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

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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 Perry [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) increased 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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Fatigue tests were performed on an 8.8 kN MTS testing machine at constant 
fatigue crack propagation rate between 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 environment 
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 the operator to 
monitor 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

Fatigue 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. Polysulphone and polycarbonate, two poly-
mers 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 = 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 [25].

A physical interpretation of this correlation may be seen with the follow-
ing model. It is generally accepted that the β peak region is related 
with enhanced plastic flow, associated with a high level of damping 
or energy dissipation. This increase in damping leads to a corresponding 
increase in hysteresis energy and a localized temperature rise. In the 
notched samples utilized in this study and others, the maximum heat rise 
is restricted to the immediate plastic zone near the crack tip while the 
bulk of the specimen experiences lower cyclical stresses and remains 
especially 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 frequency (100 Hz) should 
nevertheless produce a considerable temperature rise at the crack tip. 
This has been confirmed by Attemo 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 
Jψ 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.

EXPERIMENTAL PROCEDURE

The fatigue specimens used in this study were machined from sheets of 
commercially available PMMA (Mn = 1.6 x 10⁶), polycarbonate (Mn = 4.8 x 10⁵) 
and polysulphone (Mn = 5.0 x 10⁵). The specimen thicknesses of poly-
carbonate and PMMA were 6.4 mm and polysulphone was 4.4 mm. All test 
specimens were of the compact tension geometry with K = 0.6 mm and H/K = 
0.6.
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 polysulphone 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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Effects 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).