JOURNAL OF MATERIALS SCIENCE 21 (1986) 3279–3286

The effects of moulding geometry on the structure and mechanical properties of fibre-reinforced polypropylene structural foam mouldings

PETER R. HORNSBY, IAN R. HEAD, DAVID A. M. RUSSELL*
Department of Materials Technology, Brunel University, Uxbridge, Middlesex UB8 3PH, UK

The influence of weld lines and changes in moulding section thickness on structure and mechnanical properties has been determined for short glass-fibre reinforced polypropylene structural foam prepared using a short-shot moulding procedure at two different melt injection times. Results are discussed in terms of the variability in skin to core thickness ratio, moulding density and fibre orientation obtained in these mouldings and subsequent effects on flexural stiffness and impact energy to failure.

1. Introduction

Thermoplastic structural foams may be produced by a variety of extrusion and moulding techniques, for many applications the short-shot low-pressure injection moulding method being the preferred manufacturing route [1]. The interrelationship between structure properties and moulding conditions is complex, and has been discussed in depth previously by one of the authors together with co-workers, principally for unfilled variants of polypropylene structural foam [2, 3]. Frequently, however, short glass fibres and mineral fillers are also incorporated in commercial mouldings in order to enhance the mechanical properties in certain load-bearing applications, although at present only limited data are available to assist designer and processor in the effective use of such materials [4].

The results reported in this communication form part of a wider research investigation to study distortion, mechanical property and structural variations in reinforced polypropylene structural foam made by a short-shot injection moulding procedure [5–8]. Specific consideration is given in this paper to the characterization of structure, flexural and impact properties in mouldings containing weld lines and sudden changes in section thickness, geometries frequently encountered in commercial structural foam products. Attention is also given to affects observed from changing the melt injection speed, since earlier work has identified this processing parameter as strongly influencing structural and property changes in fibre-reinforced foam mouldings.

2. Experimental procedure

2.1. Materials, moulding procedures and specimen geometries

All samples were moulded from Propathene HW60 SF30 granular polypropylene homopolymer (ICI (Petrochemicals and Plastics Division) plc) containing 30% by weight of short glass fibres treated with a coupling agent to enhance adhesion to the polymer matrix. Foaming was achieved by dosing with a predetermined weight of Genitron EPB chemical blowing agent (FBC plc, Hauxton, Cambridge, UK) in powder form, at the feed port of the injection moulding machine.

Mouldings were prepared on a Krauss–Maffei TSG 100 purpose-built structural foam moulding machine incorporating a ram accumulator and being capable of very high rates of injection. In all cases a short-shot, low mould-pressure injection-moulding procedure was employed [1].

By introducing inserts into a conventional plaque mould, specimens with the following geometries were prepared to study the effects on structure and properties of changes in moulding section thickness and the presence of weld lines:

(i) Centre-gated plaques, with changes in sample thickness from 8 to 12 mm and 8 to 20 mm (overall moulding dimensions 250 mm × 380 mm (0.07% blowing agent used).

(ii) Offset sprue-gated plaques (530 mm × 400 mm × 6 mm thick) for the investigation of weld lines (0.35% blowing agent used).

Further details of the moulding geometry are illustrated in Figs 1 to 3, together with the location of test bars cut for subsequent analysis.

Processing conditions (namely shot weight (hence moulding density), mould and barrel temperatures) were maintained constant for both sets of sample geometry investigated and only the injection time was altered to values of 1.2 sec (fast) and 3.1 sec (slow). From previous work [2, 9], this variable was known to influence fibre orientation and stiffness anisotropy in

* *Present address*: Dow Chemical Europe, Bachtobelstrasse 3, CH-8810, Horgen, Switzerland.

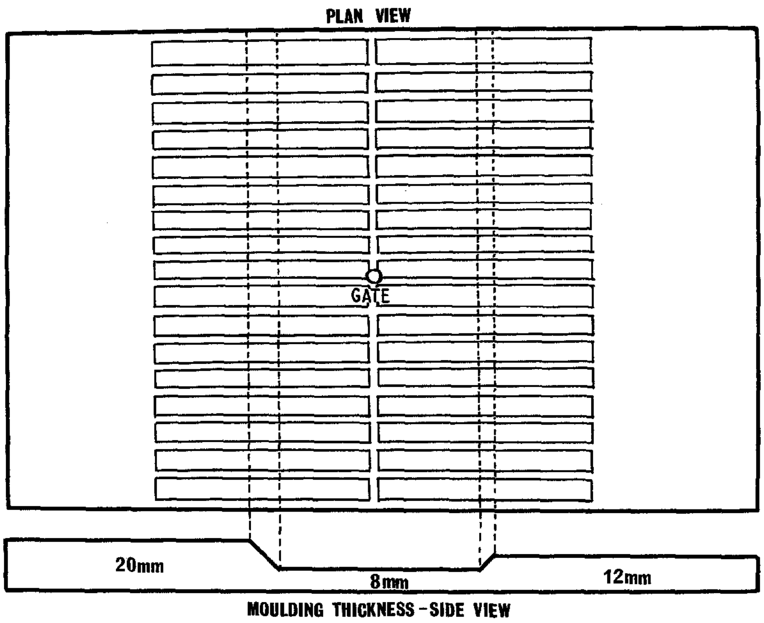

Figure 1 Location of test bar specimens taken across mouldings in regions of divergent flow.

reinforced thermoplastic structural foam mouldings, and was therefore thought likely to strongly affect the mechanical properties in samples containing weld lines or sections of variable thickness.

2.2. Specimen preparation

Test bars cut from the plaques at positions indicated in Figs 1 to 3 were machined to a width of approximately 10 mm and their edges smoothed using silicon carbide paper. Sample thickness varied according to the thickness of each plaque and sample length was altered depending on the desired span to thickness ratio, as determined in the flexural tests (see Section 2.4).

2.3. Characterization of structure

The apparent density of specimens cut from the moulded plaques was determined from measurements of their weight and volume. The skin to core thickness ratio of each bar was measured using a Kyowa Optical SD2-PL microscope in the reflected light mode and fitted with a calibration graticule. Skin thickness was taken to be the average of four measurements made on top and bottom skins near the centre of the bar, taking each thickness to be the distance from the edge of the specimen to the start of the first cell of diameter greater than 0.1 mm. In some instances, macroscopic reflected-light photographs were taken of sets of bar specimens to qualitatively compare variations in skin thickness and cell structure.

Following mechanical testing of test specimens, fibre orientation was examined in selected samples chosen on the basis of observed mechanical property trends. Analysis involved cutting 0.4 mm slices of material parallel and normal to the major axis of each specimen using an Isomet 11-1180 low speed diamond saw (Bawner Scientific, Coventry, UK). Each slice prepared in this way was mounted on a glass microscope slide using optically transparent low viscosity epoxy resin (EPO-TEK 301M, Logitech Ltd), taking care to ensure that air bubbles were not trapped between the specimen and microscope slide. Once

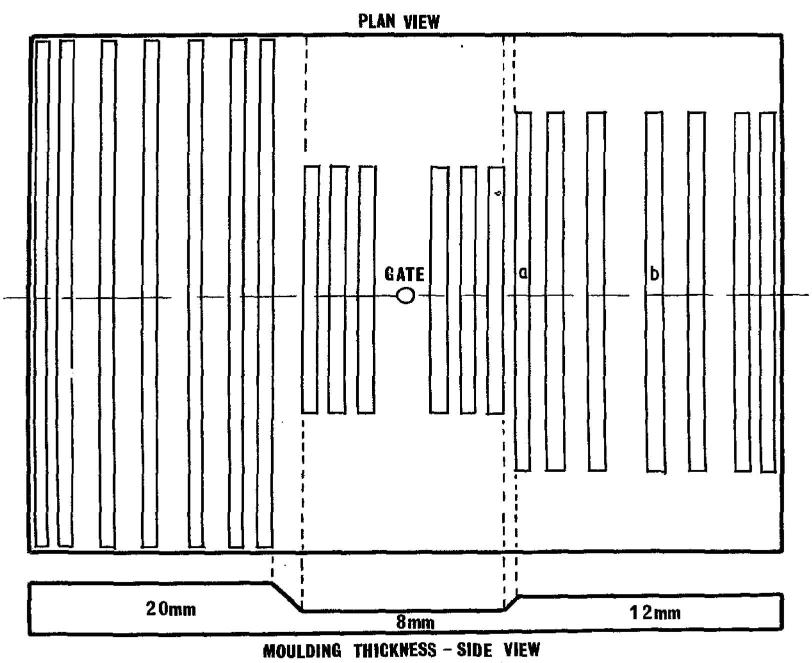

Figure 2 Location of test bar specimens taken along the length of mouldings parallel to changes in section thickness. Bars labelled (a) and (b) are referred to in Fig. 8.

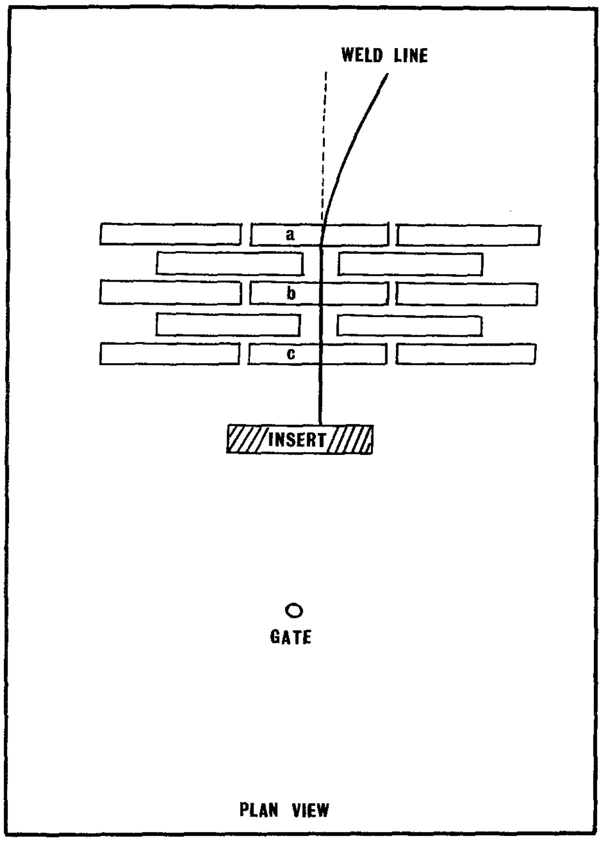

Figure 3 Position of test specimens analysed across and in regions of close proximity to weld lines. Specimens labelled (a), (b) and (c) are referred to in Fig. 13.

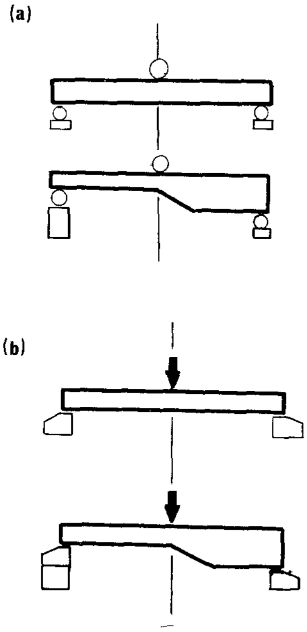

Figure 4 Specimen support geometry for (a) three-point bending flexural tests and (b) flexural impact tests.

the resin had cured, specimens were hand-lapped on silicon carbide paper of increasing fineness, until a sample thickness of about 10 μm had been attained. After placing further epoxy resin and a coverslip on top of the lapped section, samples were viewed in transmission through a light microscope at up to 100 $\times$ magnification.

2.4. Determination of mechanical properties

In this investigation the effects of moulding geometry on flexural modulus and falling weight impact strength were considered.

Flexural properties of bars sectioned from moulded plaques were determined according to ASTM D790 on an Instron tensometer in three-point bending, but with the following modifications to the standard procedure:

(i) All specimens used were approximately 10 mm wide with a span to thickness ratio chosen as near as possible to the recommended value of 16:1 (+2 or −4), in order to minimize shear deformation effects in the specimen. However, since the sample thickness used in this study varied from 6 to 20 mm, in the case of the thicker specimens the maximum practical span to thickness ratio was adopted consistent with an acceptable specimen gauge length. A separate experiment was undertaken on 20 and 12 mm thick samples to assess the effects of variation in span to thickness ratio on flexural modulus. The results indicated that for the structural foam samples used, substantial variations only become apparent at very low span to thickness ratios less than about 10:1.

(ii) Cross-head speeds were varied according to specimen thickness and gauge length in order to provide a constant strain rate in the outer fibre surface of near to 0.01 mm min^{-1}.

(iii) Samples which spanned the region of thickness change were tested in a horizontal position by locating a spacer position under one of the supports as shown in Fig. 4a.

All impact analysis was undertaken on an instrumented falling-weight impact machine (Daventest Ltd and Rosand Precision Co. Ltd, Welwyn Garden City, Herts, UK) using the same bar specimens employed in the flexural tests. A wedge-shaped tup of tip radius 1.5 mm was used with an impact velocity of 2 m sec^{-1}. Bar specimens were mounted unclamped on two parallel supports with a gauge length of 70 mm. As with the flexural tests, samples with changes in thickness along their major axis were mounted and tested as indicated in Fig. 4b.

All specimens used in both flexural modulus and impact tests were positioned with the gate side of the moulding facing upwards after conditioning at 23 $\pm$ 1° C for two days. Since one of the aims of the study was to investigate variability in properties throughout plaque mouldings, mechanical property results were recorded from each single specimen tested rather than as an average from several samples.

3. Results and discussion

3.1. The effects of divergent flow geometry on structure and properties.

Plaques containing step changes in thickness from 8 to 12 mm and 8 to 20 mm were moulded using fast and slow injection conditions. Bar specimens cut from these plaques in locations parallel to the line of the thickness change (Fig. 2) and across the region of divergent flow (Fig. 1) were characterized to determine mechanical property and structural variations present in such mouldings. Results showing values of

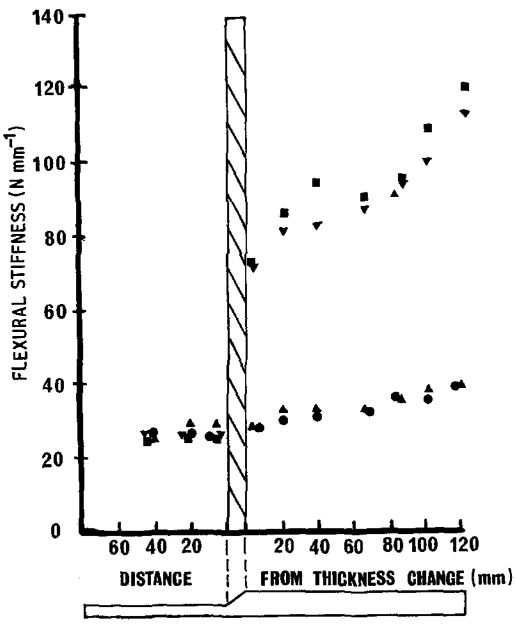

Figure 5 The influence of changing moulding thickness on flexural stiffness for specimens taken parallel to regions of divergent flow: (▲) 8 to 12 mm thickness change (1.2 sec injection time), (●) 8 to 12 mm thickness change (3.1 sec injection time), (■) 8 to 20 mm thickness change (1.2 sec injection time), (▼) 8 to 20 mm thickness change (3.1 sec injection time).

flexural stiffness, impact energy to failure, skin thickness and apparent density are presented in Figs 5, 6 and 7 for specimens taken across the plaque and parallel to the step change in thickness.

It has been identified from previous work that moulding density and skin thickness have a major effect in determining mechanical properties in unfilled polypropylene structural foam mouldings of a given thickness, although in fibre-reinforced variants the orientation of the fibres, particularly in the skin regions of a moulding, can significantly influence property anisotropy [8].

It is evident from Fig. 7 than in moving from the 8 mm thick portion of the moulding to either the 12 or

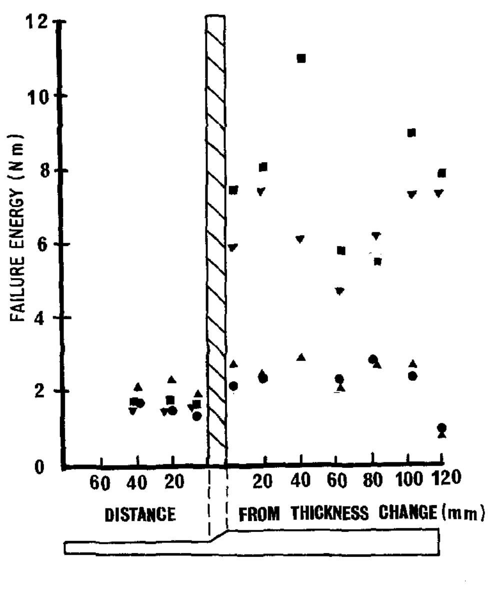

Figure 6 The influence of changing moulding thickness on impact failure energy for specimens taken parallel to regions of divergent flow. Data points as for Fig. 5.

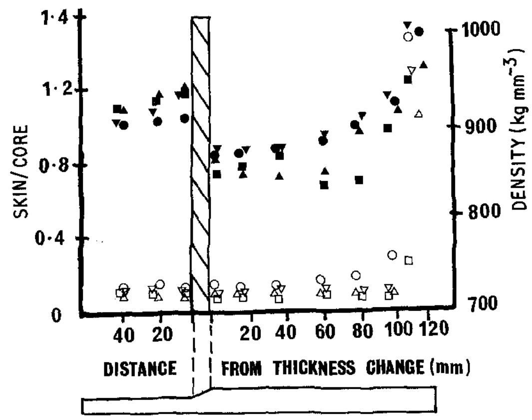

Figure 7 Structural changes in mouldings containing regions of divergent flow (data points as for Fig. 5). Open symbols: skin/core ratio, solid symbols: density.

20 mm thick section the skin to core thickness ratio remains essentially constant over the thickness change, but at the extremities of the moulding the skin thickness increases significantly. Corresponding data showing changes in apparent density demonstrate a similar but more gradual trend of rising density towards the edges of the moulding, although there is a distinct fall in the value of density immediately beyond the region of divergent flow. This is to be expected from the sudden increase in volume available for expansion of molten polymer.

Values of flexural stiffness remain essentially constant in the 8 mm thick region up to the point of divergent flow (Fig. 5), when for the 12 mm thick samples there is only a small gradual increase in stiffness up to the outer edges of the moulding. Moving from an 8 to a 20 mm thick section results in a dramatic three-fold increase in stiffness which again continues to rise towards the moulding perimeter. Similar trends are also apparent in the flexural impact results presented in Fig. 6, although there is greater scatter of these data, particularly for 20 mm thick samples.

These observations may be explained in terms of the opposing effects on mechanical properties of reducing the moudling density and increasing the section thickness. A reduction in moulding density across the region of divergent flow for both 12 and 20 mm thick specimens yields a reduction in the flexural modulus of the material relative to the 8 mm thick samples; however, when expressed in terms of flexural stiffness changes, the consequences of reduced moulding density are overriden by the opposing effects of specimen thickness. Since flexure is inversely proportional to the cube of sample thickness for a beam in bending [2], modest increases in specimen thickness result in large improvements in stiffness, as indicated by the significant increase in mechanical properties for the 20 mm thick specimens.

Figs 5 to 7 also indicate the influence on structure, flexural and impact properties of changing the rate of polymer injection into the mould. Although differences in properties resulting from changing injection time are small, in general slightly higher values of stiffness and impact strength were observed for the faster injection time used (1.2 sec), particularly in

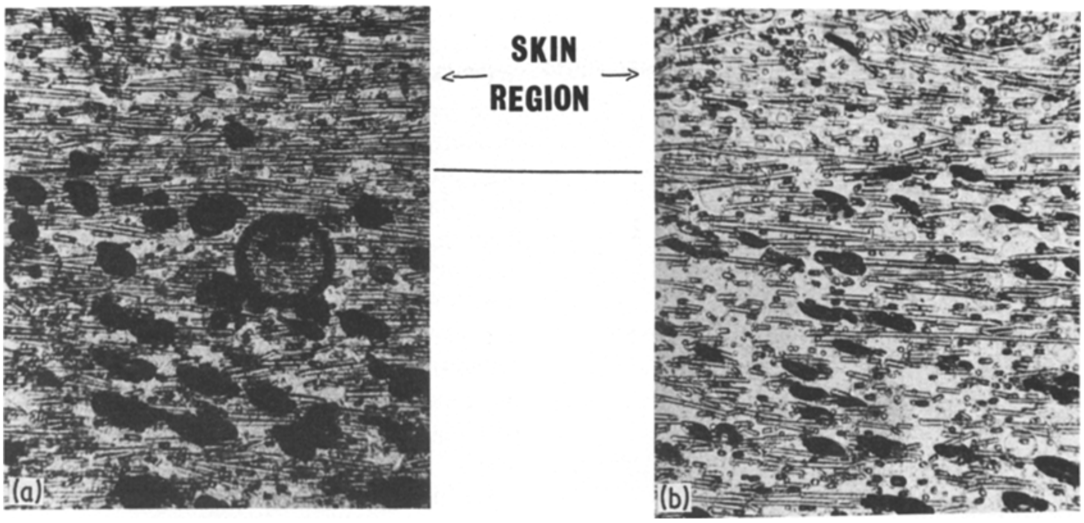

Figure 8 Glass-fibre orientation in skin region of 12 mm thick test bars as viewed down long axis of specimens normal to direction of material flow (injection time 1.2 sec). (a) and (b) correspond to bars labelled in Fig. 2. Flexural stiffness (a) 28.7, (b) 35.6 N mm^{-1}. × 54.

20 mm thick samples. Within the limits of experimental error present in the determination of structural features important in this study, it was not possible to confidently assess the individual contribution to marginal differences in mechanical properties from the three principal interrelated structural parameters, namely skin thickness, moulding density and fibre alignment, each of which varies within a given moulding. However, the importance of fibre alignment in determining flexural properties is illustrated in Fig. 8 for two 12 mm thick bars cut from positions in a plaque close to the change in section thickness and at a point some 65 mm away towards the edge of the moulding. Each sample has almost exactly the same measured value of average skin thickness and moulding density, yet they exhibit a noticeable difference in flexural stiffness. The specimen with the higher value of this property is associated with a noticeably greater degree of fibre alignment in the skin region down the long axis of the bars. Fibre alignment in the core region was essentially the same in both samples.

Moulded plaques containing 8 to 12 mm and 8 to 20 mm step changes in thickness were sectioned in order to yield test bars across the thickness change from one edge of the moulding to the other (Fig. 1). Results from mechanical property and structural analysis of these specimens are summarized in Figs 9 to 11. In all mouldings the flexural stiffness and impact energy to failure are lowest in the centre of the plaque, rising to a maximum towards the outer edges (Figs 9 and 10). This trend corresponds closely with the symmetrical density profile also observed across the width of the plaques (Fig. 11), which was associated with a substantial increase in skin thickness towards the edges of the plaque moulding relative to the central region.

As might be anticipated, samples containing an 8 to 20 mm change in thickness gave slightly higher values of flexural stiffness than bars containing 8 to 12 mm step changes (Fig. 9), although the relative difference observed was much less than between bars of constant 12 and 20 mm thickness (Fig. 5). Injection speed had little influence on flexural stiffness, although small increases in moulding density were apparent using lower injection times (Fig. 11).

As with the flexural stiffness properties, the impact energy to failure of test specimens was strongly influenced by local density variations across the width of the plaques. In all determinations, crack initiation was

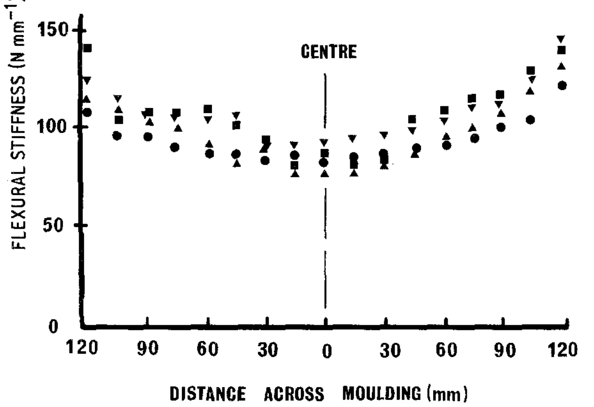

Figure 9 The variation in flexural stiffness over the width of plaque mouldings from measurements taken across regions of divergent flow: (▲) 8 to 12 mm thickness change (1.2 sec injection time), (●) 8 to 12 mm thickness change (3.1 sec injection time), (■) 8 to 20 mm thickness change (1.2 sec injection time), (▼) 8 to 20 mm thickness change (3.1 sec injection time).

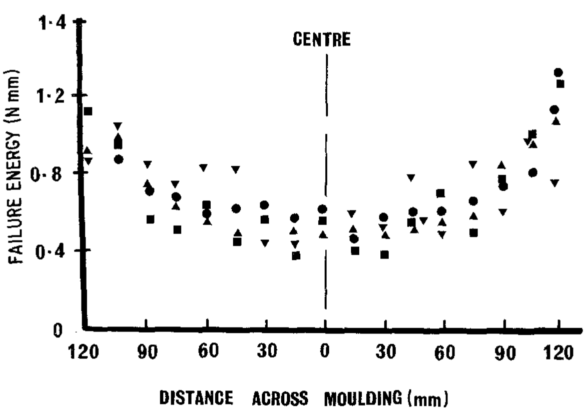

Figure 10 The variation in impact failure energy over the width of plaque mouldings from measurements taken across regions of divergent flow. Data points as for Fig. 9.

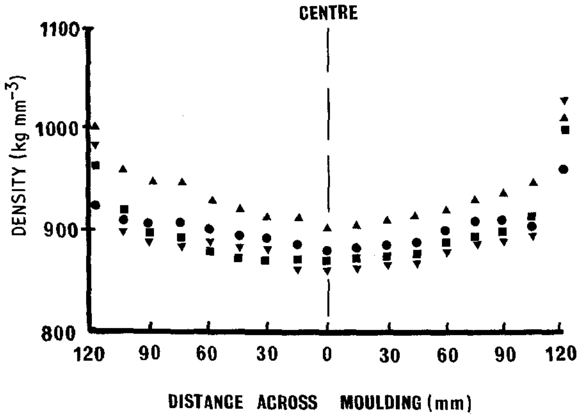

Figure 11 Variation in apparent density over the width of plaque mouldings from measurements taken across regions of divergent flow. Data points as for Fig. 9.

observed to occur at the 2 mm radius of the edge of the 8 mm section and immediately opposite the position of impact (Fig. 4). Clearly this is the weakest point of the specimen, and in design considerations this radius should be kept to a maximum to avoid localized reduction in impact strength.

It is also noteworthy that impact failure energies for specimens containing 8 to 12 mm thickness changes (at both fast and slow injection times) showed less scatter than those with 8 to 20 mm sections, and furthermore gave a more uniform property profile from the lower-density central reigon of the plaque to the higher-density perimeter.

An important consideration for the designer and end-user of fibre-reinforced structural foam components is the extent of property variation which might be expected in mouldings containing changes in section thickness. Table I summarizes stiffness and impact property data generated from this study and indicates the variability to be expected in moving from 8 to 12 mm and 8 to 20 mm thickness parts, relative to structural foam of constant thickness.

3.2. The influence of weld lines on structure and properties

Test plaque mouldings containing weld lines were prepared at two extremes of injection speed, and specimens were then cut from positions across the weld line and at locations immediately adjacent to this in "weld-free" areas (Fig. 3). Mechanical property data taken from each of these samples, together with average measurements of their density and skin to core thickness ratio, are recorded in Fig. 12, and mean values of these data are presented in Table II. It is apparent from these results that specimens made using a faster injection speed (1.2 sec injection time) gave significantly higher values of both flexural modulus and impact strength away from the vicinity of weld line rather than across it. Furthermore, it is noticeable that these increases in mechanical properties are associated with higher levels of moulding density and skin thickness.

Distinct differences are found, however, in test samples taken from mouldings formed using a much slower injection time (3.2 sec). The mechanical properties of specimens are seen to be much more uniform across and away from the weld line. Indeed it is significantly that under these conditions of moulding, the presence of the weld line gave enhanced mechanical properties in many of the samples tested. These localized improvements in properties were again associated with increases in moulding density and skin to core thickness ratio. Although the properties obtained from mouldings made at the slower injection time show reduced variation, the overall values of flexural modulus and impact strength were generally found to be lower than corresponding results taken from specimens made at the fast injection speed, away from the weld zone. This was particularly evident with the impact data.

These observations can be related to differences in structure produced resulting from the changes in injection speed used. Micrographs showing the fibre orientation across structural foam mouldings containing a weld region indicate that fibre alignment is predominantly parallel to the weld line (i.e. normal to the direction of flow) and is not greatly influenced by injection speed, being unlikely to account for differences in properties between the mouldings. This is directly analogous to the situation observed in short-fibre reinforced solid thermoplastic injection mouldings where fibres lie at a tangent to the flow front

TABLE I The effect of moulding geometry and injection time on the flexural stiffness and impact energy to failure in glass-fibre reinforced structural foam

Specimen geometry	Injection time (sec)	Flexural stiffness ($N mm^{-1}$)		Impact failure energy (N m)	
		Range of values	Average	Range of values	Average
8 to 12 mm thickness*	1.2	75.6 to 131	96.8	0.47 to 1.04	0.69
	3.1	82.2 to 122	93.8	0.47 to 1.3	0.68
8 to 20 mm thickness*	1.2	82.6 to 142	105.9	0.37 to 1.24	0.65
	3.1	88.3 to 145	105.6	0.39 to 0.98	0.68
8 mm thickness†	1.2	24.4 to 29.7	26.2	1.61 to 2.29	1.88
	3.1	24.0 to 25.9	24.8	1.32 to 1.67	1.52
12 mm thickness†	1.2	28.7 to 39.7	34.4	0.69 to 2.87	2.31
	3.1	27.3 to 38.3	32.6	0.92 to 2.73	2.13
20 mm thickness†	1.2	72.3 to 120	95.5	7.5 to 11.0	7.81
	3.1	70.6 to 113	89.5	4.7 to 7.41	6.39

*Specimens taken across section change (see Fig. 1).
†Specimens taken parallel to section change (see Fig. 2).

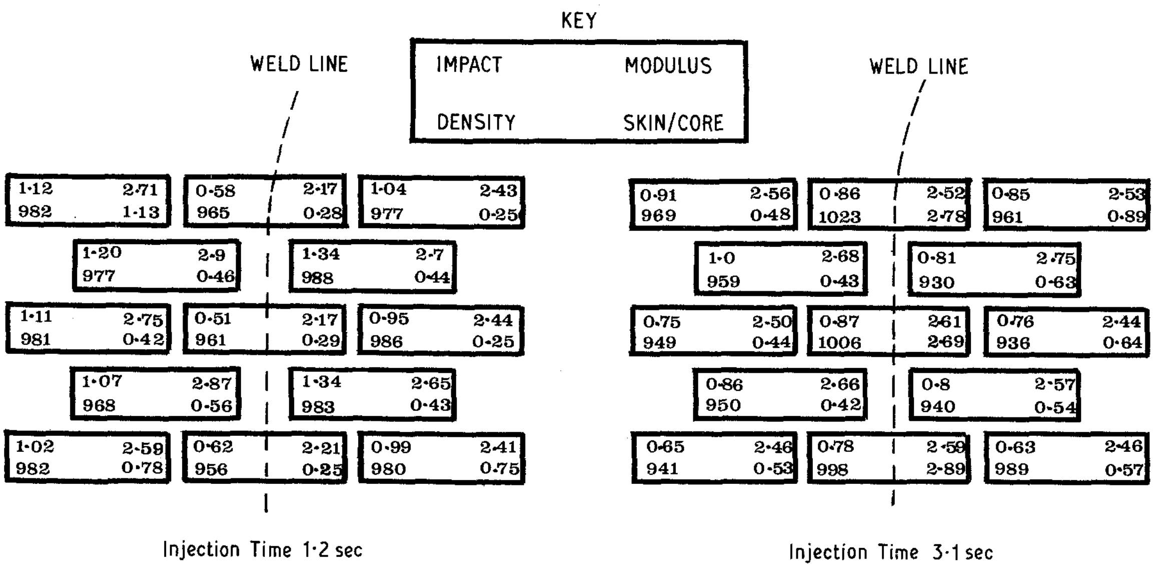

Figure 12 The influence of injection time on impact energy to failure (N m), flexural modulus (GPa), apparent density (kg m^{-3}) and skin to core thickness ratio, in fibre-reinforced structural foam mouldings containing weld lines (moulding thickness 6 mm).

during filling of the cavity, leading to weld lines with fibre alignment generally parallel to the weld line which often leads to a substantial reduction in strength in this region [10].

Macroscopic reflected-light photographs of specimens taken from across the weld zone, however, reveal distinct differences in skin core structure (Fig. 13). Mouldings made at the slow injection speed exhibit a region of high skin thickness with a limited foamed core, and consequently a high apparent density. This structure is conducive to increased levels of impact strength and flexural stiffness. Conversely, with a high injection speed extensive foaming occurs near the weld line resulting in a lower skin thickness and moulding density. The weld line is then characterized by a narrow band of solid material.

4. Conclusions

Specimens were taken from positions parallel to and across regions of divergent flow in fibre-reinforced polypropylene structural foam mouldings. Analysis revealed that the ratio of skin to core thickness remained essentially constant along the length and across the width except at the moulding periphery, where the value of this parameter increased significantly. The apparent density across mouldings (normal to the step change in thickness) decreased uniformly from a maximum at the edges to a minimum towards the centre. This corresponded well with observed changes in flexural and impact properties over this region. Specimens characterized along the length of mouldings (parallel to the change in section thickness) showed a marked drop in apparent density as the melt moved into the region of increased thickness (i.e. from 8 to 12 mm or 8 to 20 mm). The influence of this density reduction on mechanical properties was, however, overshadowed by the opposing effects of increasing moulding thickness.

The time of injection (over the range used in this study) had only a slight influence on localized values of mechanical properties in the vicinity of divergent melt flow.

Distinct differences in structure and mechanical properties were identified in the region of weld lines

TABLE II The effect of weld lines and injection time on average mechanical and structural properties of glass-fibre reinforced structural foam

Property	Injection time (sec)			
	1.2		3.1	
	Bulk*	Weld†	Bulk*	Weld†
Flexural modulus (GPa)	2.65	2.18	2.56	2.57
Impact failure energy (N m)	1.12	0.57	0.80	0.84
Apparent density (kg m^{-3})	980	961	952	1009
Skin to core thickness ratio	0.55	0.27	0.56	2.79

*Samples taken from nearby locations away from weld line.
†Samples taken across weld line.

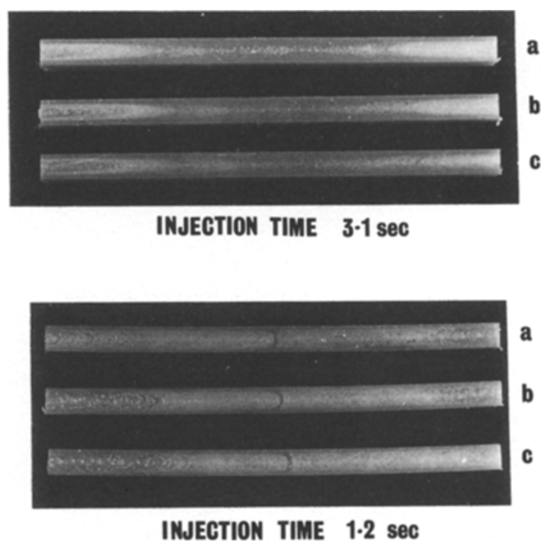

Figure 13 Skin/core structure present in test bars containing weld lines made using long (3.1 sec) and short (1.2 sec) injection times. (a), (b) and (c) correspond to test specimens identified in Fig. 3.

using long (3.1 sec) and short (1.2 sec) injection times. The greatly enhanced weld-line strength observed using slow speeds of injection, in some cases exceeding the properties in adjacent weld-free areas, is attributed to localized increases in skin thickness and moulding density across the weld zone.

Acknowledgements
The authors are grateful to ICI (Petrochemicals and Plastics Division) plc for supplying the mouldings used in this study, and also to the Science and Engineering Research Council for their financial support of one of the authors (DAMR).

References
1. P. R. HORNSBY, *Mater. Eng.* **3** (February 1982) 354.
2. A. A. AHMADI and P. R. HORNSBY, *Plast. Rubb. Process. Appl.* **5** (1985) 35.
3. *Idem, ibid.* **5** (1985) 57.
4. "Propathene for structural foams", Technical Service Note PP 137 (3rd Edn) (ICI (Petrochemicals and Plastics Division) plc, Welwyn Garden City, Herts, UK, 1980).
5. R. H. BURTON and P. R. HORNSBY, *J. Mater. Sci. Lett.* **2** (1983) 195.
6. P. R. HORNSBY and D. A. M. RUSSELL, *ibid.* **3** (1984) 1061.
7. *Idem, J. Mater. Sci.* **21** (1986) 3274.
8. *Idem*, in preparation.
9. P. R. HORNSBY, *Mater. Eng.* **3** (June 1982) 443.
10. M. J. FOULKES, "Short Fibre Reinforced Thermoplastics" (Research Studies Press, London, 1982) Ch. 5.

Received 10 October
and accepted 21 November 1985