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Flexed plate impact testing of poly(ether sulphone)

Part III Flow geometry effects

P. E. REED, S. TURNER
Department of Materials, Queen Mary College, Mile End Road, London E1 4NS, UK

Tests on various sample shapes moulded from poly(ether sulphone) show that the response to an excess energy impact may be brittle failure, ductile failure or mixed mode failure, depending on the geometrical features and the associated flow geometries at or near the point of impact. Flow irregularities and local anisotropies caused by the overall flow geometry can be as detrimental to the toughness as conventional stress concentrators are. The results, which are unlikely to be unique to poly(ether sulphone), imply that the procedures currently followed for the evaluation of impact resistance are generally insufficient for their purpose since materials are likely to differ in their susceptibility to embrittlement.

1. Introduction

During the past ten years there have been major advances in the techniques of impact testing and in the analysis of the experimental data. Even so, impact testing is still widely regarded as an unsatisfying activity, largely because the data derived from a set of specimens is never properly descriptive of the impact resistance of the material and often bears little relation to the perceived toughness in service of end-products moulded from it. The disparities between expectation and realization, between the data for nominally identical sets of specimens, etc., are important because they engender a lack of confidence and entail inefficiency in the processes of materials selection, product design and quality assurance, but when one considers the modern equipment and the routines whereby it is used there seems to be little scope for further refinement and one has to turn to the only other major component of the test situation, namely the specimen, for a possible route to better data.

It has been obvious for many years that the thermal history of the specimen is an influential variable and also that stress concentrators can reduce the strength and induce brittleness. More recently it has been recognized that factors such as the flow ratio, the gate size, the gate position and the shape of the cavity are also influential. These latter variables can be represented by the term "flow geometry", which largely embraces the moulding conditions also, because quantities such as mould temperature, melt temperature etc. affect the elasticity and viscosity of the molten polymer and hence the flow paths by which the end-product is created. In retrospect, the importance of the test specimen itself seems to have been underestimated because the substantial effects that these variables often have on the measured impact properties have been regarded more as an inconvenient obscuration of some "true" values than as an intrinsic aspect of those properties. The prospect changes as soon as the specimen is regarded as an independent variable. Systematic changes in both the geometrical stress concentration and the flow geometry can then be used just as changes in temperature or straining rate are used to locate and explore the tough–brittle transition; additionally, they can be used to establish the range of property values that have to be quoted if the impact resistance at a particular temperature and impact velocity is to be stated realistically. Almost unbelievably, this has never been the practice of the past.

The flexed plate test configuration is obviously much more suitable for those purposes than the flexed beam configuration, but it suffers from the disadvantage that normalization of the results with respect to thickness has to rely on empiricism. It transpires that the impact strength, measured as the peak force, is proportional to some power of the thickness and it further transpires that the power is unity for poly(ether sulphone) mouldings when they fail in a ductile manner, which is a convenient simplification when specimens of different thickness are being compared [1]. Furthermore, the ratio of peak force to thickness, which is virtually constant for ductile failure, is drastically reduced when the failure is brittle and its magnitude seems to reflect the severity of the embrittlement. There is an intellectual difficulty in that whereas one might expect a power of unity for an elastic–plastic material, to which poly(ether sulphone) may approximate when it is ductile, one might expect a power of two for an elastic material, to which poly(ether sulphone) may approximate when it is brittle, and therefore the ranking given by the linear ratio may be a distortion of the true ranking. Setting that aside for the present, since poly(ether sulphone) mouldings from various cavities were available the opportunity has been taken to explore the variation of impact resistance with cavity shape and point of impact. The investigation was not fully comprehensive since there were mouldings from only four different

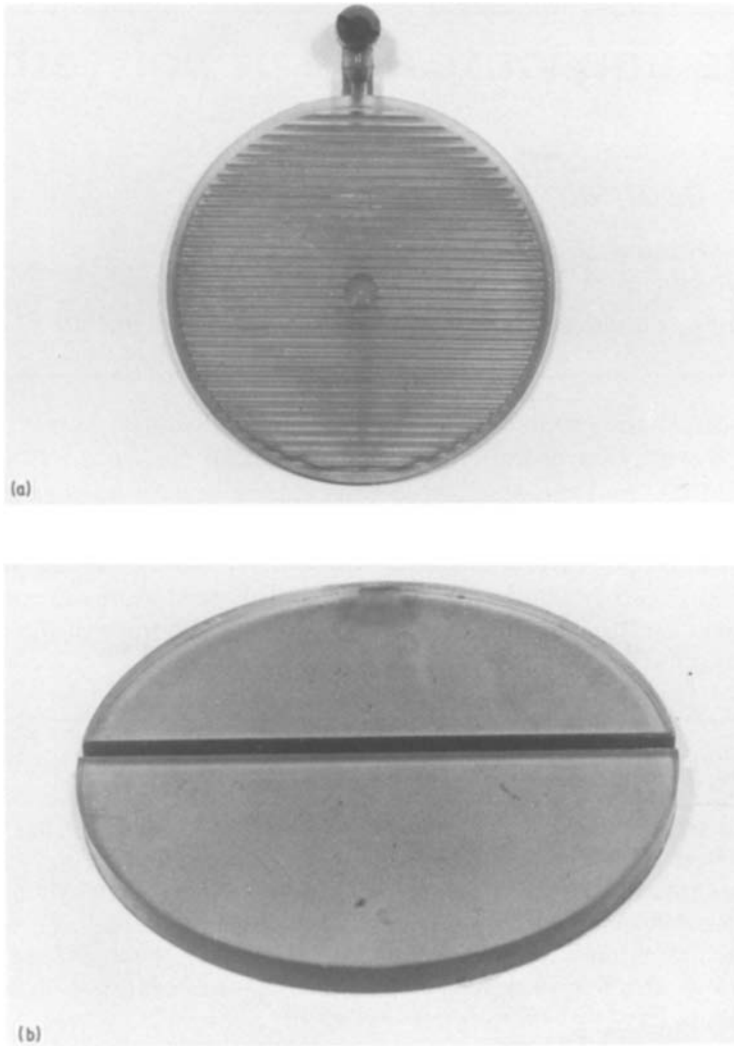

Figure 1 (a) Multi-ridged disc, (b) Grooved disc – the alignment of the groove with respect to the main flow axis could be varied, (c) Double-gated merging flow disc, (d) Double-gated opposing flow disc – the knit-line and the inadvertent boss are effective stress concentrators.

cavities, but on the other hand it was sufficiently comprehensive to show that the flow geometry exerts a dominant influence and that one cannot expect to obtain definitive data from mouldings generated in any one cavity.

2. Experimental details

The specimens that were used in this programme had been moulded in five different cavities. One was an edge-gated disc of diameter 114 mm, one face of which was smooth and the other face of which was traversed by straight, parallel grooves aligned at right angles to the main flow axis, except for a small flat circular area approximately 9.5 mm in diameter at the centre and a flat annular strip 3.2 mm wide at the edge, see Fig. 1a; this specimen is henceforth referred to as the multi-ridged disc.

Another cavity was an edge-gated disc 114 mm in diameter and approximately 6.4 mm thick with an insert of such shape that the final moulding had a diametral V-shaped groove with a tip radius of approximately 1 mm, see Fig. 1b. The groove could lie at any angle with respect to the diametral line passing through the gate but for the experiments discussed here it lay either along that diameter or at a right angle to it. In the former case the moulding was designated "0° grooved disc" and in the latter case "90° grooved disc". Some results for mouldings produced in this cavity have been published already [2].

The third cavity was a double edge-gated disc 89 mm in diameter and approximately 3.2 mm thick. The gates were closely adjacent, see Fig. 1c, so that there is a merging-flow knit line in the mouldings which virtually disappears with increasing distance from the gate. One face of each disc was marred at its centre by several concentric ridges caused by a badly adjusted ejector pin. The imperfection in the mouldings was an advantage rather than a handicap in this particular programme because the ridges constituted moulded notches, the deleterious effect of which could be ascertained by appropriate choice of the site of impact and the condition of the tension face of the specimen.

The fourth cavity was the same as the third one except that the gates were diametrically opposed to give an opposing flow knit-line which should lie along the diameter orthogonal to the flow axis when the flows are balanced. Although the flows had been so balanced, the cavity had not been properly adjusted in other respects prior to the moulding of these discs,

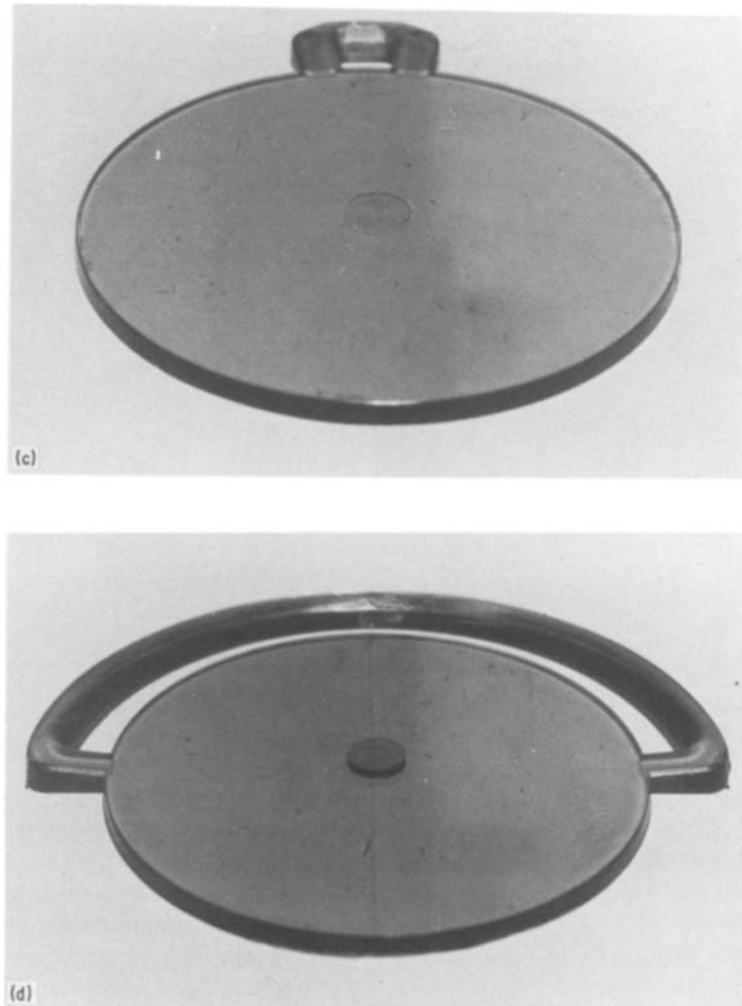

Figure 1 Continued.

each of which, therefore, had a flat topped boss at its centre, see Fig. 1d. As with the third cavity, the deficiency in the mouldings could be exploited in the experimentation.

The fifth cavity was a centre-gated disc approximately 250 mm in diameter. One face was smooth and the other was traversed, in one direction only, by parallel flat-topped ridges 36 mm apart and 3 mm wide. The ridges distort what would otherwise have been a symmetrical flow field and the relatively long flow paths provide another flow geometry variable. Mouldings from this cavity featured in only a minor way in the subsequent experimental programme. They could not be tested in their as-moulded shape – square specimens of side 60 mm were cut from them in conformity with the recommendation of the draft standard.

The mouldings had been stored for approximately nine years in virtually dry conditions (in open-mouthed polyethylene bags inside tin boxes with tightly fitting lids in a low humidity laboratory), having been intended initially for a different investigation. They were not of high quality. Some of the shapes were available in several grades of poly(ether sulphone) and one grade of polysulphone but this programme was largely restricted to the grade that, at the time of mouldings, was designated 300 P. (The present designation for what is nominally the same material is "Victrex" PES 4800 G.)

The impact tests were carried out on a CEAST Advanced Fractoscope System MK3 in accordance with the recommendations in ISO/DISS6603/1 except that in most cases the specimens were entire mouldings rather than standard-sized squares or discs cut from them. The impact velocity was 4.43 m s^{-1} and the test temperature varied from 17° C to 22° C which, for the polymer under investigation, is equivalent to constancy. The equipment allows the primary data, in the form of force against time, to be manipulated into energy, displacement etc., but such computations were eschewed in the course of this investigation since the additional information was irrelevant to the defined task. The following description of the results and the discussion centres on the peak force.

3. Results

3.1. The multi-ridged disc

After a few exploratory tests four sub-sets of five specimens each were impacted at points 42 mm and 72 mm away from the gate along the diameter passing through it, two of the sub-sets having the smooth face in tension during the impact and two of them having the ridged face in tension. Not surprisingly, the maximum force, the energy to that point and the pattern of

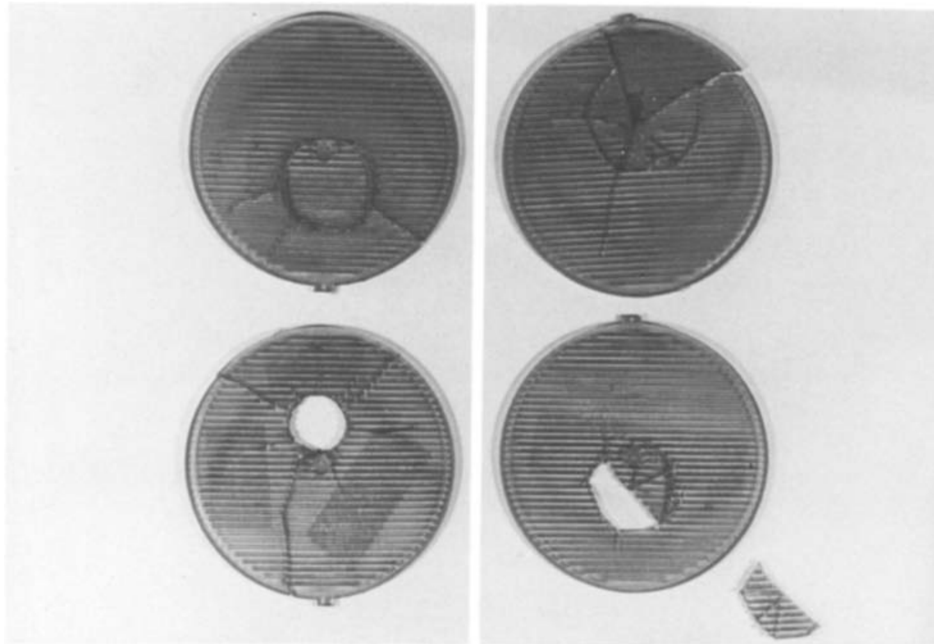

Figure 2 Impacted multi-ridged discs — Upper pair, impacted 42 mm from gate; lower pair, impacted 72 mm from gate. Left-hand pair, smooth face in tension; right-hand pair, ridged face in tension. Data in Table I.

fracture depended strongly on which face was tensioned; there was a smaller effect due to the position of the impact site with respect to the gate. The peak forces and the ratios of the mean peak force to the mean thickness are given in Table I.

The fractures were all brittle but the pattern was different for each sub-set; the principal difference was that the fracture obviously initiated at the impact site when the ridged face was the one in tension whereas it seldom, and possibly even never, did so when the smooth face was the one in tension. In the latter case a nearly circular section was punched out of the specimen but the details depended on the distance of the point of impact from the gate. For impact 72 mm from the gate, the residual hole was about 25 mm in diameter, many cracks ran radially from its edge to the edge of the specimen and the centre section was fragmented; for impact 42 mm from the gate, the hole was almost coincidental with the inner edge of the support ring, there were fewer radial cracks through the outer portion and the centre section had been expelled intact. That centre section incorporated the central boss of the original moulding and the overall appearance suggested that fracture initiated, as a circumferential crack, at the edge of that boss. When the ridged face was the one in tension, the fracture patterns varied less with distance from the gate, but nevertheless, there was less cracking for the impact site 72 mm from the gate than for the one nearer to the gate and, as can be seen in Table I, that more distant site had the lower impact strength, the difference being highly significant. Photographs of the various fracture patterns are shown in Fig. 2.

In those cases where the fracture initiated at a site remote from the point of impact, the pattern of fracture resembled what had earlier, and somewhat misleadingly, been termed "high energy brittle" [3]; in that earlier work the fracture focus was an extraneous inclusion whereas in the recent work it was apparently a geometrical stress concentrator, but the overall effect is the same. The relatively high impact strengths and energies associated with remote-point fracture are largely a consequence of the test configuration and hence they cannot be compared quantitatively with the lower values that arise when fracture initiates immediately below the point of impact. Thus, though the sub-set data in Table I correctly indicate that the disc is stronger when the smooth face is tensioned than when the ridged face is, the degree of superiority cannot be taken as the simple ratio of the tabulated values, nor can the stress concentrator effectiveness of the unridged central boss be gauged from the peak

TABLE I The impact resistance of edge-gated multi-ridged discs (temperature 17° C). The effect of distance from the gate and surface profile

Distance of point of impact from gate (mm)	Description of tensioned face	Thickness (mm)	Peak* force (N)	Mean peak force/ mean thickness ($N\,mm^{-1}$)
42	Smooth	3.01	2668(133)	886
	Ridged	3.02	828 (48)	274
72	Smooth	2.92	2800(252)	959
	Ridged	2.92	504 (39)	173

*Standard deviation in parenthesis.

TABLE II The impact resistance of flat specimens produced by the thinning of grooved discs. Machined face in tension

Specimen source	Thickness (mm)	Peak force (N)	Peak force/ thickness ($N mm^{-1}$)	Failure mode
0° grooved disc	3.30	1448(948)	439	6 specimens brittle from point of impact, 2 brittle from site far from point of impact, 2 specimens ductile
90° grooved	3.24	5963(691)	1840	5 specimens brittle from site far from point of impact

force. These limitations constitute an important deficiency in the flexed plate method and yet they demonstrate why impact resistance in service situations is so variable and so difficult to quantify; in particular, failure does not necessarily occur at the point of impact but where the associated stress field exceeds the local strength.

3.2. The grooved disc

Some results pertaining to the impact resistance of the discs containing a single moulded groove have been published [2] and those quoted here are both a postscript to that earlier work and a logical component of this programme.

It was demonstrated in the earlier paper that the discs with the so-called 0° groove had higher impact strengths and impact energies than those with the 90° groove. That result was in contrast to the order of merit for beams cut from the discs in such a way that the groove constituted a notch. At first sight the flexed plate could be deemed to be anomalous but the behaviour was accounted for qualitatively in terms of the flow geometry in the earlier paper [2]. However, in the course of the investigations being discussed in this paper it seemed possible that further light might be shed on the general issue of flow geometry effects by the impacting of specimens in which the moulded groove had been machined away, since the geometrical stress concentration would thereby have been removed whereas the local anisotropy caused by the flow geometry in the zone below the groove would be unchanged. Some pilot tests on discs in which the grooved face had been machined down to the layer just below the tip of the groove indicated that the brittleness persisted and therefore attention was focused on discs that had been thinned to a level about 0.25 mm below the tip of the groove. They were impacted with the machined face in tension, since one would expect the other face of the disc to be relatively free of any detrimental influence of the flow geometry associated with the groove. There was a possibility, of course, that the impact resistance would be affected by the surface state of the machined face but the appearance of the specimens, their behviour under impact and the behaviour of other specimens (see later) all suggested that any such effect was negligible.

With a few exceptions the specimens were brittle but whereas the original 0° grooved discs had superior impact resistance to the 90° grooved discs, the same could not be said of the thinned ones. One might even claim that the order of merit had been reversed but that would depend on what criterion was taken as a basis for comparison. Of nine specimens that had originally been 0° grooved discs, two were ductile, six were brittle from the point of impact and one was brittle from a point far from the site of impact, whereas all of the five specimens that had originally been 90° grooved discs were brittle from a point far from the site of impact. If it is argued that such fractures would have been ductile failures but for the presence of an inadvertent inclusion – the fracture of one specimen initiated at a void which was converted into a surface crater by the thinning operation – then the sub-set that had been 90° grooved discs may be judged the tougher, which is the reverse of what was found when the unmodified grooved discs were impacted. The numerical values, Table II, support that conclusion, though the reservations as to the significance of the numerical values are the same as those expressed in relation to the data of Table I.

Four 0° grooved discs, all that remained of the sample, were thinned to about 1 mm below the groove tip. One of them was ductile and the others were brittle from a point far from the site of impact so that one can conclude that the further thinning had removed more of the unfavourable molecular alignment attributable to the groove. The peak force/thickness ratio for the three brittle specimens was $1577\,N\,mm^{-1}$ which is approaching the value quoted in Table II for the 90° grooved disc thinned to a level 0.25 mm below the groove tip. Sparse though these data are, they seem to show that the local flow geometry in the region of the groove tip had contributed an embrittlement factor which was radically different for the two groove alignments.

3.3. The double-gated merging flow disc

When the smooth face was in tension during the test these mouldings were tougher than any of the others. Impact at the centre of the disc created a small dome of biaxially stretched material from the boundary of which cracks ran more-or-less radially to the edge of the disc whilst one crack ran along an approximately circular path to excise the thinned, but otherwise intact, central section. The behaviour was similar when the impact was at a point further from the gate, i.e. at a distance of 55 mm as compared with 44.5 mm for impact at the centre, but the central deformed region, the peak force and the energy to the peak were all larger. The numerical data in the first two rows of Table III are among the highest that have been reported for brittle fracture initiating at a site far from the point of impact and those in the second row may even be regarded as approaching the magnitude of

TABLE III The impact resistance of double-gated, merging-flow discs

Details of the impact	Peak force (N)	Peak force/ thickness ($N\,mm^{-1}$)	Energy to peak (J)	Comments on fracture
Impact at centre. Smooth face in tension.	6900(237)	2104	23.0(1.7)	Brittle, but substantial plastic deformation.
Impact 55 mm from gate. Smooth face in tension.	9500(200)	2905	56.2(3.7)	Brittle, but more plastic deformation than when impact was at the centre.
Impact at centre. Marred face in tension.	890(107)	272	0.49(0.17)	Brittle.
Impact at centre. Marred face machined smooth, then in tension.	1767*(1677)	554	–	3 brittle fractures 2 ductile fractures

*Data for the brittle specimens.

those published elsewhere [1] for ductile failure in unblemished single-edge-gated discs, namely a peak force of 10740 N, a peak force/thickness ratio of 3388 $N\,mm^{-1}$ and an energy of 124 J.

The impact resistance was drastically lower when the marred face was in tension. Brittle cracks initiated either directly below the point of impact or nearby, the edge of the ridged patch often being the focus. When the concentric rings were eliminated by the removal of material to a depth of about 0.09 mm and the machined face was tensioned in the subsequent impact event the discs were stronger though still very inferior to what they were when the unblemished face was tensioned. The scatter within the sub-set was large; two of the five specimens were ductile and the others were variably brittle (see the very large standard deviation, bottom row in Table III). The data in Table III clearly demonstrate that the concentric rings were very efficient stress concentrators despite their inoccuous appearance.

A minor lateral excursion in the experimental programme warrants a brief mention. It entailed a few tests on nominally identical double-gated merging flow discs moulded in a lower molecular weight grade, then designated at 200 P and now known as "Victrex" PES 4100 G. The mouldings were of better quality and appearance than those in the main batch but their impact resistance was inferior, as would be expected. With the marred face in tension, the higher molecular weight grade had a mean peak force of 879 N (124 N) a range from 720 to 1100 N and a peak force/thickness ratio of 269 $N\,mm^{-1}$. (The initial value of 879 N incorporates the values for the five specimens in the sub-set of Table III, plus the values for another 10 specimens. The mean value for the latter sub-set was 874 N (136 N).) The lower molecular weight grade had a mean peak force of 743 N (59 N), a range from 660 to 900 N and a ratio of 226 $N\,mm^{-1}$. The difference is highly significant. The results are not quoted as yet another example of the well known effect that molecular weight has on the strength and toughness of plastics but rather as evidence that, erratic though data relating to brittle failure tend to be, the mean values nevertheless give reliable indications of trends and of relative strengths, which is helpful for a paper such as this in which virtually all of the experimental data relate to the brittle state.

3.4. The double-gated opposing flow discs

The pronounced knit-line that is a dominant feature of the opposing flow discs ran through the central boss that would not have been there had the cavity been properly set up. When the discs were impacted in such a way that the boss was on the tension face, the mean peak force was 892 N and the cracks started at the root of the boss. Thus the combined effect of the inadvertent boss and the knit line was equivalent to that of the circular ridges that marred one face of the double-gated merging flow discs (see Table III). The comparison is not entirely straightforward since there is some uncertainty as to whether the effective thickness should be taken as that of the main part of the disc or that at the boss, though the initiation of cracks at the root of the boss suggests that it should be the former. There is usually a notch-like surface defect associated with the knit-line; it has been observed previously [4] that the weakness of the knit-line and the embrittlement arises largely from that surface defect, which is a consequence of the local flow geometry as the melt fronts meet, rather than from a failure of molecules to bridge the knit-line in the core of the moulding. Accordingly, the boss plus a thin surface layer was removed from some discs and a comparison made between the impact resistance when the smooth machined face was in tension and that when the moulded face with knit-line surface notch was in tension. Of the four specimens in the former sub-set, three were ductile and the other, though brittle, had a relatively high peak force of 2400 N; all five specimens in the latter sub-set were very brittle.

The data are summarized in Table IV. They strongly support the earlier, unpublished, findings that the physical notch associated with the knit-line in poly(ether sulphone) mouldings is more deleterious than the knit-line itself. It could be inferred that the surface notch reduced the impact strength of the knit-line to one third of what it would otherwise have been, but that relies on the peak force for the one brittle failure in the third sub-set of Table IV and the reduction would be deemed much greater if the ductile failures were to be taken into account. A few tests on discs moulded in the same cavity from a lower molecular weight grade give a confirmatory picture though the effect attributable to the knit-line is less dramatic. In those tests the discs were tested in their original

TABLE IV The impact resistance of double-gated opposing-flow discs

Details of the impact	Peak force (N)	Peak force/ thickness ($N\,mm^{-1}$)	Comments on fracture
Intact disc, boss in tension.	892(58)	257	Brittle fracture initiated at root of boss.
Boss + knit-line notch removed. Moulded face in tension.	772(91)	223	Brittle fracture initiated directly below point of impact.
Boss + knit-line notch removed. Machined face in tension.	2400*	719*	1 specimen brittle 3 specimens ductile (date not given)

*Single specimen.

state, the face with the boss was in tension during the impact, the point of impact was 29 mm from the edge of the disc and the blow was either on the knit-line or well away from it, all of which will be obvious through reference to Fig. 1d. The use of a distance of 29 mm from the edge of the moulding was dictated by the configuration of the specimen, the inner radius of the support ring and the requirement that the impact site be as far as possible from the boss. Impact far from the knit line (two sites) yielded peak forces and standard deviations (in parenthesis) of 2652 N (498 N) and 2860 N (583 N) respectively and impact on the knit-line yielded the values 1452 N (757 N). All the failures were brittle and all initiated at a point directly below the impactor. The knit-line, or more probably the surface notch associated with it, was less deleterious than the circular ridges on the merging flow discs moulded in the same low molecular weight grade (peak force = 743 N) and apparently less deleterious than it was for the opposing flow discs moulded in the higher molecular weight grade. The latter result may reflect the easier flow characteristics of the lower molecular weight material which should have given more effective merging of the melt fronts at the knit-line and also a less pronounced surface notch. For impact away from the knit-line the mouldings in the lower molecular weight grade seem to be the more brittle, though the relevant sub-sets are not directly comparable.

3.5. The centre-gated disc

The material moulded into this shape was the lower molecular weight grade. The small squares that constituted the specimens for this part of the programme had their centres 30 mm and 70 mm from the gate along a radius parallel to the ridges and 70 mm from the gate along a radius at right angles to the ridges. The smooth face of the moulding was the tension face during the test. The failures were mainly ductile and the data, set out in Table V, show little variation with flow length or direction. The main interest in the results is that the low molecular weight grade moulded into this simple shape is tougher than the higher molecular weight grade moulded into less simple shapes.

4. Discussion

It is clear, even from a casual inspection of the experimental results, that the impact strength of a poly(ether sulphone) moulding depends very strongly on the type of moulding, the site of the impact, the level of the geometrical stress concentration and the local flow geometry. However, interesting though any one particular facet of the behaviour may be in its own right, it will be of little practical value if it cannot be set in the wider perspective of a general map of impact resistance or, failing that, against a scale of relative toughness. The principal impediments to the generation of a map or to the identification of cause and effect are the large number of influential variables, and the interactions between them. The precise effect of those variables has never been resolved satisfactorily, mainly because it would be almost impossible to organise a moulding programme that could generate the requisite specimens and exclude extraneous factors, and even if it could be done the cost would be prohibitive. In addition to that, however, the pervasive and influential effects of the flow geometry have often wrongly been attributed to one or other of the more obvious processing variables in the past, with the result that erroneous, and often conflicting correlations have contributed confusion rather than enlightenment.

TABLE V The impact resistance of specimens cut from centre-gated discs. The effect of distance from the gate (low molecular weight grade)

Details of the impact site	Thickness (mm)	Peak force (N)	Mean peak force/ mean thickness ($N\,mm^{-1}$)	Type of failure
30 mm from gate along line parallel to ridges.	3.66	11 600(158)	3169	5 dustile, one nearly so.
70 mm from gate, along line parallel to ridges.	3.72 3.71	11 025(222) 3500	2964 943	4 ductile 1 brittle from site of impact
70 mm from gate, along line orthogonal to ridges.	3.79 3.64	11 700(424) 2500	3087 687	4 ductile 2 brittle from site of impact

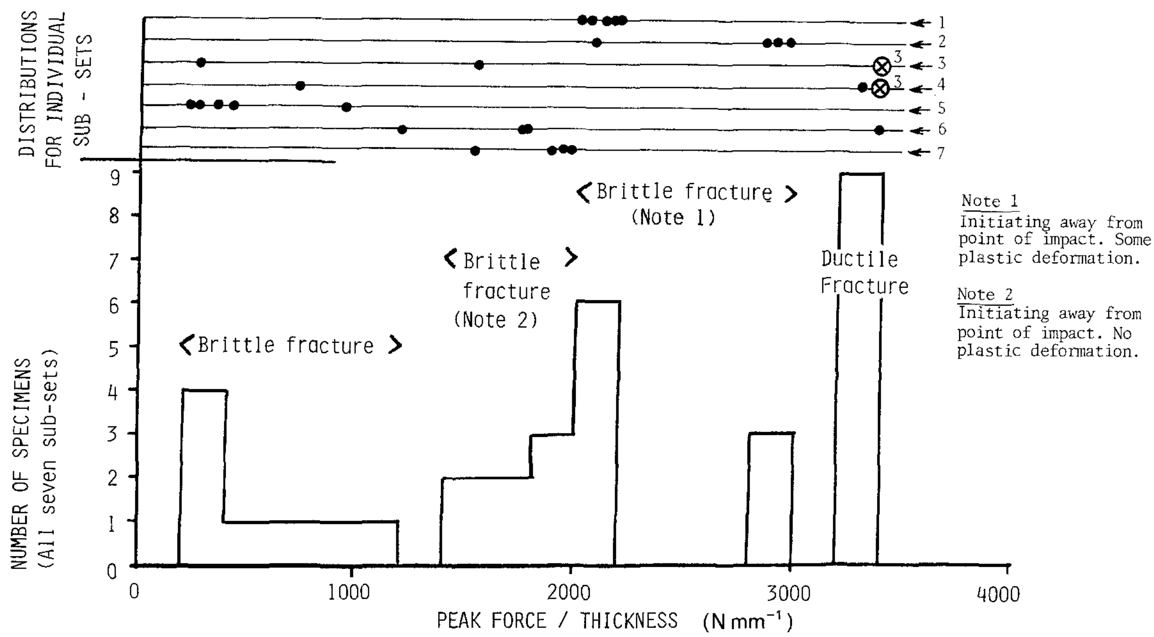

Figure 3 Distribution of peak force/thickness ratio for specimens with no geometrical stress concentrator. Key to sub-sets: 1, merging flow, impact at centre; 2, merging flow, impact 55 mm from gate; 3, opposing flow, machined flat; 4, as 3 but thinner; 5, 0° grooved disc, machined flat; 6, as 5 but thinner, 7, 90° grooved disc, machined flat. ⊗^{3} denotes three specimens.

Some of the data generated in the course of the experimental programme discussed here, namely those relating to moulded notches or equivalent stress concentrators, exemplify the hidden and complicating influence of the flow geometry. Thus, for example, the results set out in Section 3.2 demonstrate that the physical removal of a moulded notch does not itself necessarily eliminate the associated embrittlement though the impact resistance increases and the brittleness decreases progressively as material is machined away to greater distances below the tip of the original notch. It is not surprising, therefore, that no clear picture of the sensitivity of the impact strength of poly(ether sulphone) to moulded notches emerges from the relative values of appropriate pairs of data subsets taken from the Tables; the ridges in the multiple-ridged disc reduce the impact strength to 0.37 of the unnotched value if the impact site is 42 mm from the gate and to 0.18 of the corresponding unnotched value at 72 mm from the gate, the sharp notch associated with the opposing flow knit-line reduces the impact strength to 0.32 of the unnotched value and the central marring of the double-gated merging flow discs reduces it to 0.13 of the corresponding unnotched value. One would not expect the reduction factors to be identical, since the notches are not equally severe and the "control" specimens in the separate paired data sets are neither ideal nor intrinsically similar to one another, but the large change in reduction factor with distance from the gate (the multi-ridged discs) and the severe effect of a seemingly innocuous surface irregularity (the double-gated merging flow discs) are nevertheless examples of the degree to which the direct effect of geometrical stress concentrators can be distorted.

Any suspicions about the legitimacy of some of the data pairings are eliminated in a different presentation of the data, in Fig. 3. It makes use only of sub-sets for which the tension face was smooth and featureless, either directly from the cavity wall or as a consequence of a subsequent machining operation, and for which the compression face was free of gross features such as the multiple ridges. In the upper part of Fig. 3 individual results, expressed as peak force/thickness, are given for several sub-sets which are segregated by vertical displacements. In the lower part of the diagram the data have been collected into a histogram. The picture that emerges, therefore, is that the peak force/thickness datum for a smooth flat disc of poly(ether sulphone) impacted at room temperature may lie anywhere between a value of about 200 N mm^{-1}, associated with extremely brittle failure initiating at the point of impact, and a value of 3400 N mm^{-1}, associated with ductile failure [1], depending on the flow geometry of the original moulding. Since the total number of tests was relatively small, the apparent multimodality of the distribution of impact strengths cannot be taken as self-evidently the true picture, but there seems to be four clearly distinguishable classes of failure which are set in relation to the histogram in Fig. 3, and it is very likely, therefore, that the distribution is actually multimodal. The middle two classes both merit the simplistic designation of "high energy brittle" that was used, possibly misguidedly, in the early stages of the investigation [3]; they have the common feature that the brittle fractures initiated at some point remote from the actual impact site, but they are distinguishable by either the presence of extensive plastic deformation in the impacted specimen or the virtual absence of such evidence of ductility.

The issue that has to be addressed is whether the distribution of impact strength that is recorded in Fig. 3 has arisen as a consequence of the distorted flow geometries that would have been associated with the various cavities in which the specimens were moulded or whether it is attributable to some other factor. For example, in the first phase of the experimental programme, edge-gated discs moulded in grade 3600 G with a simple hole bored at the centre were found to have a trimodal distribution with brittle, high-energy brittle and ductile sub-sets [3]. The high-energy brittle failures all appeared to have initiated at microscopic inclusions but for which these specimens would presumably have been ductile, and if we so count them the incidence of brittle failure was 5 out of 14. It subsequently transpired that the incidence of brittleness in intact discs (i.e. discs with no bored hole) was much less [1]; discs moulded at two thicknesses, some of which were thinned mechanically prior to the impact test, had no cases of brittle failure initiating at the point of impact, four of high-energy brittle failure and twenty-five of ductile failure. Ten discs moulded from a higher molecular weight grade, 5200 G, were all ductile. Thus it would seem that unblemished plate-like mouldings with a simple flow geometry should be ductile under the test conditions used in these experiments, with a relatively low probability of high energy brittle failure arising from contaminant. However, it does not necessarily follow that the inferior impact resistance displayed by Fig. 3 is attributable to distorted flow geometries because the samples being compared differ in important respects. The unblemished plate-like mouldings were tested within a few months of being moulded from what may be described as modern polymer whereas the main results given in this paper relate to discs that had been stored prior to being impacted for approximately nine years after being moulded from the polymer being produced in 1977. Since polymers tend to embrittle to some degree during prolonged storage and since the modern polymer may differ in some respects from that being produced several years ago, a direct comparison between the results could be misleading.

The only sample, among the old sets of mouldings, that might be regarded as constituting a valid control was the large centre-gated discs, but they are nevertheless not ideal for the role because they were moulded from what is now designated as "Victrex" PES 4100 G which is of lower molecular weight than the grade used for the other sets. One would expect, via a simple argument, that any bias arising from the difference in molecular weight would be in the safer sense, since the lower molecular weight material should be the more prone to brittleness, but that ignores the possible compensating benefits of its easier flow into the cavity and therefore the likely effect of the difference cannot be quantified. However, assuming that the large discs can be used as the control sample, the results in Table V give an estimate of the incidence of brittleness as 3 in 16 for flat specimens with a simple flow geometry, and the observed incidence of Fig. 3 can be compared with that expectation by the χ^2 test. The outcome is not entirely satisfactory since the conclusion depends on what criterion is adopted for "brittle"; if it is deemed that only 8 specimens should be classed as brittle the difference between that proportion and the expectation is statistically insignificant but if the criterion is relaxed to include brittle fractures that originated at a point some distance from the site of impact, but not those accompanied by plastic deformation, i.e. an additional 7 specimens (see Fig. 3), $\chi^2 = 13.7$ which, for one degree of freedom, is very highly significant. That particular criterion for brittleness encompasses situations in which the peak force/thickness ratio was as high as $2000\,\mathrm{N\,mm^{-1}}$, which is substantially higher than any of the values that were associated with unambiguously brittle failure in the early phases of the study [1, 3]. However, those earlier brittle failures were induced by the introduction of conventional geometrical stress concentrators or by the inadvertent presence of particulate contaminant, both of which perturbed the stress field whereas, in contrast, the brittleness in the current experiments was induced by distorted flow geometries or flow irregularities that created local anisotropy and weakness. It is arguable as to whether the latter situation is likely to give higher peak forces but it does seem reasonable to expect that the associated fractures would be more erratic than those arising in the former situation of a symmetrical stress field with an isolated perturbation and there is empirical evidence in support of the expectation in that the fractures attributable to a distorted flow geometry were generally irregular, highly fragmented and variable whereas those attributable to a specific stress concentrator were generally straightforward and predictable.

Although the arguments relating particularly to Fig. 3 are tentative, when the other evidence is also taken into account it seems probable that the high incidence of brittleness and the apparent multimodality depicted in the figure are due to distorted flow geometries and flow irregularities in the otherwise featureless flat plates. It would not be sound practice to generalize from a particular case but there are indications from a limited range of subsidiary experiments that other polymers of similar structure, including polysulphone, show a sensitivity to the flow geometry, from which it probably follows that the current practice of basing the assessment of the impact resistance of a material on one type of moulding, which may also be chosen arbitrarily, is defective; the least harmful consequence will be uncertainties and errors in the ranking of materials and the worst consequence will be the failure to identify the lower bound of the potential service performance. It would be unrealistic to expect that evaluation programmes should always test specimens from a range of cavities but the absolute minimum must be two cavities, one of which would provide an approximation to the "worst case" the other being, say, the edge-gated disc that is currently popular.

It had been suggested, on the basis of rather sparse experimental data, that poly(ether sulphone) was not as tough as had been widely believed [3] and the results reported here strongly support that contention. It now seems desirable that the popular classification as "tough except when sharply notched" for the impact resistance at room temperature should be modified to "tough except when sharply notched or when the flow geometry has been irregular". That judgement should not affect the relative standing of poly(ether sulphone) since it is reasonable to assume, on the basis of

TABLE VI Peak force/thickness ratios for specimens with machined and moulded notches

Stress concentrator details (Stress concentrator in tension face of specimen)	Peak force/ thickness ($N\,mm^{-1}$)
Machined surface notch*	370–390
Orthogonal machined surface notches*	223–249
Multi-ridged disc, impacted 42 mm from gate	274
Multi-ridged disc, impacted 72 mm from gate	173
Double-gated merging flow disc, concentric ridges at point of impact	272
Double-gated opposing flow disc, sharp shallow notch associated with the knit-line	233

*Data from Ref. [1].

plausible arguments and some direct evidence, that many classes of polymer are similarly affected by flow irregularities and local anisotropies due to the flow geometry. Such features are generally detrimental to the impact resistance as manifest in service articles and as measured by the flexed plate method but not necessarily as measured by the flexed beam method because the outcome of the latter test depends on how the main axis of stressing relates to the molecular orientation distribution function.

Variable and complex though these data might seem to be at first sight, the patterns of behaviour and the threads of argument are clearer than they might otherwise have been thanks to the simplifying role of the peak force/thickness ratio. Despite the fact that linear proportionality is unlikely to persist into those situations where the specimens are brittle, the ratio has reflected the variations in impact resistance without resort to any lengthy analysis of the response curves. Table VI, for instance, summarizes the ratios for several moulded features; when they are set alongside the data for machined notches from the earlier work [1] they fall into place as severe, and sometimes very severe, stress concentrators. It remains to be seen whether other classes of polymer can be assessed by analogous simplifications of the data analysis processes, but such a development would be helpful if flow geometry is to be added to the list of influential variables because the volume of data that emerges nowadays from a single instrumented impact test can obscure rather than illuminate. Lest that should be interpreted as a rejection of detailed analysis, it must be cautioned that the peak force, which is rightly popular because of its apparent lack of ambiguity, does not necessarily mark a specific point or an important point in the development of damage in the impacted specimen [5].

5. Conclusions

(i) Moulded features such as grooves, bosses and surface scars have a deleterious effect on the impact resistance of poly(ether sulphone).

(ii) When the feature has been removed by machining, the residual flow geometry or flow irregularities associated with that feature exert their own detrimental effect.

(iii) The impact resistance varies with distance from the gate (which is thereby a flow geometry effect though it is not always acknowledged as such).

(iv) The combined effects of the several influential variables often yield confused and conflicting data. The use of the ratio peak force/thickness reduces the chaotic data to reasonable order and quantifies the embrittling effect of various features that are commonly found in poly(ether sulphone) mouldings.

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