Effect of moulded and machined notches upon the fatigue strength of an acetal copolymer

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Uniaxial and rotating bending fatigue tests have been carried out on acetal copolymer specimens containing moulded-in notches and holes. The effects of these stress concentrations were compared with earlier work in which the same stress concentrations were machined into the specimens. It was found that in all cases the moulded stress raisers exhibited longer endurances than those which were machined although the effects in each case could not be predicted from a knowledge of elastic stress concentration factors.

INTRODUCTION

In recent years polymeric materials have become well established in load bearing applications. In many of these applications the plastic component is subjected to a cyclic variation of stress in which case the possibility of fatigue failure must not be overlooked. In 1970 a programme of research was set up to study the problem of fatigue in thermoplastics in detail. The results of this work have been reported in ref 1–4.

Initially using a uniaxial and subsequently a rotating bending mode of deformation, it was found that the principal difference between the fatigue behaviour of metals and plastics was the temperature rise effect due to the high damping and low thermal conductivity of the latter materials. Energy is dissipated every cycle during cyclic loading of a thermoplastic material and this appears in the material as heat. As a result, there is a temperature rise which can take one of two forms:

(a) an initial temperature rise which stabilizes at a value depending on the stress amplitude. The material remains at this temperature until cycling is stopped or a conventional fatigue failure occurs;

(b) the temperature continues to rise until failure of the material occurs through a drastic drop in modulus.

The net result is that the fatigue characteristics for a thermoplastic material have two distinct regions. At any selected frequency there is a critical stress amplitude above which short-term thermal runaway failures occur and below which failure occurs through the more conventional fatigue mechanism of crack initiation and propagation. If the cyclic frequency is reduced then the occurrence of thermal failures is delayed until higher stress amplitudes are reached.

Another important aspect of fatigue is the effect of stress concentrations. In the field of metal fatigue problems are much more serious if notches or other stress raisers are present in the component. It has been shown[2,5] that a similar situation exists for thermoplastic materials. The inherent hysteresis in these materials during cyclic loading means that there can be additional problems in the form of very high stress concentrations at the tips of microcracks[6]. In the previous studies[2,3] it was expedient to machine the stress raisers into the moulded specimens. However, in many practical situations the plastic component will be moulded with the stress raisers included. In the present work therefore, the effects of moulding sharp corners and holes into a component is examined and compared with the earlier results. In both cases the frequencies and stress amplitudes were selected so as to avoid thermal failures.

SPECIMENS AND APPARATUS

The shape of the plain specimen is shown in *Figure 1*. The following stress raisers were moulded or machined into the parallel length of the specimen in *Figure 1*:

(a) a circumferential 45° V groove of 1 mm depth and 0.05 mm root radius;

(b) a transverse hole of 2.55 mm diameter

For the initial programme of work[1] the plane specimens were moulded at ICI Plastics Division, Welwyn Garden City, whereas for the present work the mouldings were produced at Queen's University, using a single gate at one end of the specimen.

Uniaxial fatigue tests were performed on a 5 kN servo-controlled hydraulic machine. In all cases load feedback control was used with a zero mean load. A sinusoidal waveform was employed at frequencies in the range 1–10 Hz. The other fatigue tests were of the rotating bending type at 25 and 50 Hz frequency as described in detail previously[4]. The material used in this study was the same acetal copolymer as in the previous programmes.

To facilitate the moulding at Queen's University, the wall thickness of the specimens was reduced from 5 mm to 3.5 mm. Initially, therefore the fatigue behaviour of these new specimens in the unnotched state was investigated and found to agree very closely with the earlier fatigue data for the thicker specimens.

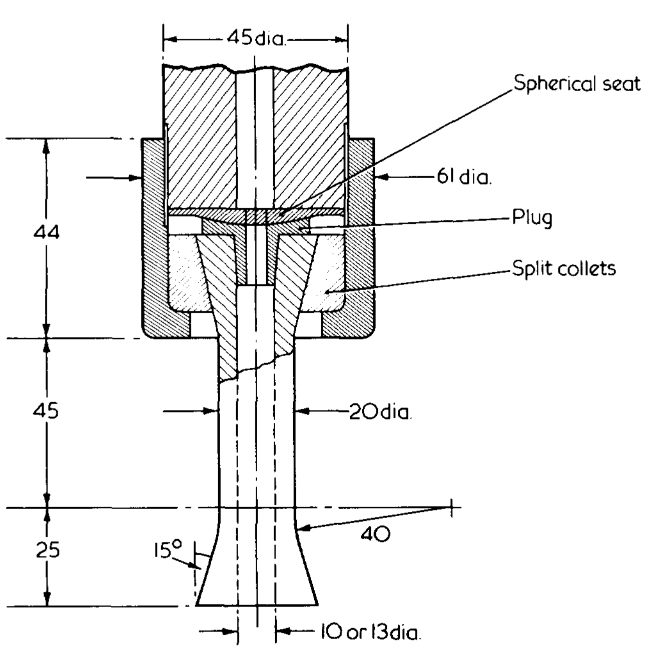

Figure 1 Specimen and grips. Dimensions in mm

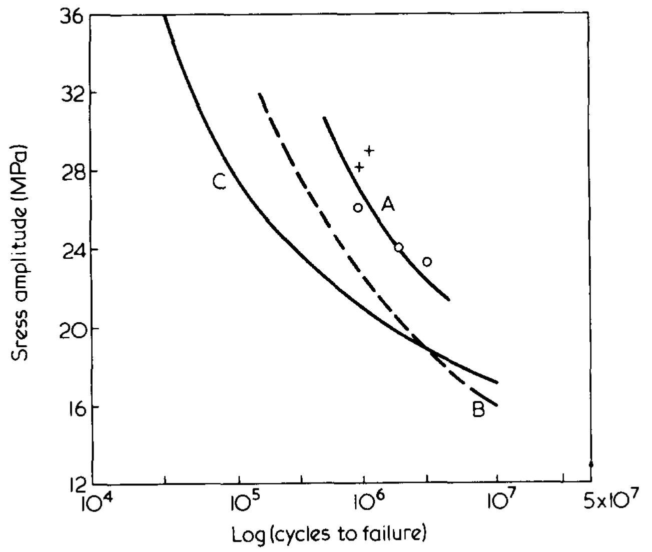

Figure 2 Fatigue curve for moulded V-notch. Load control; sinusoidal waveform; mean stress = zero. A, Moulded V-notch; B, plain specimens (ref 3); C, machined V-notch (ref 2). +, 1.67 Hz; O, 5 Hz

It should be emphasized that the use of a range of frequencies was examined in detail in the earlier work[1–4] and there was no significant frequency effect for this material both in uniaxial and rotating bending fatigue. Specimen surface temperature was monitored in most tests using infrared thermometry in order to observe any hysteresis effect at the various stress levels and frequencies used.

UNIAXIAL FATIGUE TESTS

Effect of a V-notch

In the initial studies on the effect of notches a sharp V-notch was machined into a number of moulded specimens and their fatigue behaviour examined as shown in *Figure 2*. Bearing in mind that this notch produced an *SCF* (elastic stress concentration factor) of 8, the vertical shift in the fatigue curve is less than might have been expected. For endurances in excess of 3 x 10^6 cycles the fatigue behaviour of the notched specimens is as good or better than the plain specimens.

The mould was next modified so that the sharp V-notch could be moulded into the specimens, and further fatigue tests carried out. There are a number of interesting points in relation to the comparison of machined and moulded notches illustrated in *Figure 2*. Firstly, the specimens with the moulded notch have longer endurances than those with the machined notch, and longer than for unnotched specimens. The first observation is probably not surprising, in that moulded components tend to have a skin layer which is different in structure to the bulk of the material. It has been shown[4] that this skin resists fatigue crack initiation and hence acts as a protective coating under dynamic loading. When the notch is moulded into the specimens the protective skin is effective right around the notch area as shown in *Figure 3*. When the notch is machined into the specimen, however, the skin layer, which was measured to be approximately 0.75 mm thick, is penetrated and fatigue crack initiation and propagation is no longer inhibited.

The second observation regarding the greater endurances of the moulded notch specimens in comparison to the plain specimens is probably because the so-called 'plain' specimens are only plain in the sense that they do not contain deliberately introduced stress concentrations, but they may contain defects as a result of the moulding process. The protection offerred by the moulded skin means that, unlike metal fatigue failures, the cracks initiate and propagate from within the bulk of the material. The site of this initiation is probably determined by the major incipient moulded stress concentration in the material. This could account for the apparent anomaly between the plain and notched specimens. In the moulded notch specimens, failure will be initiated at the root of the notch unless by chance, during moulding, a larger stress concentration has been introduced within the bulk of the material at the notch section. In this unlikely event, the fatigue endurance would be expected to lie on the dotted plane fatigue curve shown in *Figure 2*. In the more usual case where fatigue initiates from the notch root, the moulded skin apparently offers sufficient protection for the material to exhibit a longer fatigue endurance.

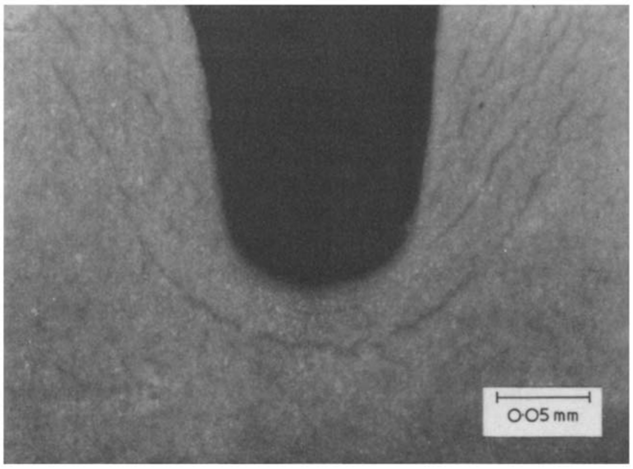

Figure 3 Micrograph of longitudinal section through notch root, showing orientation in the skin

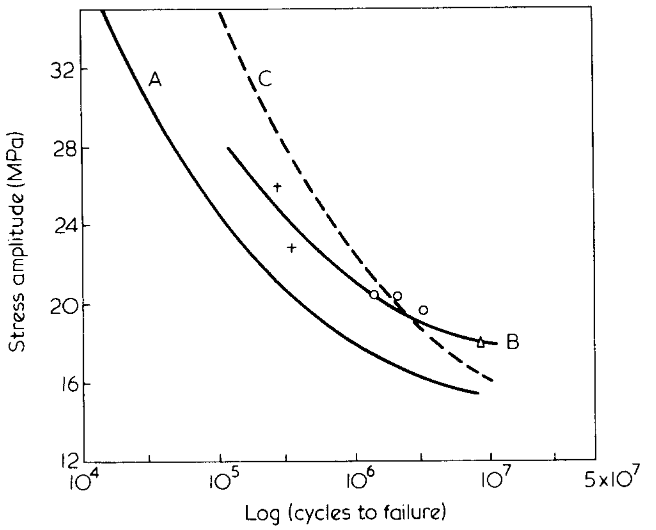

Figure 4 Fatigue curve for specimen with moulded diametral hole. A, Machined diametral hole (ref 2); B, moulded diametral hole; C, plain specimens (ref 3). +, 1.67 Hz; ○, 5.0 Hz; △, 10.0 Hz. Load control; sinusoidal waveform; mean stress = zero

Effect of a hole

Since the circumferential V-notches did not cause the reduction in fatigue endurances which might have been expected from the theoretical elastic stress concentration factors, a different geometry of stress concentration was introduced for comparison. A 2.55 mm hole was drilled transversly through the parallel part of specimens to give an *SCF* of 2.6. *Figure 4* shows that with this new stress raiser the material exhibits a considerable reduction in fatigue endurances compared with the plain specimens and even less than those of the specimens with a machined V-notch. The reason for this is thought to be connected with moulded anisotropy in the specimens.

Examination of the fracture showed that in the V-notched specimens the cracks propagated in the radial direction whereas in the specimens with a diametral hole, the cracks propagated in the circumferential direction. It was concluded therefore that the latter direction was more conducive to crack growth. This was borne out by the fact that when cracks propagated from within the wall of a plain specimen, the crack was always markedly elliptical in shape with the major axis in the hoop direction. Another contributory factor is that in the notched specimens, the stress concentration is effective only in the vicinity of the notch root and crack initiation and propagation is therefore dependent on the structure of the moulding in that area. In the specimens with a diametral hole, however, the cracks can initiate and grow at the weakest zone across the wall thickness.

The effect of moulding a hole, compared with machining, on the fatigue strength is shown in *Figure 4*. The moulded skin in the region of the hole once again delays fatigue crack initiation so that endurances are improved in comparison to the machined hole.

ROTATING BENDING FATIGUE TESTS

In the initial programme to investigate the fatigue behaviour of polymeric materials the bulk of the work was carried out using uniaxial loading but the effect of using a rotating bending mode of testing was also examined. It was found that in common with metal fatigue behaviour, the endurances observed in rotating bending tests on thermoplastics are always greater than those which result from uniaxial loading. The main reasons for the large differences in endurances are:

(i) there is a stress gradient across the specimen during rotating bending fatigue, and

(ii) fatigue failures must initiate from the surface in rotating bending whereas under uniaxial loading any weak point across the wall of the specimen is vulnerable.

Effect of a notch

When the specimens containing the machined V-notch were tested under rotating bending conditions, *Figure 5* shows that there was a significant reduction in the endurances, particularly at high stresses. It is interesting to compare this notch fatigue curve with that in *Figure 2* obtained under uniaxial loading. Since cracks are propagating from the tip of the notch in both deformation modes, then point (ii) above is no longer applicable and it is possible to obtain some idea of the effect which the stress gradient has on fatigue behaviour. It may be seen that at low stresses, approaching the fatigue limit, there is little difference in behaviour but as the stress amplitude is increased, the deterioration in behaviour under uniaxial stress becomes more pronounced.

When the specimens containing the moulded notch were tested under rotating bending fatigue conditions the improvement in behaviour over the machined notches was not as significant as in the uniaxial loading case. *Figure 5* shows that at the highest stress amplitudes used (approximately ± 32 MPa) there is very little difference in behaviour. As the stress amplitude decreases towards ± 20 MPa the performance of the moulded notch specimens becomes progressively better.

Since rotating bending fatigue ensures that the fatigue cracks initiate and propagate through the moulded skin in both the moulded notch and the plain specimens, this mode of loading probably gives a more realistic indication of the effect of the notches.

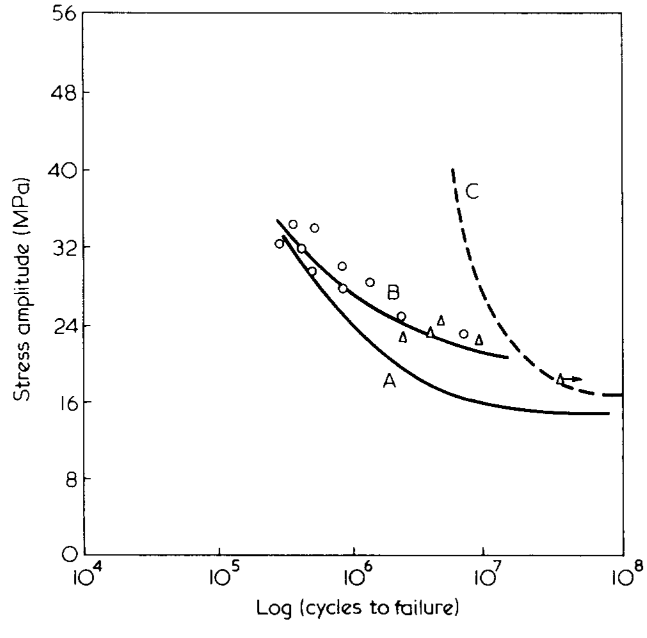

Figure 5 Effect of moulded V-notch on rotating bending fatigue. A, Machined notch (ref 4); B, moulded notch; C, plain specimens (ref 4). ○, 25 Hz; △, 50 Hz

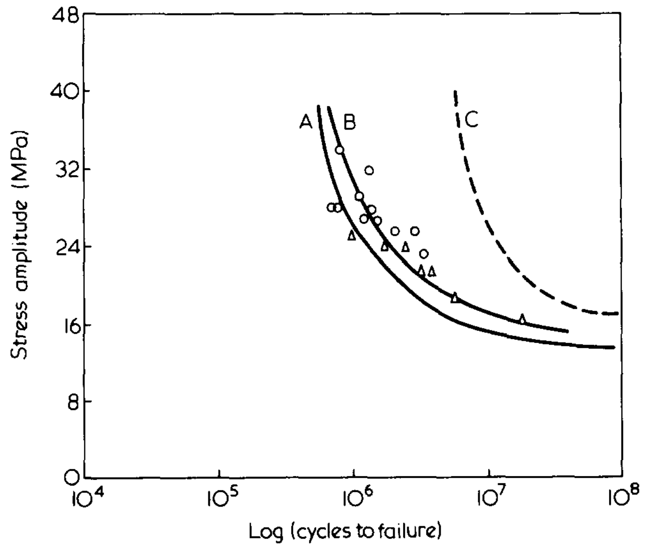

Figure 6 Effect of moulded diametral hole on rotating bending fatigue. A, Machined diametral hole (ref 4); B, moulded diametral hole; C, plain specimens (ref 4). ○, 25 Hz; △, 50 Hz

Effect of a hole

The reduction in fatigue endurance caused by a machined transverse hole was quite similar to that caused by the machined circumferential V-notch (see *Figures 5* and *6*). As mentioned earlier, the respective elastic stress concentration factors are 2.6 and 8 and the most feasible explanation for the similarity in their fatigue behaviour is anisotropy in the mouldings as discussed earlier. When the hole was moulded into the specimens the improvement in behaviour as compared with the machined hole is small. This is probably to be expected in that, in both cases, the cracks are obliged to initiate and grow at the surface layers of the specimen. Therefore, there will be a moulded skin layer to be overcome irrespective of whether the hole is machined or moulded.

RESULTS

The relative effects of the machined and moulded stress raisers are summarized in the following *Table 1* in terms of the fatigue strength reduction factor, F_f, where:

$$F_f = \frac{\text{Plain fatigue strength at } N \text{ cycles}}{\text{Notched fatigue strength at } N \text{ cycles}}$$

Table 1 Effects of machined and moulded stress raisers

		Machined		Moulded	
	Cycles	Notch	Hole	Notch	Hole
Uniaxial	10^5	1.26	1.48	–	1.26
F_f	10^6	1.08	1.24	0.77*	1.06
Rotating	10^7	1.5	1.5	1.07	1.43
bending F_f	10^8	1.1	1.2	0.92*	1.18

*Notched specimens lasted longer than plain specimens

CONCLUSIONS

As a result of these fatigue tests on an acetal copolymer the following conclusions may be drawn:

(a) machined stress raisers are more severe than those which are moulded into components;

(b) components which are moulded without any apparent stress raisers do, nevertheless, contain internal defects which can cause premature failure under cyclic stressing;

(c) injection moulding tends to produce a skin layer which inhibits fatigue crack initiation;

(d) the severity of fatigue strength reduction produced by a geometric stress raiser depends on the position of the stress raiser relative to the surface and flow orientation, and not simply on the magnitude of the elastic stress concentration factor;

(e) the severity of any particular geometric stress raiser depends on the mode of deformation

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REFERENCES

1 Crawford, R. J. and Benham, P. P. *J. Mater. Sci.* 1974, **9**, 18
2 Crawford, R. J. and Benham, P. P. *J. Mech. Eng. Sci.* 1974, **16**, 178
3 Crawford, R. J. and Benham, P. P. *Polymer* 1975, **16**, 908
4 Crawford, R. J. and Benham, P. P. *J. Mater. Sci.* 1974, **9**, 1297
5 Wolf, L. J. and Diboll, W. B. *J. Eng. Ind.* 1965, p 319
6 Zilvar, V. *PRI Conference at Cranfield* 1971, Paper 8