EFFECT OF ENVIRONMENT AND STRESS RATIO ON THE FATIGUE CRACK PROPAGATION OF POLYCARBONATE

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ABSTRACT

Effects of environment and stress ratio on the fatigue crack propagation of polycarbonate have been studied. In first group, the effect of weathering whereas in the second group of specimens, the effect of annealing at 50°C, 100°C and 150°C was studied. Tests were conducted at stress ratios of 0.1, 0.25 and 0.50. The study showed that the fatigue crack propagation rate (da/dn) of this material was influenced very much by the environmental conditions and temperature at each stress ratio. da/dN and the fatigue life were found to be faster and shorter, respectively, for specimens either exposed in the environmental conditions or higher temperatures. Stress ratios below 0.25 gave rise to softening in front of crack-tip leading to increase in fatigue life. Long exposure at ambient conditions or higher temperature of 150°C lead the material to become opaque.

KEYWORDS

Fatigue crack growth rate, stress intensity factor range, cycle frequency, stress ratio, controlled condition, fatigue life.

INTRODUCTION

Environment and stress ratio have marked influence on the fatigue crack growth rate of many materials [1-9]. In polymer also, the crack growth behaviour may be different in different environments because of environmental attack on the crack front. The effect of environment on the crack growth under monotonic or static loading has been discussed by Williams and Marshall [10]. According to them, the rate of crack growth (da/dN) is well correlated with stress intensity factor range (ΔK) and energy release rate. In recent years, increased attentioin was paid to the analysis of fatigue processes in engineering plastics and polymer based composites because of its light weight nature which reduces energy costs in automobiles, boats and planes etc.. Polycarbonate is a thermoplastic polymer which has numerous uses. It is used in a variety of industrial parts chiefly in business machines, electrical and electronic components as well as in window shields of airplanes where it is subjected to repeated and varying stresses. The details of environmental crack growth under these repeated and varying cyclic loadings remain unclear. It is, thus, worthy and of interest to investigate the faigue crack propagation behaviour of this material in different environmental conditions and stress ratios.

EXPERIMENTAL METHOD

Specimen pretreatment and preparation - Tensile type of specimens were prepared from a big sheet of polycarbonate having 4mm thickness. Specimens were divided in two groups and each group had three sets of specimens. The specimens of first group were exposed to local ambient conditions in the yard of DMSRDE where temperature variation was minimum $6^{\circ}C$ in winter to a maximum of $42^{\circ}C$ in summer and humidity variation was from 20% to 95%. Specimens were exposed to the ambient environmental conditions for 3 months, 6 months and 2 years duration. Ist set of specimens from group first, consisting of 20 specimens, was exposed to the environment for a period of three months whereas the second set of specimens of this group was exposed to the environment for a period of six months. Specimens of third set of this group were exposed for a duration of 2 years. Second group of specimens, consisting of ten specimens in each set, was heat treated at different temperatures. The first set of specimens was annealed at $50^{\circ}C$ for a period of 480 hours (20 days) whereas the second set of specimens of this group was annealed at $100^{\circ}C$ for the same duration. The last set of specimens was annealed at $150^{\circ}C$ for the same period of 480 hours. Single edge notched and un-notched specimens of dimensions as shown in Fig. 1(a) and 1(b), were prepared from each set of each group for monotonic test (Tensile test) and for fatigue tests at different stress ratios, R (R=minimum load/maximum load).

Monotonic tests - Tensile tests were conducted on the unexposed (controlled) and environmentally exposed un-notched specimens. Due to shortage of specimens, this test was not conducted for all the conidtions. The tests were conducted in a 10 tonnes hydraulic univeral testing machine (MTS) in load control mode. The obtained results have been given in Table-1.

Fatigue tests - Fatigue tests were carried out in order to generate crack growth rate(da/dN) against various stress intensity ranges (ΔK) on both environmentally exposed and heat treated specimens. For this, all the specimens were provided with 45° notch having 1.5mm depth. Maximum load for fatigue test was determined. Un-notched specimens were used for the determination of fatigue lives at different stress amplitudes.

Crack growth rate determination - Fatigue tests were conducted at different stress ratios of 0.1, 0.25 and 0.50 so as to cover most of the probable conditions experienced by this member in actual service condition. The applied load range was recorded using the load cell of MTS machine. The crack growth was measured maintaining the frequency of fatigue test at 3Hz. The test was discontinued after the failure of a specimen. The fatigue tests were conducted under load control mode. From $\Delta\sigma$ (calculated based on maximum and minimum loads during the crack growth determination) and the value of crack length (a) obtained from the experiment, the stress intensity range, ΔK, was determined using the equation

$$\Delta K = \Delta\sigma . Y . (a)^{1/2} \quad \text{........(i)}$$

where $Y = [1.99-0.41(a/w)+18.7(a/w)^2-38.48(a/w)^3$

$+53.85(a/w)^4 .] \quad \text{..(ii)}$

and W = Width of the specimen

The increase in crack length after various number of fatigue crycles at different R values and stress ranges were recorded.

Based on these recorded data and the above mentioned equations, the plots between da/dN versus ΔK were drawn.

Fatigue tests for fatigue life determination - Fatigue tests with un-notched specimens, for environmentally exposed, heat treated and controlled conditions were carried out in order to determine the fatigue life of material under various conditions by exploring the total number of cycles required for failure of a specimen. These tests were also carried out at different values of stress ratios. Fatigue life determination tests with notched specimens were also conducted at all the stress ratios.

RESULTS AND DISCUSSIONS

Table-1 shows the tensile tests data for controlled and environmentally exposed un-notched polycarbonate specimens. The obtained results show clearly that the tensile strength of the controlled specimens are higher with respect to the specimens either exposed at ambient environmental conditions or heat treated conditions. It can also be seen from the obtained data that percentage of elogation does not show major difference in its values for all the conditions, although an increasing treand was observed by increasing the duration of exposure. It was also observed that either by exposing in the DMSRDE environment for the longest duration of 2 years or by exposing at $150^{\circ}C$ for 480 hours, the transparency of the polycarbonate specimens got affected. Specimens were quite transparent for controlled, 3 months and 6 months environmentally exposed conditions whereas specimens exposed for 2 years become opaque and were found to be slightly yellow in colour.

It can be seen clearly from fig.2 to Fig.5 that both the fatigue life (expressed in terms of total number of cycles, N, for failure) and da/dN are getting very much influenced by exposing the polycarbonate specimens in ambient environmental conditions and also at higher temperatures. Fig. 2 presents the data between increase in crack length and number of fatigue cycles at R = 0.5 for the specimens exposed in DMSRDE environmental conditions. The same data at high temperatures at R = 0.5 have been presented in Fig.3. From these data it can be seen that required number of cycles for a given increase in crack length is maximum for the controlled specimen. The number of cycles required to grow the crack for a known length goes on decreasing either by increasing the duration of exposure in the ambient environment or by increasing the temperature of the environment. Minimum fatigue cycles were obtained for the extreme conditions such as exposure for a period of 2 years or annealing at maximum temperature of $150^{\circ}C$. The same behaviour between the increase in crack length at various numbers of fatigue cycles was als observed at other R values of 0.1 and 0.5. It is significant to observe that fatigue life of polycarbonate is getting drastically reduced either by increasing the duration of exposure at the ambient conditions or by exposing the material at higher temperatures. The material becomes brittle under both the situations. The slope between crack growth rate versus stress intensity factor range at a particular R value gets influenced very much either by the environment (Fig.4) or by annealing the specimens at higher

temperatures (Fig.5) at R = 0.5. At other stress ratios (R = 0.1 and 0.5) also these two parameters have been observed to influence the slope between da/dN and ΔK. Absorption of moisture for a period of 2 years in the local environmental conditions or a maximum temperature of 150°C is sufficient to make the material brittle either by reaction of water molecules with the material or by changing the glass transition temperature of polycarbonate and thereby diminishing the strength of the material. As a result of this, the fatigue life of the material is getting appreciably reduced. It was observed, from the present study, that stress ratio has appreciable influence on the crack propagation rate between 10^{-8} metre/cycle and 10^{-4} M/cycle in the case of notched specimens of this material (Fig.6&7). There is remarkable difference in the slope between da/dN versus ΔK for R=0.5 but the difference is less for R=0.1 and 0.25. Maximum crack growth rate has been experienced at R=0.5 for the notched and un-notched polycarbonate specimen. These experimental results highlight that the effect of either environment or temperature is quite appreciable at all stress intensity values under investigation. It was observed experimentally that at higher stress intensity range (lower stress ratio of 0.1) at the crack tip, the crack propagation is so fast that the effect of either environment or temperature on the crack growth rate is less in some cases. Because of this phenomenon, the specimens from various exposure times and heat treated conditions show more or less same magnitudes of crack growth rate.
The plots between the percentage loss of fatigue life [percentage loss of fatigue life =(no. of fatigue cycles for controlled specimen - number of cycles for environmentally exposed specimen)/(number of fatigue cycles for conctrolled specimen) x 100] versus different R values both for environmentally exposed and heat treated un-notched specimens show a minimum value at R = 0.1. As expected, the number of cycles required for failure (N) of a specimen at R=0.5 (lower ΔK value) should be more than R= 0.25. In the same way, N for R=0.25 should be more than R=0.1. But the data presented in Fig. nos.8,9 & 10 emphasise that the N value for R = 0.1 is more than R=0.25 and R=0.50, which is an unexpected behaviour. The behaviour can be explained only on the basis that higher ΔK range (for R =0.1) may make the material comparatively soft at the crack tip due to heat generation effect and as a result of this the value of N is more because the crack finds it difficult to negotiate through softer material. It has already been reported [11] that an increase in cycle frequency decreases fatigue resistance of several un-notched and nothed polymers due to hysteretic heating of the material in front of crack-tip. It appears from this investigation that a load cycle frequency of 3Hz and high ΔK values at the crack-tip, obtained for stress ratios less than 0.25, are sufficient conditions for generating heat effect on the fatigue propogation rate. A frequency of 3Hz alone is not sufficient to generate heat effect at the crack-tip. It was observed from the present investigation that the da/dN decreases at low R values of 0.1 and 0.25 as compared to high value of R = 0.5 due to softening effect at the crack-tip. Softening at crack-tip of specimen was physically observed in

the present investigation. However, it needs further elaborate study in future.

CONCLUSIONS

1. Ambient environmental conditions, temperature and stress ratio influence the fatigue crack growth rate as well as fatigue life of polycarbonate.
2. Stress ratios below 0.25 give rise to heat generation at the crack-tip to an appreciable level at operating fatigue cycle of 3Hz.
3. Both, long exposure in the ambient environmental conditions and higher temperature, change the material from transparent to opaque.

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Table 1 Mechanical properties of polycarbonate specimens exposed to various durations in the ambient conditions

Condition of specimens	Ultimate Tensile Strength (MPa)	Young's Modulus (GPa)	Percentage elongation
Controlled	64,76	1.52	4.67
Set 1	63.57	1.33	4.77
Set 2	63.13	1.27	4.98
Set 3	60.12	1.27	5.06

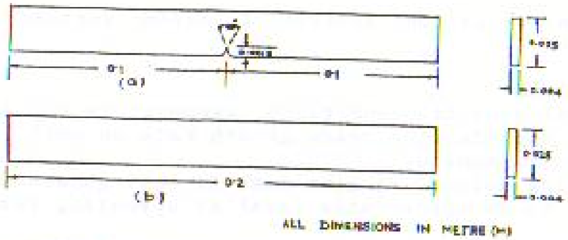

FIG.1. DIAGRAM OF POLYCARBONATE SPECIMENS FOR FATIGUE TESTS (a) NOTCHED SPECIMENS (b) UN-NOTCHED SPECIMENS

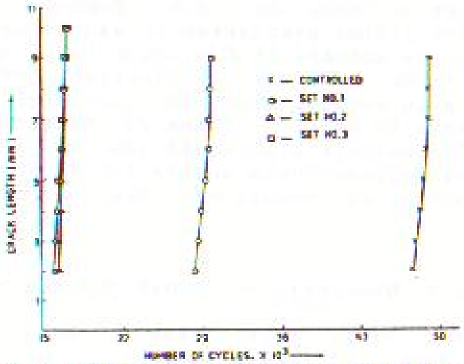

FIG.2 - CRACK LENGTH VERSUS NUMBER OF CYCLES DATA FOR THE SPECIMENS EXPOSED IN THE ENVIRONMENT AT AMBIENT CONDITIONS FOR VARIOUS DURATIONS AT A STRESS RATIO OF 0.50

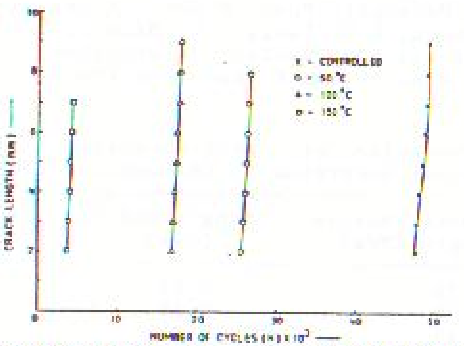

FIG.3. CRACK LENGTH VERSUS NUMBER OF CYCLES DATA FOR THE HEAT-TREATED POLYCARBONATE SPECIMENS AT A STRESS RATIO OF 0.50

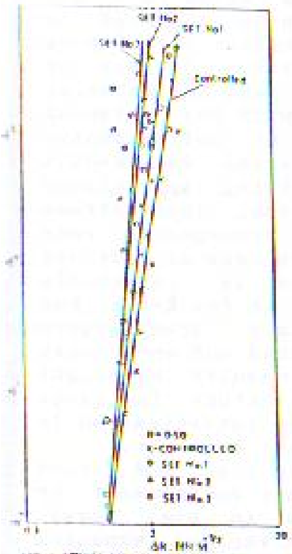

FIG. 4. STRESS INTENSITY RANGE (ΔK) VERSUS FATIGUE CRACK PROPOGATION (da/dN) RATE AT R = 0.50 FOR THE POLYCARBONATE SPECIMENS EXPOSED IN THE AMBIENT ENVIRONMENTAL CONDITIONS FOR VARIOUS DURATIONS. × CONTROLLED SPECIMENS; ○ 3 MONTHS EXPOSURE; △ 6 MONTHS EXPOSURE; □ 2 YEARS EXPOSURE

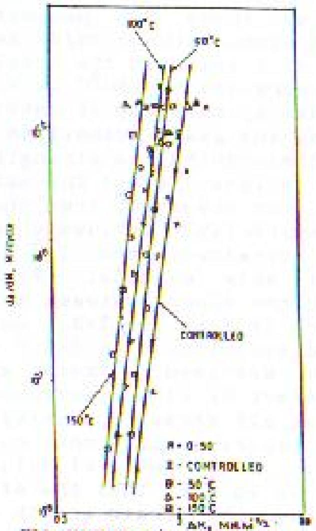

FIG.5: STRESS INTENSITY FACTOR (ΔK) VERSUS FATIGUE CRACK PROPOGATION RATE (da/dn) AT R = 0.50 FOR THE POLYCARBONATE SPECIMENS HEAT-TREATED AT VARIOUS TEMPERATURES FOR 30 DAYS: × - CONTROLLED SPECIMENS; ○ HEAT TREATED AT 50 °C; △ HEAT TREATED AT 100 °C; □ HEAT TREATED AT 150 °C.

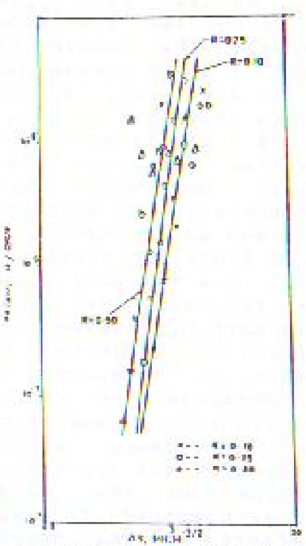

FIG.6. FATIGUE CRACK GROWTH RATE (da/dN) VERSUS STRESS INTENSITY RANGE Data AT VARIOUS STRESS RATIOS FOR THE POLYCARBONATE SPECIMENS EXPOSED AT AMBIENT CONDITIONS FOR 2 YEARS (SET NO.1)

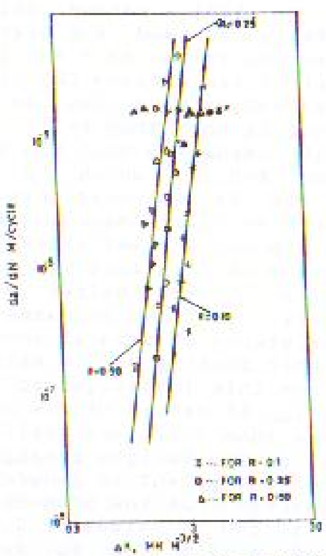

FIG.7. PLOT OF FATIGUE CRACK PROPAGATION RATE VERSUS STRESS INTENSITY RANGE AT DIFFERENT VALUES OF STRESS RATIOS FOR THE POLYCARBONATE SPECIMENS HEAT-TREATED AT 100 °C.

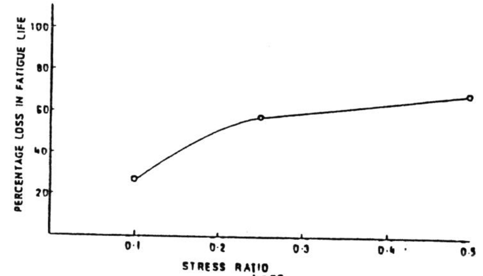

FIG. 8. PLOT BETWEEN PERCENTAGE LOSS OF FATIGUE LIFE AND STRESS RATIO FOR UN-NOTCHED POLYCARBONATE. SPECIMENS EXPOSED IN THE ENVIRONMENT FOR 6 MONTHS DURATIONS.

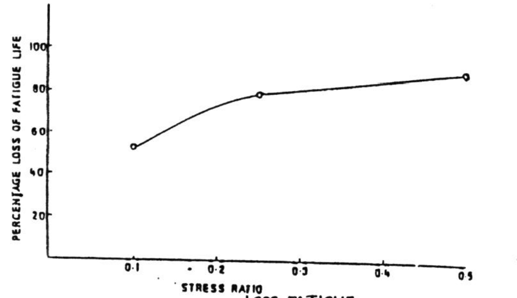

FIG.9. PLOT BETWEEN PERCENTAGE LOSS OF FATIGUE LIFE AND STRESS RATIOS FOR NOTCHED POLYCARBONATE SPECIMENS EXPOSED IN THE ENVIRONMENT FOR 6 MONTHS DURATION.

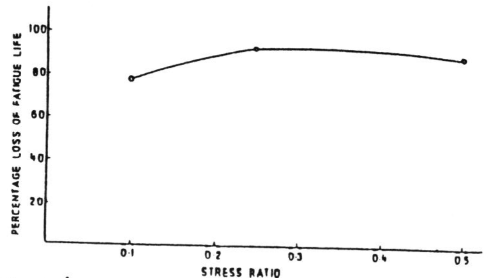

FIG.10. PLOT BETWEEN PERCENTAGE LOSS OF FATIGUE LIFE AND STRESS RATIO FOR NOTCHED POLYCARBONATE SPECIMENS HEAT-TREATED AT 150°C FOR 20 DAYS