THE EFFECT OF TEMPERATURE ON THE FREQUENCY SENSITIVITY OF FATIGUE CRACK PROPAGATION IN POLYMERS

M. D. Skibo, R. W. Hertzberg and J. A. Manson*

INTRODUCTION

The effect of cyclic frequency on the fatigue characteristics of a wide range of polymeric materials has been the subject of considerable study [1 - 9]. Earlier investigators found that an increase in specimen temperature could result when the rate of deformation-induced hysteretic heating exceeded the heat transfer rate from the cyclically heated gage section to cooler portions of the specimen and to the environment. As expected, the extent of such heating increased with cyclic frequency as predicted by Ferry [8]. The resulting temperature rise was found to increase material compliance to the point where failure occurred (failure being defined in terms of the specimen's inability to sustain a load) [3 - 7]. It should be appreciated that thermal failures have, up to this point, been identified only with unnotched specimens. Presumably, unstable heat build-up is found in situations where the volume of material which generates the heat (such as a highly stressed gage section) exceeds some critical quantity for a given set of test conditions. On the other hand, when the zone of highly stressed material is localized, as at the crack tip of a prenotched sample, the material surrounding this damage zone and the surrounding environment is capable of conducting away enough heat to preclude unstable heating conditions. Therefore, although some crack tip heating does occur [9], an uncontrolled temperature rise is prevented and crack growth occurs by mechanical processes. (Mechanical failures can also arise in unnotched samples when the stress level is too low to generate runaway heating but still high enough to cause mechanical crack nucleation and propagation.) It is striking to note, however, that when prenotched samples are tested over a range of cyclic frequencies, the associated fatigue crack propagation rates (da/dN) for a number of polymers such as poly(methyl methacrylate) (PMMA), polystyrene, poly(vinyl chloride) and poly(phenylene oxide) *decreased* with increasing frequency while da/dN of other polymers such as polycarbonate, polysulfone, nylon 66 and poly(vinylidene fluoride) showed no apparent frequency sensitivity [1, 2]. Apparently, gross thermal melting does not occur in the case of notched samples. It was speculated by the authors that the observed frequency response could be explained by a variable creep component which would make a larger contribution to da/dN as frequency decreased [2]. However, further studies in our laboratory suggest that this model may not be generally applicable to all polymers. Fatigue tests on selected polymers have shown a strong frequency sensitivity at stress intensity levels where no creep crack growth was measurable [10 - 18]. It was also noted that the sensitivity of fatigue crack propagation to frequency may be related to the propensity of a polymer for crazing [1, 2]. Those polymers which crazed very easily (e.g., PMMA, polystyrene) showed the largest effect of frequency while polycarbonate and polysulfone which were not believed to craze readily [19] were unresponsive to changes in test fre-

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*Materials Research Centre, Lehigh University, Bethlehem, Pa., U.S.A.

quency. Recent work has revealed that this relationship must be tempered with the knowledge that at least under fatigue loading at low ΔK and high test frequency, polycarbonate and polysulfone are found to craze [20].

In previous publications [2, 21] a comparison was made between the frequency sensitivity factor (defined as the change in da/dN per decade change in test frequency) and the frequency of molecular motions responsible for the β peak (jump frequency) for a wide range of polymers at a common test temperature. This resulted in a most interesting relationship (see Figure 2). Polymers which exhibited a jump frequency close to the mechanical test frequency regime showed a high frequency sensitivity factor, while those polymers with a jump frequency much greater than the test frequency range had no frequency sensitivity (frequency sensitivity factor = 1) [2, 21]. Although no polymer with a jump frequency much less than the test frequency has been tested, a frequency sensitivity factor at about 1 for such a material would be expected. This relationship suggests a condition of resonance of the *externally* imposed test *machine* frequency with the meterials *internal* segmental mobility corresponding to the β peak.

On the basis of the correlation shown in Figure 1, one would expect the room temperature frequency sensitivity factor of polycarbonate, polysulfone, nylon 66 and poly(vinylidene fluoride) to increase were it possible to excite these materials at test frequencies in the range of 10^6 Hz. Unfortunately, this could not be studied directly because of test machine limitations. However, since the segmental motion jump frequency varies with temperature, it should be possible to choose a particular test temperature for each material that will bring the jump frequency into the cyclic frequency range permitted by our test machine. For this case, the frequency sensitivity should be maximized. Correspondingly, the frequency sensitivity of PMMA should be attenuated at test temperatures below ambient.

Therefore the objective of this study was to further clarify the correlation between cyclic frequency and the jump frequency by changing test temperature. The polymers chosen for this study were PMMA, polysulfone and polycarbonate. Polycarbonate and polysulfone which show no frequency sensitivity at room temperature, were tested at lower temperatures where the β peak at the test frequency is maximized. Corresondingly, PMMA, a polymer with a high frequency sensitivity factor at room temperature, was tested at lower temperatures where the test frequency and the jump frequency differ by orders of magnitude. In this manner, the frequency sensitivity factor for this material should be reduced. (With all specimens, it should be noted that since each frequency corresponds to a somewhat different value of the temperature for the β-process, experiments at constant temperature are not rigorously comparable. However, inspection of typical β-peak data [22] shows that the consequent error in the frequency sensitivity factor will not affect the conclusions.)

EXPERIMENTAL PROCEDURE

The fatigue specimens used in this study were machined from sheets of commercially available PMMA ($M_v = 1.6 \times 10^6$), polycarbonate ($M_v = 4.8 \times 10^4$) and polysulfone ($M_v = 5.0 \times 10^4$). The specimen thicknesses of polycarbonate and PMMA were 6.4 mm and polysulfone was 4.4 mm. All test samples were of the compact tension geometry with W = 63.6 mm and H/W = 0.6.

Fatigue tests were preformed on an 8.8 kN MTS testing machine at test frequencies of 1 and 100 Hz with a constant R value of 0.1 where R = Kmin/Kmax. Crack growth measurements were made with a travelling microscope at intervals of approximately 0.25 mm. The test temperatures ranged from 148 K to 298 K.

All fatigue testing was carried out in a small well-insulated metal environmental test chamber. The desired temperature was obtained by carefully controlling the flow of cooled nitrogen vapor through the chamber. A double glass window separated by dry nitrogen enabled crack measurements to be made readily without fear of frost forming on the external glass pane. Temperatures and frequencies for the β-transition were determined as described previously [21].

RESULTS AND DISCUSSION

Frequency sensitivity factors were calculated for all test specimens from fatigue crack propagation data obtained at 1 and 100 Hz. The values of frequency sensitivity factor were then plotted as a function of temperature and are shown in Figures 3 - 5. Polysulfone and polycarbonate, two polymers which showed negligible frequency sensitivity at room temperature, exhibited a maximum in frequency sensitivity factor (>2.4) at temperatures corresponding to a jump frequency between 1 and 100 Hz for both materials. In preliminary testing PMMA which demonstrated a maximum frequency sensitivity factor at room temperature (jump frequency $\sim$ test frequency) responded to a lowering of test temperature with a considerable decrease in frequency sensitivity factor as the jump frequency became much lower than test frequency. These data lend further support to the correctness of the β jump frequency-test frequency correlation. Such a correlation is not surprising, for the β-process may be associated with yielding, creep, crazing and crack growth phenomena [23].

A physical interpretation of this correlation may be seen with the following model. It is generally accepted that the β peak represents a region of maximum loss compliance, associated with a high level of damping or energy dissipation. This increase in damping leads to a corresponding increase in hysteretic energy and a localized temperature rise. In the notched samples utilized in this study and others, the maximum heat rise is restricted to the minute plastic zone near the crack tip while the bulk of the specimen experiences lower cyclical stresses and remains essentially at ambient temperature. Although heat transfer from the plastic zone to its cooler surrounding environment might limit the rate of crack tip heating, fatigue testing at high frequencies (100 Hz) should nevertheless produce a considerable temperature rise at the crack tip. This has been confirmed by Attermo and Ostberg [9] who recorded a maximum increase in crack tip temperature of 20 K in fatigue testing of polymers at only 11 Hz. With a significant increase in temperature, yielding processes in the material surrounding the crack tip should be enhanced. This should lead to an increase in the crack tip radius. This greater radius of curvature at the crack tip should result in a lower effective ΔK. As this effective ΔK decreases, da/dN is expected to decrease accordingly. While no attempt was made to measure crack tip radii or temperatures in this study, high frequency fatigue tests performed on another polymer (internally plasticized PMMA) with a very high value of J" caused the crack tip region to rapidly become hot to the touch [18]. In addition, the crack tip became visibly rounded. At this point, stable crack growth ceased.

It is conceivable then that frequency sensitive factor is maximized when the rate of crack tip heating is greatest since crack growth rates will be slowest in comparison. This could occur at temperatures where extensive energy dissipation or damping is present within a polymer, and occurs in resonance with the test frequency.

CONCLUSIONS

The correlation between the β jump frequency and test frequency as it relates to the sensitivity of crack growth rates to test frequency, is convincingly supported by fatigue crack propagation data obtained for PMMA, polycarbonate and polysulfone over a range of temperatures. This behaviour may be reasonably explained in terms of hysteretic heating at the crack tip which is maximum at the β-peak. The resulting crack blunting causes a drop in da/dN which is believed to be responsible for the observed frequency sensitivity of fatigue crack propagation in numerous polymeric solids.

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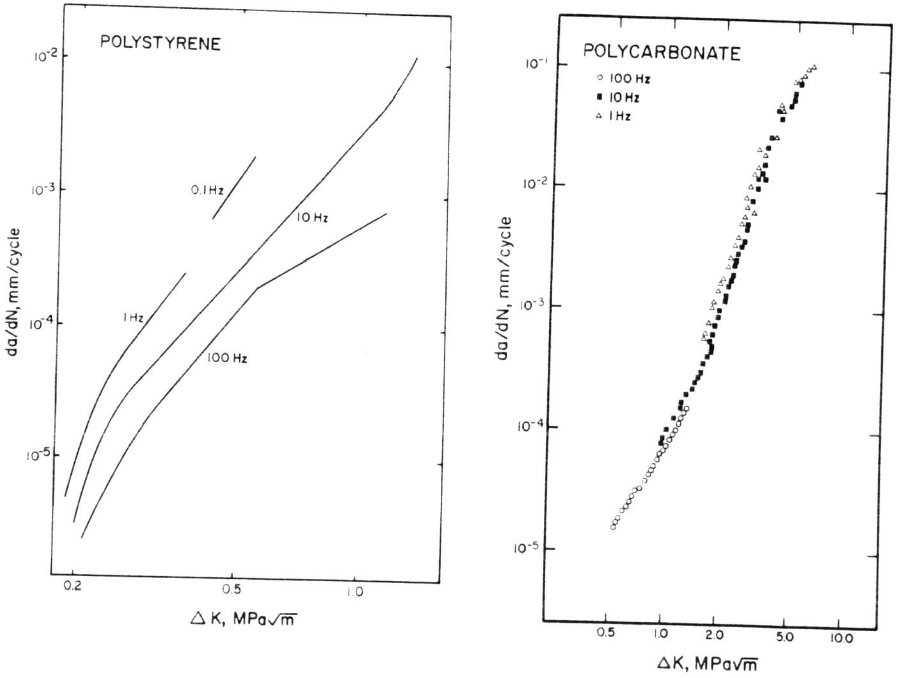

(a)

(b)

Figure 1 Effect of cyclic frequency on fatigue crack propagation in (a) polystyrene (2,10) and (b) polycarbonate (2).

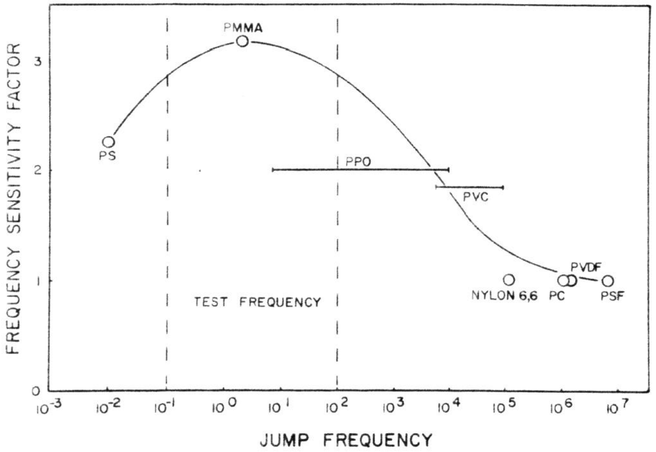

Figure 2 Relationship between fatigue crack propagation frequency sensitivity and the room temperature jump frequency for several polymers [2,21].

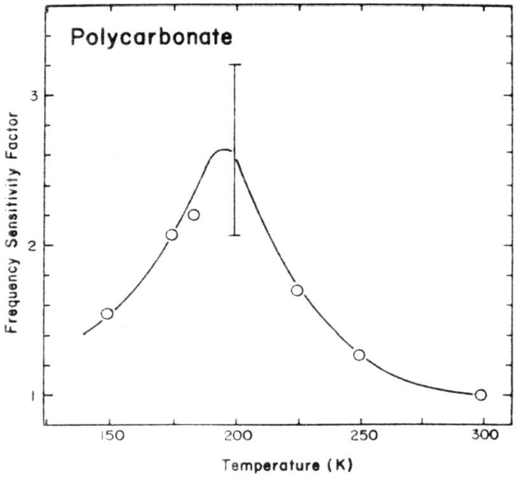

Figure 3 Effect of temperature on the frequency sensitivity factor of polycarbonate.

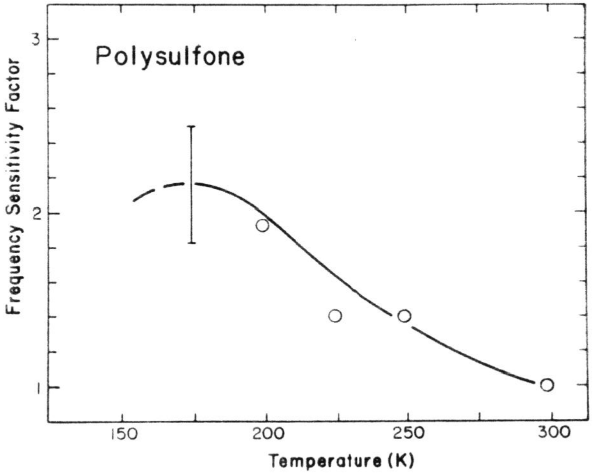

Figure 4 Effect of temperature on the frequency sensitivity factor of polysulfone.

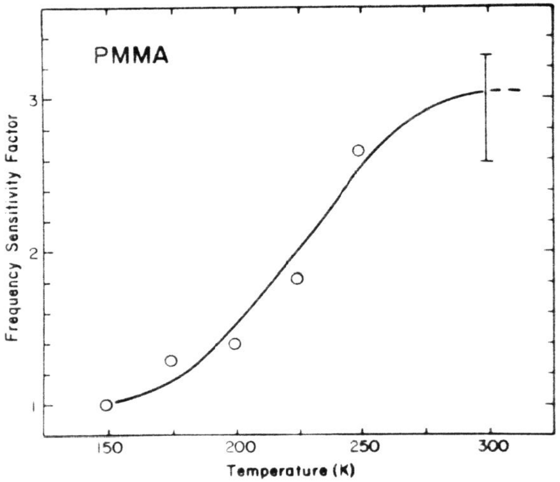

Figure 5 Effect of temperature on the frequency sensitivity factor of poly(methyl methacrylate).