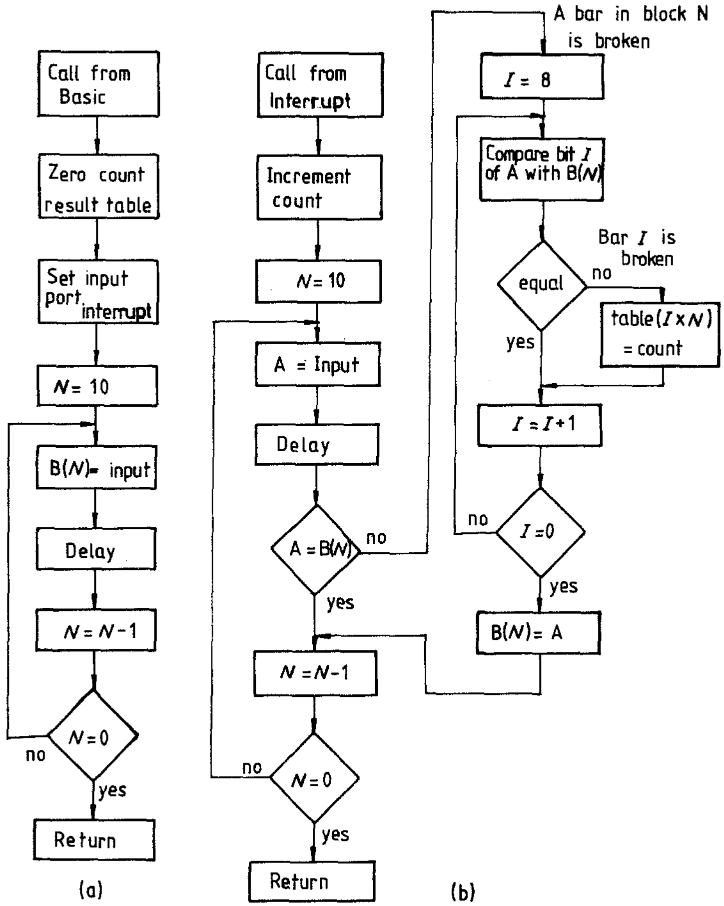

Figure 7 Flow diagrams for machine language programme: (a) initialization; (b) scanning.

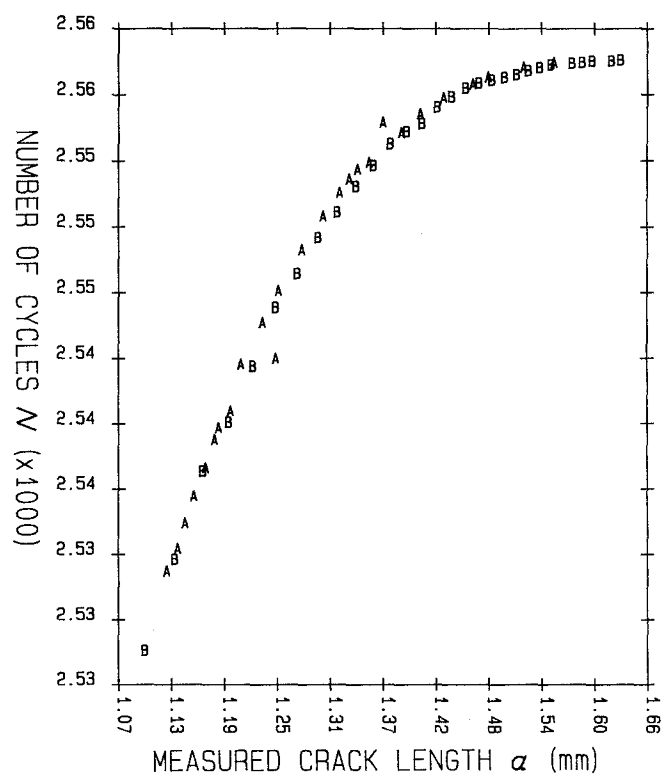

Figure 8 Comparison of crack length (a)–number of elapsed cycles (N) results obtained by optical and computer scanning methods for ABS tested at 10° C. A = optical, B = electric.

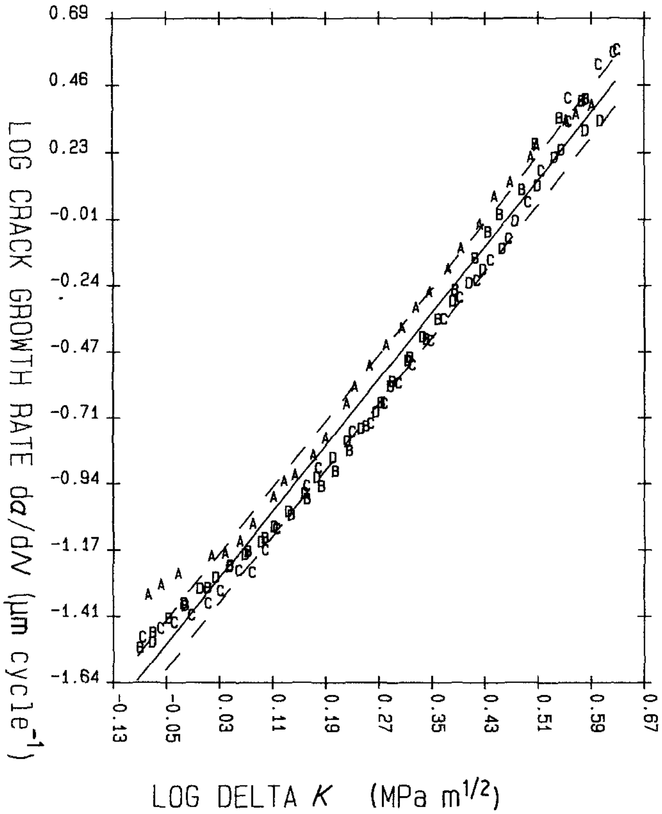

Figure 9 da/dN as a function of ΔK for uPVC by the computerized crack monitoring system. Dashed lines represent ± 90% confidence limits from the mean line. A = PVCAT 6, B = PVCAT 10, C = PVCAT 13, D = PVCAT 17. Regression parameters-correlation = 0.990; intercept = − 1.359, slope = 2.917, standard deviation = 0.087.

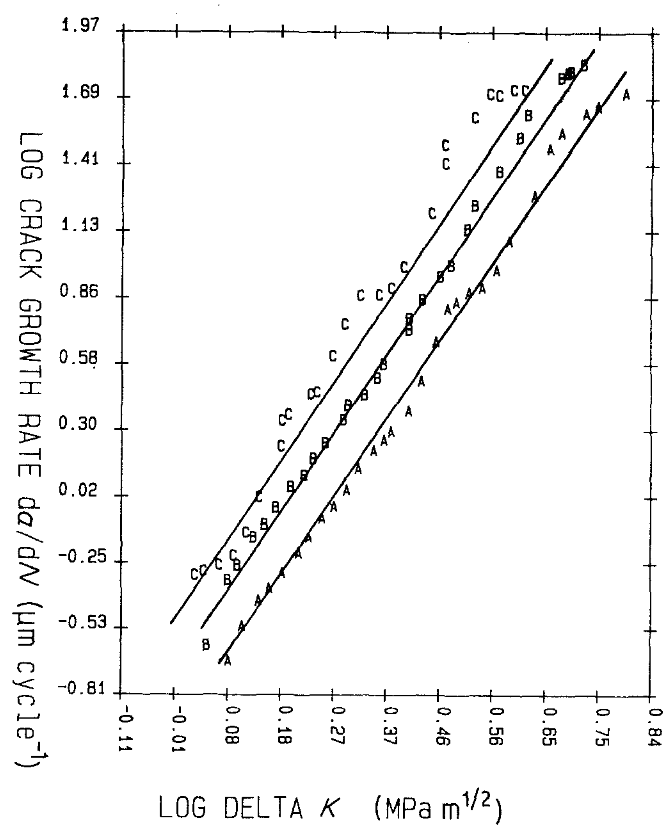

Figure 10 da/dN plotted against ΔK for ABS at various temperatures by computer scanning technique. (A = 10° C, B = 40° C, C = 60° C. Although single test results are given here, least square lines for each temperature shown are calculated based on at least 3 tests.) A = ABS20T 10, B = ABS18T 40, C = ABS11T 60.

particular, it was noted that the method even worked well for ABS fatigue tested at various temperatures as shown in Fig. 10. This was because the conductive bars broke as the crack passed through them being unaffected by temperature effects.

4. Conclusion

The computerized automatic method described in this paper is a simple reliable technique for fatigue crack growth measurements. It gives experimental results of comparable accuracy to the conventional optical technique but with greatly reduced time and effort. For example, a series of sixteen tests each taking an average of 2 days to finish were performed on uPVC over approximately 40 days with the servo-pulser operating 80% of the time. If the optical technique was used this would have required over three times longer in test time and much greater attention by the experimenter. The use of screen printing grid is simple and effective and allows suitable matching conductive inks to be printed. The (a, N) results are collected in a form which may be directly analysed by the computer to produce plots of $\mathrm{d}a/\mathrm{d}N$ against ΔK.

We believe this is the first time a computerized automatic technique, which is useful for fatigue crack growth studies in polymers, is reported.

Acknowledgement

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