Cyclic Fatigue and Thermal Softening of Polypropylene

It is well known that fatigue failure in thermoplastics takes one of two modes: fatigue crack propagation and thermal softening. Because of the low thermal conductivity and high damping properties of many thermoplastics, heat is continuously built up within the body of the specimen as it is subjected to cyclic fatigue. If the temperature rise reaches an equilibrium or saturation temperature without thermal failure, true fatigue crack propagation characteristic of metals takes place. However, if the temperature at a critical section increases to an extent that the heat distortion temperature of the plastic is exceeded thermal softening failure occurs. Previous investigations[1–7] on this subject include polymers such as PMMA, polyacetal, PVC, nylon, and polyethylene. In the present note the fatigue failure behavior of another tough polymer—polypropylene—is reported. In particular, the effects of notches on the failure mode are investigated as flaws like surface scratches and part-through cracks are likely to appear during repeated use of the polymers concerned.

The polypropylene rods were extruded and supplied by ICI Ltd. and were turned into cantilever rotating bending specimens. Circumferential notches in the range 0.38–2.25 mm were machined by sharp razor blades mounted on the lathe at positions approximately 5 mm away from the fixed end of the specimen (see inset of Fig. 1). This critical section was chosen since it would experience the largest temperature rise in the fatigue experiments. The surface temperature rise during cyclic loading was measured by an infrared radiation pyrometer and the dynamic viscoelastic properties of the polymer were measured by a Dynamic Viscoelastomer Rheovibron.

Figure 1 shows the S–N curves for the polypropylene specimens for rotation speeds in the range 450–4000 cpm. The mode of failure was always by thermal softening at the critical section. Figure 2 shows some typical temperature-time curves at 2000 cpm. The critical temperature at which the specimens failed was difficult to define and measure. However, it is possible to define the onset of thermal softening by $d\theta/dt \rightarrow \infty$ and this temperature varies from 50°C to 60°C and is apparently

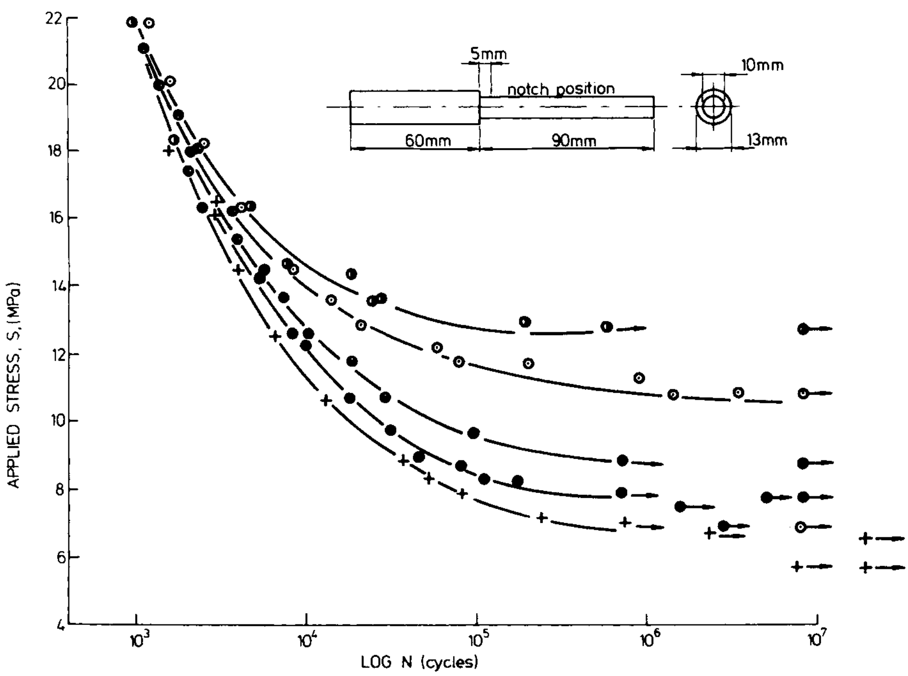

Fig. 1. S–N curves for unnotched PP specimens. (◑) 450 cpm; (⊙) 1000 cpm; (⊗) 2000 cpm; (●) 3000 cpm; (+) 4000 cpm. Arrows indicate no break. θ_0 = 22°C.

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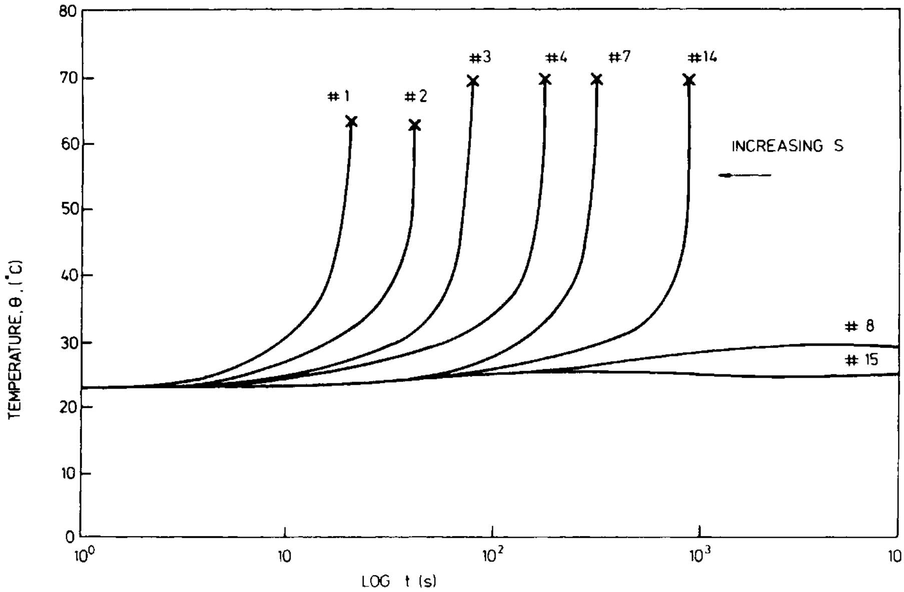


Fig. 2. Temperature rise-time curves for unnotched PP specimens at 2000 cpm.

independent of cyclic frequency. It is also noted that the fatigue endurance strength (S_0), as shown in Figure 1, decreases with increasing frequency. For practical purposes, S_0 may be identified as the thermal softening limit stress below which thermal failure does not occur. S_0 can be obtained from[1]

$$S_0 = \left[\frac{E^*(\theta - \theta_0)(1 + \tan^2\delta)}{\tan\delta}\right]_p^{1/2} \left(\frac{2\beta h}{wk^2}\right)^{1/2} \tag{1}$$

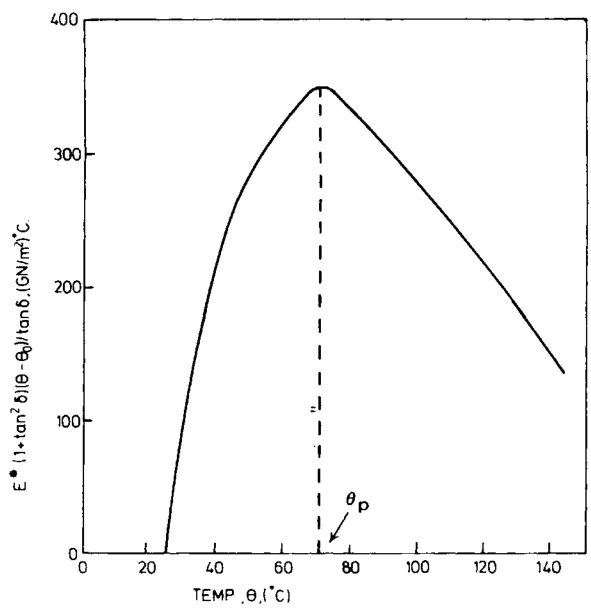


Fig. 3. Thermal failure mechanism for PP. Frequency = 7 Hz; θ_0 = 22°C; $\theta_p \approx$ 70°C.

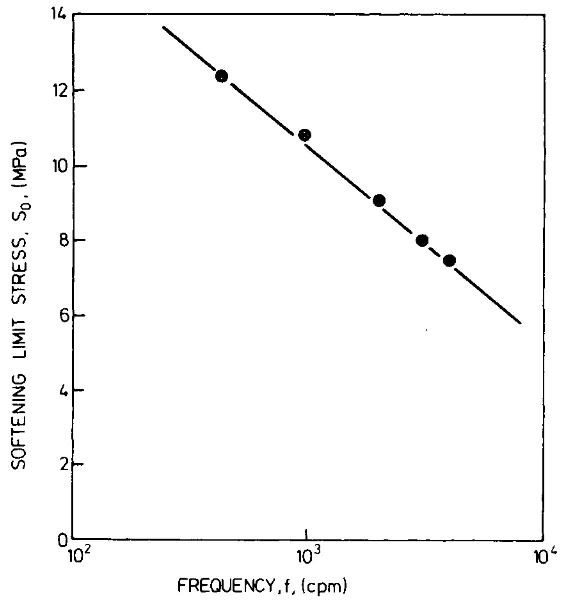


Fig. 4. Variation of S_0 with log w. $\beta = A/V = 0.4\ \mathrm{mm}^{-1}$; w = f/60 (Hz); $S_0 = 17.10 - 5.32 \log w$.

where E^* is the real modulus of the polymer, θ and θ_0 are the instantaneous and ambient temperatures, tan δ the loss tangent, w the cyclic frequency, h the heat transfer coefficient, β the shape factor, and k the conduction coefficient. The variation of the expression: $E^*(\theta - \theta_0)(1 + \tan^2\delta)/\tan \delta$ with θ for $w = 7$ Hz is given in Figure 3 and the maximum value occurs at $\theta = \theta_p$. Using this value together

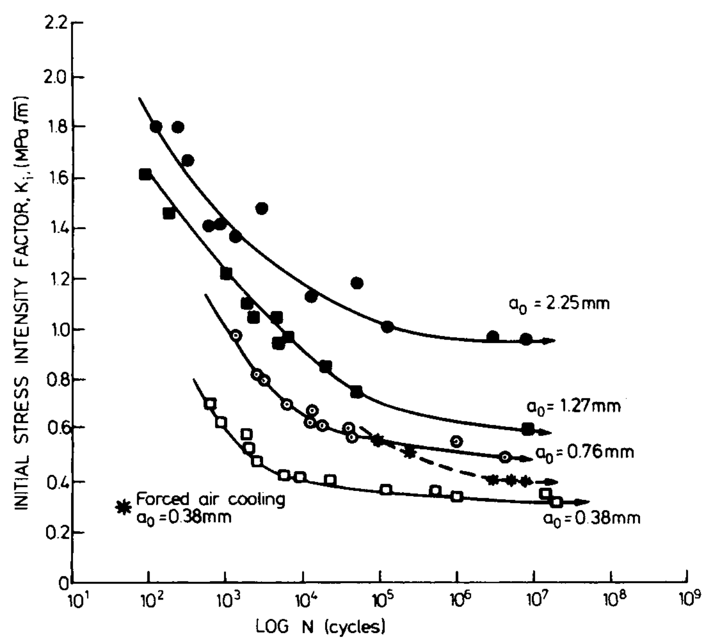


Fig. 5. K_i–N curves for notched PP specimens at 450 cpm.

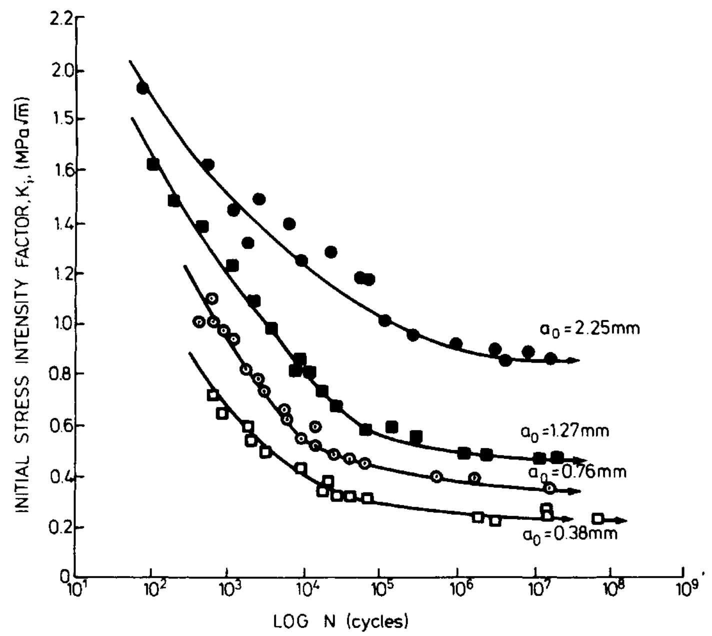


Fig. 6. K_i–N curves for notched PP specimens at 2000 cpm.

with $k = 1$, $\beta = 400\ \mathrm{m}^{-1}$, and $w = 7.50$ Hz (i.e., 450 cpm), eq. (1) gives $S_0 = 10.6$ MPa and 15 MPa for $h = 20$ and 40 N/m°Cs respectively. These results agree reasonably well with the experimental value of 12.8 MPa (Fig. 1). For engineering design with this polymer an empirical equation can be developed for convenience. In Figure 4 an S_0–log w plot is shown for polypropylene, which gives good fit to the following equation:

$$S_0 = 17.10 - 5.32 \log w \tag{2}$$

where S_0 is in MPa and w in Hz. Attempts to promote true fatigue crack propagation by forced cooling with an air stream jet and a detergent fluid failed and tests were stopped after N reached 10^7 cycles. It was therefore concluded that polypro\ lene would not display "brittlelike" fatigue fracture without notches or stress raisers.

Figures 5 and 6 show the K_i–N curves for the notched cantilever rotating bend specimens at 450 and 2000 cpm, respectively. K_i is the initial stress intensity factor to be used instead of S for unnotched specimens and is given by[8]

$$K_i = \frac{8M}{D^3}\left[\frac{d}{\pi}\left(\frac{\alpha - 1}{2}\right)\right]^{1/2}\left[\frac{3}{2}\left(\frac{\alpha + 1}{\alpha}\right) + \alpha^3\right] \tag{3}$$

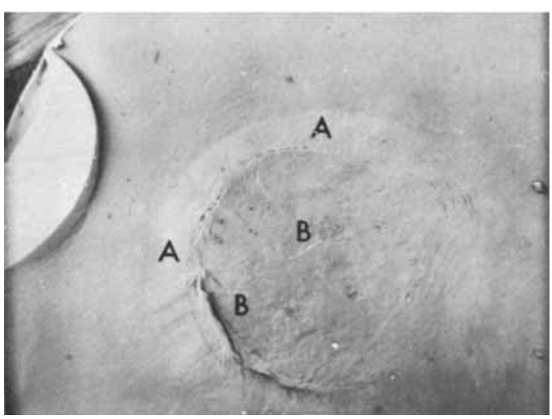
where $\alpha = D/d$, D is the specimen diameter, d is the net section diameter, and M is the applied bending moment at the notched section. Again, despite the presence of the notches, all specimens failed by thermal softening, although a very limited amount of slow fatigue crack growth was observed in specimens with moderate K_i levels and large notch depths. Figure 7 shows some typical failure surfaces. The fatigue threshold stress intensity factor (K_0) which may be considered as the equivalent of S_0 is plotted in Figure 8 as a function of the starter notch depth (a_0). It is clear that K_0 increases with a_0 but decreases with w.

With the notched specimens it is possible to promote some form of brittle fatigue fracture by forced air cooling at the notch section, as shown in Figure 9. However, the final failure mode is still by thermal softening as the net cross-sectional area becomes too small to take up the applied load. It may however, be noted that the K_i–N curves can be considerably changed by forced air cooling, as shown by the chained curve for $a_0 = 0.38$ mm in Figure 5.

It is apparent from the present investigation that under normal cyclic loading conditions (excluding forced air cooling), polypropylene (whether notched or unnotched) does not usually exhibit "brit-

(a)

(b)



(c)

Fig. 7. Typical failure surfaces for notched PP specimens: (a) thermal failure showing drawn fibrils, $a_0 = 0.38$ mm (×9.5); (b) thermal failure showing circumferential drawn ridges, $a_0 = 0.76$ mm (×9.5); (c) Failure surface showing a ring region of brittlelike failure (A) and a core region of thermal failure (B), $a_0 = 2.25$ mm (×9.5).

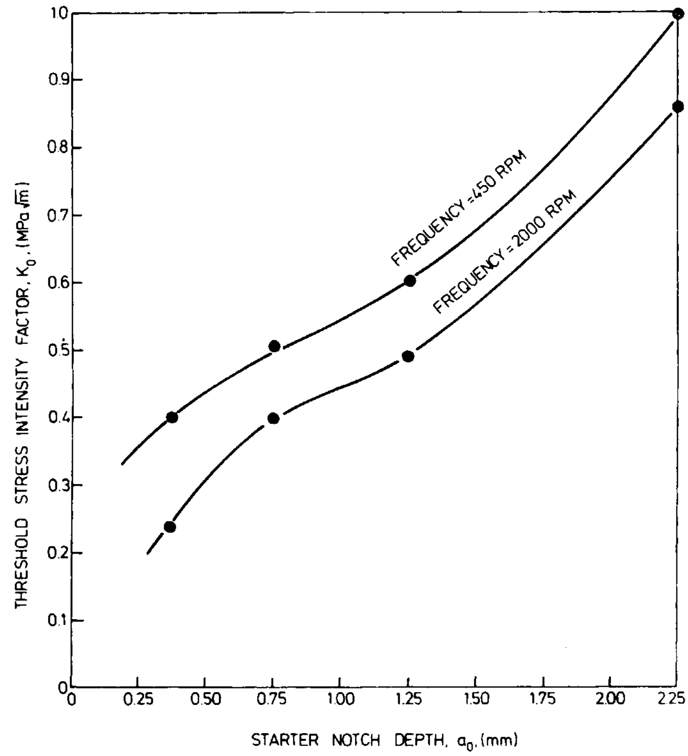


Fig. 8. Variation of K_0 with a_0.

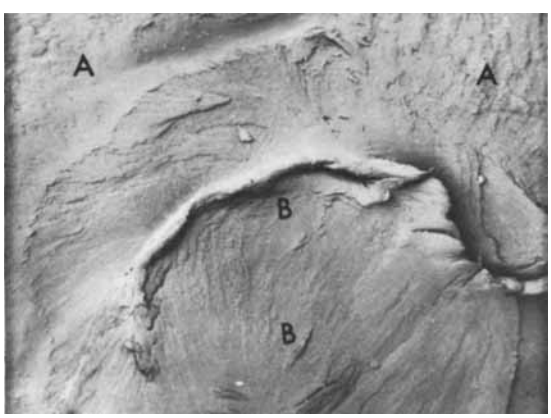


Fig. 9. Fractured surface of a notched PP specimen showing a region of brittle fatigue crack propogation (A) and a core region of thermal softening failure (B), $a_0 = 0.38$ mm. Forced air cooling was used in this experiment.

tlelike" fatigue fracture. To avoid thermal softening failure, a suitable design criterion should be one based on the thermal softening limit stress (S_0) as given by eq. (2) and shown in Figure 4.

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