JOURNAL OF MATERIALS SCIENCE 21 (1986) 3801–3809

Flexed plate impact testing of poly(ether sulphone)

Part 2 *Notched specimens*

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Injection-moulded discs of poly(ether sulphone) impacted at 5 m sec^{-1} in a standard flexed-plate configuration fail by a ductile penetration process and the peak force is proportional to the specimen thickness. The peak force is reduced, and the specimen is often embrittled, if there is a machined stress concentrator at the point of impact. The simplest stress concentrator, a hole bored through the specimen, reduces the peak force by about one-third and reduces the overall ductility, even to the point of brittleness in some cases, but it does not constitute a severe notch. The results can all be rationalized in terms of the ratio of peak force to thickness.

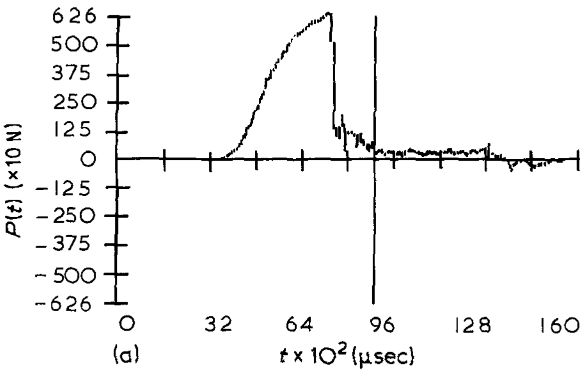
1. Introduction

It is common practice for impact tests to be subdivided into "notched" and "unnotched" classes and the relative values of the various quantities that can be derived from the experimental procedures give useful information about the "notch sensitivity" of a material. In this respect flexed-plate impact tests have been at a disadvantage relative to the tensile and flexed-beam methods for which notches present no particular practical or analytical difficulty.

The flexed-plate method became popular initially because of its practicality, one aspect of which is that the impact resistance of both test specimens and end-products is sensitive to the condition and quality of the tensioned surface. "Surface condition" can refer either to the molecular state or to the gross surface texture, and in relation to the latter it was a common practice at one time for fitness-for-purpose to be assessed on plaques with appropriate surface textures. Such surface features are notches, of course, but the investigations have never been more than semi-quantitative.

Recently, in the course of a major study involving the flexed-plate method we have explored various possibilites for a notched specimen. Leaving aside any discussion of the relative merits of machined and moulded notches, and accepting that the former will always be a necessary option since it leaves the overall flow geometry of the notched specimen identical with that in the unnotched one, the initial experiments were very encouraging in that a hole bored through the specimen at its centre (i.e. through the point of impact) embrittled injection-moulded discs of polypropylene and high-density polyethylene that otherwise would have been tough. Such a hole is easily produced and does not disturb the axial symmetry of the flexed-plate test, so the favourable outcome of the early tests implied that the method might be suitable for general use. Its applicability to other materials had to be examined, however, and attention turned therefore to poly(ether sulphone) which is generally regarded as tough at room temperature except when sharply notched.

The first series of experiments were carried out on a general-purpose moulding grade of poly(ethyl sulphone) (PES). They revealed that edge-gated injection-moulded discs at a thickness of about 3.4 mm and with a small hole bored at the centre failed either by brittle cracks originating at the hole, by brittle cracks originating at an included contaminant or by a splitting process that was classified as ductile. Discs with a surface notch, or merely with a scratch, were very brittle and discs without a hole were ductile (though such specimens were not studied in detail because the force transducer would thereby be at risk). The overall conclusions had to be that the hole is less effective than a surface scratch as an embrittling feature for mouldings of PES at room temperatures, and that PES is probably not quite so tough as might have been supposed. These results were presented at a symposium [1, 2] shortly after they were obtained, on the grounds of their pertinence to the rapidly increasing usage of the flexed-plate impact method. However, the experimental work did not cease after the presentation and, indeed, the subsequent programme was more extensive than the original one. It involved a comprehensive study of the behaviour of a higher molecular-weight grade and an investigation of the effect of specimen thickness. The new results given in this paper do not contradict those published earlier or modify the



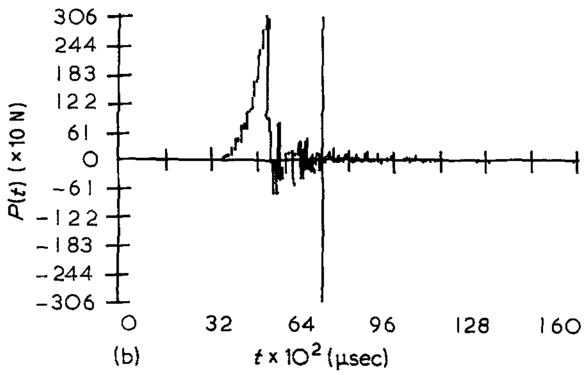


Figure 1 Primary force–time data: (a) ductile penetration failure (see Fig. 2); (b) brittle failure.

conclusions drawn from them; on the other hand, they extend them, set them in a wider perspective and combine with them into a concise statement about the impact resistance of PES.

2. Experimental details

The materials studied were two gades of poly(ether sulphone): Victrex PES 3600G (an easy-flow grade intended for injection moulding), and Victrex PES 5200G (a high melt-viscosity grade normally processed for extrusion). Both grades were supplied in the form of injection-moulded edge-gated discs 114 mm in diameter and two thickness of approximately 1.8 and 3.3 mm. One might have expected the specimens moulded from the high-viscosity grade to be anisotropic due to molecular orientation, but there was no evidence of it; the only consequence seemed to be some interspecimen variability of the thickness.

The impact tests were carried out on a Ceast Advanced Fractoscope System MK3 (Turin, Italy). The specimens were freely supported on an annulus of internal diameter 40 mm and the impactor had a hemispherical tip of diameter 20 mm, in accordance with the specification in ISO/DIS 6603/1. Strict compliance with the standard requires that the specimen be either a disc of diameter 60 mm or a square of side 60 mm but it is the usual practice in Britain for small plaques to be tested at their as-moulded size and this was done in the programme, though it was first ascertained by subsidiary experimentation that the results were not influenced by the lateral dimensions.

The specimens were tested either intact or with a notch at the point of impact. The "notches" were variously a hole, a part-through cylindrical hole with either a flat or a round bottom, a part-through conical hole or a surface groove. They were produced by standard machining techniques and, except in the case of conical holes, there were no associated difficulties. The impact speed was $5\,\mathrm{m\,sec^{-1}}$ and the test temperature was that of the laboratory, which varied from day to day over the range 13 to 20° C. In view of the known properties of PES, no control of the temperature or adjustment of the data for such variation was deemed to be necessary.

Figs 1a and b show typical force–time traces for a ductile failure and a brittle failure, respectively, in PES. From such primary data the quantities deformation, energy etc. are derived by the usual operations. Force–time curves and the data derived therefrom are not always easy to interpret but they are fairly straightforward for PES, and in the subsequent discussion interest is focused particularly on the peak force and the energy absorbed up to that point. The values quoted are the mean values from multiple tests. Most of the sub-sets contained five specimens, which constitutes a very small sample, but the coefficients of variation were not large and the resolution of the data sub-sets was adequate, which justifies the economies in specimen usage and testing time. At no stage were any of the issues clouded by inadequacies in the data.

3. Results and discussion

3.1. The effect of specimen thickness

Because of the nature of this particular investigation, the effect of thickness was apparently of only secondary importance and accordingly it was not studied explicitly until late in the experimental programme, by which time there was already some casual evidence that the peak force was approximately proportional to the thickness whenever the failure was ductile. That linear relationship was in contrast to what had been observed in the case of toughened polystyrene [3].

Sub-sets of specimens were tested at each of several thicknesses. Apart from the two directly moulded thicknesses, others were attained by material being machined from one face of the mouldings. Usually such mechanical thinning changes the properties of the residual specimen because the molecular orientation and texture vary through the thickness, but no such effects were manifest in these mouldings. Irrespective of polymer grade, specimen thickness and thickness of the original mouldings, the values of mean peak force divided by mean thickness were approximately constant, as can be gauged from Table I.

The mode of failure was essentially the same for all the sets. A hemispherical or nearly hemispherical dome developed and usually split along a single line as is shown in the photograph of Fig. 2. Very occasionally the direction of splitting changed before the impactor nose penetrated completely and a flap was thereby created. The appearance of the specimens always suggested failure by tension rather than by shear. The evidence in Table I is at variance with the conclusion in the previous paper [1] that there was probably a tough to brittle transition for the 3600G grade at a specimen thickness of about 2 mm. That conclusion was based on insufficient evidence, part of which was also distorted by embrittlements due to the microscopic

TABLE I Mean peak force/mean thickness for ductile failures in injection-moulded discs of PES

Specimen thickness (mm)	Mean peak force/mean thickness ($N mm^{-1}$)	
	Grade 3600G	Grade 5200G
3.35	3278	
3.17		3388
2.09		3284
2.00	3240	
1.92	3653	
3.4 to 1.74	3251	
1.9 to 1.74	3362	
1.9 to 1.10	3645	
Mean value of measured ratio = 3388(170)*		

*Standard deviation in parentheses.

contaminant that induced the brittle fractures at points remote from the actual impact site. The new evidence from the additional tests carried out recently is more exhaustive; it does not reveal a tough to brittle transition in the thickness range covered, but it does detect a significant tendency to embrittlement by contamination at specimen thicknesses of 1.7 mm and greater.

If one assumes that the dome is created by a shear yielding process that progresses outward from the point of impact to a radius equal to that of the nose of the impactor, the vertical force should be given by

$$P = 2\pi r h \gamma_y$$

where r = radius of impactor nose, h = thickness of specimen and γ_y = shear yield stress. For r = 100 mm, h = 3.35 mm and $\gamma_y = 84/3^{1/2}\,MN\,m^{-2}$, P = 10 200 N.

The observed value of peak force is about 11 000 N and the dome is never deeper drawn than hemispherical, which conforms to the simple model. The dome is sometimes slightly less developed than a hemisphere, but this is not quantifiable because of the distortion induced by the splitting of the specimen and the penetration by the impactor but it is probably that this slight variability in behaviour is linked to the observed variance in the peak force data. Some indication of the experimental scatter can be gained from Fig. 3, which is included for a different purpose, namely to illustrate that the response curves (i.e. force–time curves) for Grades 3600G and 5200G are identical within the usual scatter band. There is close superposition of the four curves until they approach their peaks, when some inter-curve variability develops. The full sets of data for the two grades show that there is no significant difference between the mean peak forces (see also Table I).

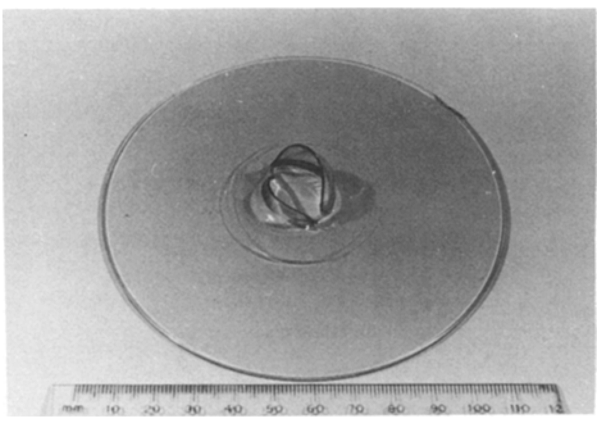


Figure 2 Ductile penetration failure.

From the slope near the origin of the composite curve, with the assumption that the velocity of the impactor had not been reduced significantly from the incident value of $5\,m\,sec^{-1}$ and taking Poisson's ratio equal to 1/3, Young's modulus may be derived as $2.9\,GN\,m^{-2}$. This value is slightly higher than the one reported in the first paper [1] and about 10% higher than the value quoted by the manufacturers. The latter was based on tests entailing a lower rate of straining, which accounts for at least some of the difference. The gradient used in the calculations is essentially governed by the first datum point, which is more or less the earliest one that can be extracted with confidence from the experimental P–t record: the later points correspond to deflections greater than the 0.5 × thickness, which entail the development of membrane stresses. In the case of some thinned specimens the first reliable datum corresponded to a deflection greater than the thickness; for them, use of the elastic formula implied a modulus of $3.8\,GN\,m^{-2}$ but correction with the formula

$$\frac{\delta_0}{h} + 0.253\left(\frac{\delta_0}{h}\right)^3 = 0.513\,\frac{Pa^2}{Eh^4}$$

reduced this to $2.86\,GN\,m^{-2}$ (δ_0 is the central deflection of the plate, h the thickness of the plate, P the force, and E is Young's modulus).

That value, the one quoted above for the thick specimens and the one quoted in the first paper for specimens with a central hole are all in close agreement and between 7% and 10% higher than the value published by the manufacturers, based on tests entailing a lower rate of strain. Another reason for some disparity may be the assumption that Poisson's ratio is equal to 1/3; the relevant part of the elastic

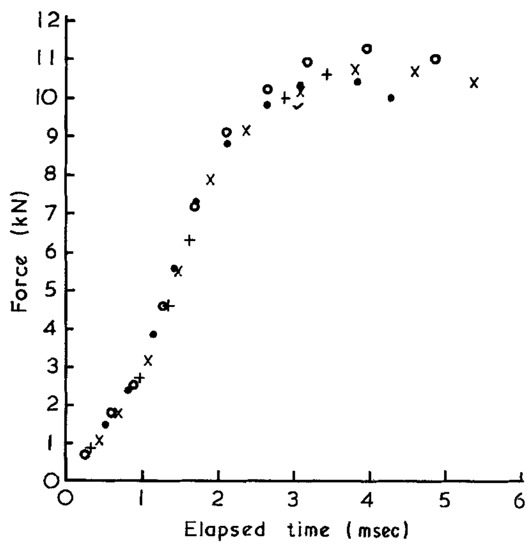


Figure 3 Response curves for grades of different molecular weights. Curves coincide except near peaks. Differences near peaks are not statistically significant; they reflect minor variations in the course of failure development. (●, ○) Grade 3600G; (×, +) Grade 5200G.

equation is

$$(3 + \nu)(1 + \nu)$$

which has the values 2.22, 2.18 and 2.07 for $\nu = 0.33$, 0.35 and 0.39, respectively.

Reverting now to the force–time curve, only a very small section near the origin is attributable to the linear viscoelastic properties of the material and the peak and its vicinity is attributable to the yielding and immediate post-yielding characteristics; the intervening region, which is by far the greater part of the curve, is attributable to membrane stresses in the severely distorting plate rather than to the properties of the material.

3.2. The effect of a hole at the point of impact

The first phase of the initial study of the effect of a hole on the impact resistance of the easy-flow injection moulding grade (3600G) was exploratory and no simple pattern of behaviour emerged from the early results. It subsequently transpired that random brittleness arising from an extraneous factor was superposed on to the genuine effects of the hole. Apart from confusing the initial pathfinding phase, this factor inevitably complicated whatever statement was to be made about the impact resistance. For instance, of fourteen specimens with a hole 1 mm in diameter, four were brittle with the fracture starting at the hole, five were brittle with the fracture not starting at the hole and five were ductile, so that nine out of fourteen were brittle but in only five out of fourteen had the hole acted as an embrittling agent. This would all have fallen into place more readily had the work on Grade 3600G followed, rather than preceded, that on Grade 5200G, the higher molecular weight of which tended to suppress the extraneous embrittlement.

There is nothing sacrosanct about 1 mm as the diameter of the hole. It was chosen originally as a working compromise inspired by intuition overlain by random brittleness, and it subsequently seemed desirable that the effect of hole size should be explored systematically in case a different size chanced to be more effective as a stress concentrator when factors such as ease of preparation and accurate location of the axis of the impact along that of the hole are given due weight. As was shown previously [1], the hole sometimes induces brittleness in Grade 3600G and sometimes induces a failure mode that is best described as ductile, though it is distinctly different from the failure mode in specimens with no hole. The first stage in such "ductile" failure is the development of radial splits in the tension face of the specimen at the edge of the hole. Low-energy blows proved that these develop long before the peak force is reached, which is consistent with the observation that their surfaces have the visual characteristics of brittle fracture. The splits grow and the triangular flaps so formed flex under the advancing impactor, allowing it to penetrate the specimen.

The behaviour of Grade 5200G is identical with that of Grade 3600G when the failure is ductile, and differs from it only in that the incidence of brittleness is much lower. Thus, although the hole is not an embrittling feature as such for the tougher grade it does have an effect as a stress concentrator which can be studied systematically in 5200G without distortion by extraneous or induced brittleness. Data for specimens moulded from the grade at two nominal thicknesses and with bored holes of various diameters are given in Table II. The main facts to emerge are:

(i) the presence of a hole reduces the impact resistance of the specimens;
(ii) the reduction is almost independent of the diameter of the hole; and
(iii) In terms of the peak force/thickness ratio, the reduction is by about one-third.

Since the splits develop long before the force has reached its maximum value, the stress concentration effect is likely to be that implied by the elastic equations. Thus, the circumferential stress, σ_t, at a point r from the centre for an edge-supported, centrally loaded plate with no hole is given by

$$\sigma_t = \frac{3P}{2\pi h^2}\left[(1 + \nu)\ln\left(\frac{a}{r}\right) + (1 - \nu)\right]$$

where P = force applied, a = support radius, h = plate thickness and ν = Poisson's ratio; whereas for a

TABLE II The effect of a central hole on the impact resistance of PES 5200G (impact velocity 5 m sec^{-1}, temperature 17 to 19° C)

Thickness (mm)	Hole diameter (mm)	Peak force (N)*	Energy to peak (J)*	Total failure energy (J)*	Peak force/thickness (N mm^{-1})
2.09	No hole	6870(147)	75.4(7.1)		3284
2.13	0.5	5225(115)	27.1(2.7)	46.6(2.8)	2455
2.05	1.0	4740(353)	22.4(3.4)	41.2(3.4)	2314
2.09	2.0	4550(184)	21.6(2.6)	41.3(3.8)	2173
2.13	3.0	4640(107)	21.9(1.4)	41.0(1.5)	2178
2.15	4.0	4642(405)	22.9(4.6)	41.4(3.8)	2155
3.17	No hole	10740(182)	124(7)	157(12)	3388
3.26	0.5	8000(544)	45.9(5.3)	81.6(6.0)	2457
3.21	1.0	7870(112)	44.1(0.8)	78.2(1.0)	2453
3.25	2.0	7506(483)	41.3(4.4)	74.2(4.1)	2306
3.26	3.0	7825(109)	43.7(2.8)	77.8(1.3)	2393
3.51	4.0	8420(308)	54.4(3.2)	85.8(2.8)	2396

*Standard deviation in parentheses.

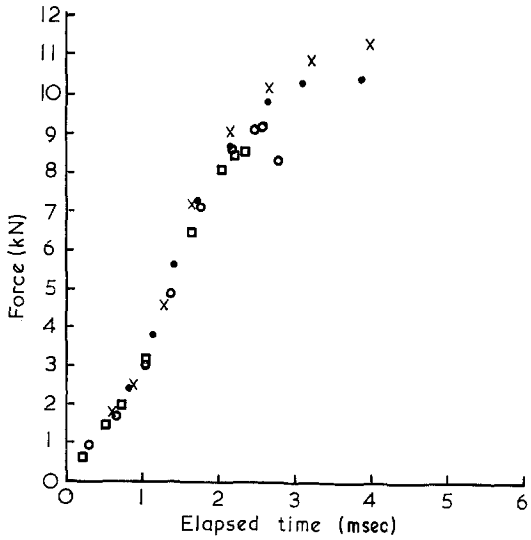


Figure 4 The effect of a hole on the the force–time relationship. Grade 3600G. (●, ×) Intact specimens; (○, □) specimens with hole.

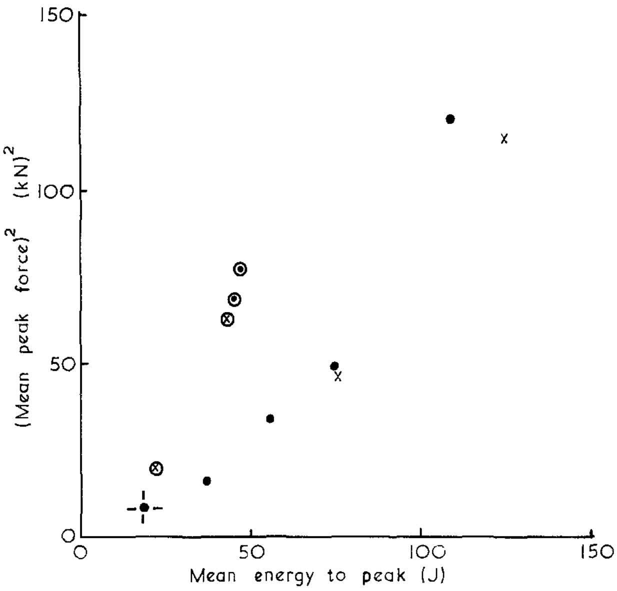


Figure 5 Relationship between peak force and energy to peak. Relationship insensitive to molecular weight, but affected by presence of a hole. Intact specimens (●) Grade 3600G, (×) Grade 5200G; specimens with hole (⊙) Grade 3600G, (⊗) Grade 5200G.

plate with a hole of radius b it is

$$\sigma_t = \frac{3P}{2\pi h^2}\left[(1+\nu)\ln\left(\frac{a}{r}\right) + (1+\nu)\left(\frac{b^2}{a^2-b^2}\right) \times \left(1+\frac{a^2}{r^2}\right)\ln\left(\frac{a}{b}\right) + (1-\nu)\right]$$

where P is uniformly distributed about the edge of the hole. By equating r to b in both equations, the stress-concentrating ratio (defined by the ratio of the circumferential stress at the edge of the hole to the circumferential stress at a radial distance $r = b$ from the centre of the intact plate) is found to be

$$\frac{(1+\nu)\left(\frac{2a^2}{a^2-b^2}\right)\ln\left(\frac{a}{b}\right) + (1-\nu)}{(1+\nu)\ln\left(\frac{a}{b}\right) + (1-\nu)}$$

which is not very sensitive to the value of b but which approaches 2 as $b \to 0$.

That theoretical ratio is greater than the observed ratio of the corresponding peak forces (Table II). There is little to be gained by seeking a quantitative explanation, firstly because it is unlikely that the stress field at a late stage of the impact event can be properly quantified, but more pertinently because the two cases are not directly comparable anyway. The latter conclusion is based on the observation that the presence of a hole changes the failure mode, as was described above, and changes the response curve itself, as may be gauged from the comparison in Fig. 4 between appropriate force–time data. Fig. 5, in which the square of the peak force is plotted against the energy up to the peak, emphasizes the point; datum points (mean values) for intact specimens of various thicknesses* lie on a curve, the upward concavity of which is attributable to the development of membrane stresses as the deformation develops; datum points for specimens with a hole lie on their own different curve, the relative displacement of which reflects the more abrupt collapse that such specimens undergo.

3.3. The effect of other stress concentrators

During the first phase of the experiments a few exploratory tests were carried out on the effects of a surface scratch, of surface indentations and of small nicks in the tension edge of bored holes. It was noted in the previous paper [1] that the results all conformed with the established view that PES is brittle when sharply notched. Subsequently, when it had become clear that a hole reduces the impact resistance but is not an effective embrittling feature, the effect of other stress concentrators was examined again, more quantitatively than before though still not comprehensively.

Grade 5200G was used. The surface scratches of the early tests gave way to machined grooves which were circular arcs in profile for the most part. Grooves were cut parallel to the main flow axis, at 45° to it and perpendicular to it, to depths of 0.5 and 1.0 mm in the thick mouldings. The specimens were all brittle, the notch developed into a linear crack which later deflected on to a circumferential path approximately coincident with the inner edge of the support ring, and the final stage entailed the development of radial cracks out to the edge of the specimen, all of which can be inferred from Fig. 6. Data on the peak force, energy to the peak and total failure energy for those specimens are given in Table III.

There is no evidence of anisotropy in that the results for the three notch directions ar indistinguishable; similarly the data for the two notch depths are indistinguishable. The ratio of mean peak force to mean

*One of these points, identified by a different symbol, refers to tests using an impactor tip only 10 mm in diameter. In this case of ductile failure, nothing untoward seems to have arisen in the response as a consequence of the changed dimensions of the impactor, though the evidence is sparse. There is a change when the hemispherical tip is replaced by a flat one, but see later.

TABLE III The effect of a surface notch on the impact resistance of PES 5200G (impact velocity 5 m sec^{-1}, temperature 13 to 18° C)

Specimen thickness (mm)	Notch depth (mm)	Notch length at surface of specimen (mm)	Notch direction w.r.t. flow axis (deg)	Peak force (N)	Energy to peak (J)	Total failure energy (J)
3.16	0.5	12.0	0	1250	2.6	2.7
3.25	0.5	13.4	0	1300	2.7	2.8
3.28	0.5	14.5	45	1000	2.5	3.0
3.30	0.5	14.0	45	1300	2.8	3.0
3.25	0.5	14.6	90	1200	2.7	2.9
3.32	0.5	14.8	90	1250	2.9	3.3
3.26*		13.9*		1217(113)*	2.7(0.2)*	3.0(0.2)*
3.32	1.0	16.5	0	1250	3.0	3.0
3.32	1.0	19.0	0	1250	2.6	4.0
3.32	1.0	19.2	45	1250	2.9	2.9
3.57	1.0	19.0	45	1600	3.5	3.5
3.20	1.0	17.1	90	1150	2.2	2.9
3.32	1.0	20.0	90	1300	2.9	3.0
3.34*		18.5*		1300(156)*	2.9(0.4)*	3.2(0.4)*

*Mean values with standard deviations in parentheses.

thickness is much lower than that for the holes, namely 373 and 389 for the shallow and the deeper notches, respectively, which is not much greater than one-tenth of the value typical of unblemished specimens.

Five specimens were notched with two orthogonal grooves 1 mm deep. Two out of the five broke with the same pattern as those with a single groove, except that damage developed initially with linear cracks growing from both grooves; the other three specimens broke simply along the two orthogonal lines with no circumferential crack path. The total energy for the latter sub-set was approximately double that for the former sub-set, which would be rather surprising were it not for some photographic evidence from a different experimental programme [4] that the segments produced by radial cracking tend to be trapped between the impactor and the inner edge of the support ring, and produce an impedance that contributes to the apparent energy to fracture. The same type of result arose with shallower orthogonal grooves produced by a scalpel. The results obtained for orthogonal grooves are summarized in Table IV. They indicate more severe embrittlement that that induced by a single groove and, at a value of 239, a lower peak force/thickness ratio.

The final tests in this part of the programme reverted to the use of axisymmetric stress concentrators in the form of cylindrical part-through holes with flat and rounded bottoms and part-through conical holes. The former yielded data that were very similar to those for complete holes, but the latter were variously effective depending on the geometrical features (i.e. depth and cone angle). The results are given in Table V from which the following can be inferred:

(i) A deep conical hole with a 90° cone angle reduces the impact resistance but does not embrittle the specimens. It is more severe than a cylindrical round-bottomed hole.

(ii) A similarly deep hole with either a 30° angle or

TABLE IV The effect of orthogonal surface notches (specimens 3.3 mm thick)

Notch type	Fracture type	Number of specimens	Peak force (N)	Energy to peak (J)	Total failure energy (J)
Arcs, 1 mm deep, 19 mm long	Orthogonal linear cracks creating quadrants	3	833	–	6.0
	Orthogonal linear cracks + circular crack	2	750	2.4	2.7
Shallow surface scratches 10 mm long	Orthogonal linear cracks creating quadrants	1	950	3.1	7.0
	Orthogonal linear cracks + circular crack	1	750	1.8	2.1

TABLE V The effect of conical part-through holes

Specimen thickness	Stress concentrator details	Peak force (N)*	Energy to peak (J)*	Total failure energy (J)*	Type of failure
3.17	No concentrator	10740(182)	124(6.3)	157.2(11.6)	Ductile splits
3.26	Cylindrical, round-bottom hole, 2.7 mm deep	8200(307)	50.9(3.0)	88.9(2.0)	Ductile splits
3.19	90° cone 2.7 mm deep	6630(169)	35.6(0.6)	69.8(0.2)	Ductile splits
3.25	63° cone 2.7 mm deep	1980(420)	4.5(1.3)	4.5(1.4)	Brittle
3.21	30° cone 2.7 mm deep	3290(285)	9.3(1.3)	9.3(1.3)	Brittle
2.09	No concentrator	6870(147)	75.4(7.1)	75.4(7.1)	Split ductile dome
2.12	63° cone 0.5 mm deep	613(54)	0.9(0.1)	1.3(0.1)	Brittle
2.12	63° cone 1.5 mm deep	930(194)	1.8(0.6)	1.8(0.5)	Brittle
2.00	63° cone 1.5 mm deep in compression face	4925(428)	24.5(5.2)	41.2(5.0)	Ductile splits

*Standard deviations in parentheses.

a 63° angle embrittles, the former more severely than the latter; the fracture patterns for both angles are similar but they differ from those initiated by surface notches (see Fig. 7).

(iii) A shallow 63° cone (0.5 mm deep in a specimen 2 mm thick) is more severe than a deep 63° cone (1.5 mm deep).

(iv) A conical hole that embrittles when it is in the tension face of the plate does not necessarily do so when it is in the compression face, though it reduces the impact resistance.

The lowest peak force/thickness ratio for the data in Table V is 289, for the shallow cone in the thin moulding; it is not quite so low as the value for two orthogonal surface notches but, taken in conjunction with the fracture pattern and the obviously severe embrittlement, it nevertheless confirms that values as low as 240 are probable in service. It so happens that as this paper was being written an opportunity arose for some old mouldings of an unknown grade to be impacted. The mouldings were edge-gated discs, one face of which was smooth and the other face covered by parallel grooves lying normal to the main flow axis. The discs were brittle at an impactor velocity of 4.4 mm sec^{-1} but much more brittle when the grooved face was put into tension than when it was put into compression, and different in nature also. A small number of specimens, with a different point of impact in each case, yielded a ratio of 224 for the grooved face in tension and 1165 for the same face in compression. The former value is in gratifying agreement with the values associated with machined notches; the latter value has no real significance because the fractures did not initiate at or near the point of impact, i.e. they corresponded to what was designated as "high energy brittle" in the first paper.

4. Summarizing discussion

Although the main objective of the programme described and discussed in this paper was the development, if possible, of a notched specimen for the flexed-plate impact test and in particular the use of a simple hole as the notch, the subsidiary revelation that the peak force is proportional to the thickness for unnotched specimens is very germane to the principal argument, because the simplicity of that result offers a very practical framework within which the effects of holes and other stress concentrators can be summarized concisely. It seems appropriate, therefore, that this subsidiary matter should be disposed of first in this concluding discussion.

Theory indicates that the peak force should be proportional to the square of the thickness if the plate is linear elastic, and proportional to thickness if it is plastic. Experiment shows that the power is approximately two in the case of poly(methyl methacrylate)

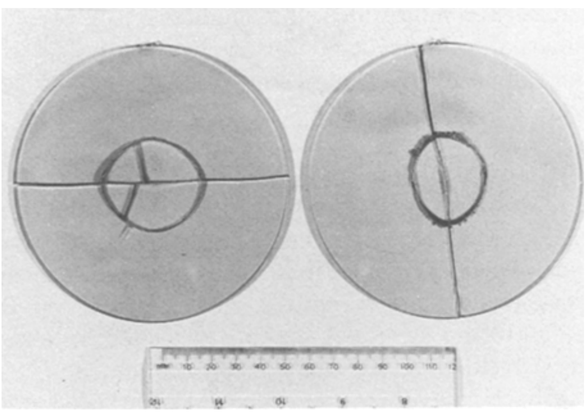


Figure 6 Brittle failure of specimens with a sharp linear notch. Left-hand specimen, notch axis orthogonal to main flow axis; right-hand specimen, notch axis parallel to main flow axis.

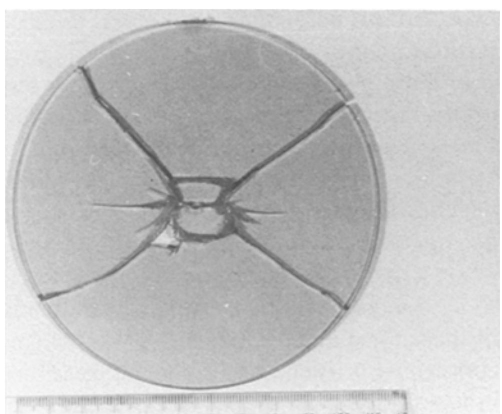


Figure 7 Brittle failure of specimen with conical part-through hole.

[5] which fractures within or just outside its linear viscoelastic region, is about 1.5 for polypropylene and toughened polystyrene [3] which fracture in their non-linear viscoelastic region and, in this paper, is about unity for poly(ether sulphone) when it fractures after definite localized yielding. In the last material, the elastic–plastic boundary is sharp; approximately three-quarters of the specimen remains unyielded with the elastic strain having varied from point to point up to about 0.03 and the other quarter having undergone biaxial strain up to about 0.40, so that plasticity outweighs elasticity as the dominant factor and the power tends to unity.

Apart from its neatness, the linear proportionality between peak force and thickness is very convenient in that the ratio can be used as a characterizing number to summarize the impact data. Thus, for discs injection-moulded from two grades of poly(ether sulphone) of very different molecular weights and impacted at $5\,\mathrm{m\,sec^{-1}}$ in the standard configuration postulated by ISO/DIS 6603/1, the peak force/thickness ratio had the same value 3388 (standard deviation 170) $\mathrm{N\,mm^{-1}}$ when the failure was ductile (Table I). The specimens ranged in thickness from 1.1 to 3.4 mm, having been machined to desirable thicknesses from the original as-moulded thicknesses of 3.4 and 2.0 mm; they were isotropic or nearly so. A hole at the point of impact reduces that value substantially; there appeared to be no significant dependence on hole size over the range 0.25 to 2.0 mm radius, and when all the data (Table II) are combined the ratio for plates with a hole was 2328(122) $\mathrm{N\,mm^{-1}}$. More severe stress concentrators induce brittleness and a corresponding reduction in the ratio. Thus, for example a surface notch in the form of an arc 0.5 mm deep led to a value of 373 and one 2.0 mm deep led to 389; two such notches lying orthogonally gave a ratio of 223 and orthogonal shallow scratches gave 239. The lowest ratio for part-through conical holes was 289. For those specimens of Grade 3600G in which a hole had induced brittleness, reported fully in the first paper [1] but not tabulated here, the ratio was 506. Thus, for the various notch geometries that induced brittleness, the mean values of the ratio varied between 223 and 506; this presumably reflects the different levels of stress-field intensification and probably correlates also with the different fracture paths associated with the various notches.

Table VI is a rounded-off summary of what can be expected of poly(ether sulphone) tested under the standard conditions used in these experiments. They would not necessarily be valid for other test configurations, though when the standard impactor tip, a hemisphere 20 nm in diameter, was replaced by one 10 mm in diameter the ratio for intact plates was 1576 which is close to what one would have hoped for. A flat tip 20 mm in diameter gave a ratio of 3730, which again is reasonable since one would expect such a tip to have a larger radius of influence than a hemisphere of the same diameter, but the sparse evidence to hand concerning brittleness with the flat tip is far from clear in its implications, mainly because the fracture paths are radically different from those arising with hemispherical tips.

TABLE VI Summary of the impact strength of Victrex PES 3600G and 5200G impacted at $5\,\mathrm{m\,sec^{-1}}$ but otherwise in accordance with draft ISO specification

Specimen details	Peak force*/ thickness ($\mathrm{N\,mm^{-1}}$)†	Mode of fracture
Intact plates, thickness 1.1 to 3.4 mm	3388(170)	Ductile. Hemispherical dome, single split.
Plates with hole (radius up to 2 mm)	2328(122)	Ductile. Three or four splits starting at hole, forming flaps.
Plates with hole, radius 0.5 mm, Grade 3600G	506	Brittle. Cracks initiated at hole
Single surface notch 0.5 to 1.0 mm deep	370 to 390	Brittle. Linear crack + circumferential one.
Orthogonal surface notches 1 mm deep	223 to 249	Brittle. Lower value for linear orthogonal cracks + circumferential one, higher value for linear orthogonal cracks.
Conical, part-through hole	289 to 1025	Brittle. Various values depending on depth and cone angle. Shallow cones the most severe.

*The values of the ratio vary with the radius of the support ring and the size and shape of the impactor nose (see Section 4).
†Standard deviations in parentheses.

Viewed against this framework, the simple hole is clearly not a sufficiently severe stress concentrator to embrittle poly(ether sulphone) at room temperature. On the other hand, since it is known to be effective on some polymers it could be regarded as analogous to the blunt notch of flexed-beam impact testing, and a hole of radius 1 mm could be recommended as a suitable compromise between ease of preparation and reproducibility. A concical hole penetrating less than half-way through the specimen could be regarded as analogous to a sharp notch and very similar in overall effect to a surface scratch. Since the latter would be much easier to prepare than the conical hole, there may be a practical preference for it despite the virtues of axial symmetry. This can only be resolved by additional experiments, and such are intended. A very suitable material for that final phase would be polycarbonate, since that choice would extend the range of polymers over which the effectiveness of such notions had been demonstrated and simultaneously provide impartial toughness comparisons between two glassy amorphous polymers commonly used in serious load-bearing applications.

5. Conclusions

1. Injection-moulded discs of poly(ether sulphone) freely supported on an annular ring 20 mm in radius and impacted at $5\,\mathrm{m\,sec^{-1}}$ at room temperature by an excess-energy striker with a hemispherical tip of radius 10 mm are tough except in isolated instances where brittle fracture initiates at a contaminant.

2. Such inadvertent embrittlement is fairly common in Grade 3600G and rare in Grade 5200G.

3. A hole at the point of impact reduces the impact strength by about 30% and changes the mode of

failure. It induces brittleness in approximately 30% of the specimens of Grade 3600G (first paper) but does not induce brittleness in Grade 5200G.

4. Where the hole induces brittleness it reduces the impact strength by about 85%.

5. Conical part-through holes reduce the impact strength and generally embrittle the specimen and, depending on depth and cone angle, can be almost as detrimental as a surface notch or a scratch.

6. Surface notches or scratches reduce the impact strength by about 93% and invariably embrittle the specimen.

7. Simple holes should be regarded as equivalent to blunt notches and shallow conical part-through holes as sharp ones.

8. If the specimen is isotropic, there is no advantage to be gained by using a concial hole in preference to a surface notch but much to be lost in convenience.

9. Poly(ether sulphone) mouldings are likely to be brittle if they are impacted on any feature that resembles a notch.

Acknowledgements
This work was carried out whilst A.M. was on sabbatical leave at Queen Mary college. He is grateful to the Ministerio de Educación y Ciencia, Espagna, and his co-workers acknowledge the financial support of the Polymer Engineering Directorate and the supply of the mouldings by the Petrochemicals and Plastics Division of Imperial Chemical Industries plc.

References
1. S. TURNER and P. E. REED, paper presented at ASTM symposium on Instrumented Impact Testing of Plastics and Composite Materials, Houston, Texas, March 1985.
2. *Idem.* ASTM STP in preparation.
3. P. E. REED and S. TURNER, *Plast. Rubb. Process. Appl.* **5** (2) (1985) 109.
4. A. E. JOHNSON, D. R. MOORE, R. S. PREDIGAR, P. R. REED and S. TURNER, *J. Mater. Sci.* **21** (1986) 3153.
5. M. MOONEY, private communication.

Received 18 October
and accepted 9 December 1985