Distortion of short-fibre reinforced thermoplastics structural foam injection mouldings

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Considerable distortion has been observed in injection-moulded thermoplastic structural foams reinforced with short glass fibres, whereas this condition is not usually found in unreinforced or particulate-filled variants of this material. Consideration is given in this paper to the origin of distortion in short glass-fibre reinforced polypropylene structural foam, with reference to the influence of processing conditions, density and blowing agent concentration on this parameter. Results are discussed in terms of the structure produced in the material and in particular the effects of fibre orientation.

1. Introduction

The use of thermoplastic structural foams is increasingly widespread for a variety of engineering or load-bearing applications, most components being produced by modified forms of injection moulding. Details of moulding procedures and the general properties commonly encountered have been reviewed by one of the authors for a range of thermoplastic structural foams [1, 2]. More recently the interrelationship between processing conditions, structure and properties were considered in some detail for polypropylene structural foams made by a low pressure short-shot injection moulding technique [3, 4]. Although this work was principally concerned with unmodified grades of polypropylene, some preliminary studies were undertaken on short glass-fibre variants of this material, which indicated that properties such as flexural stiffness, cell structure and surface finish were greatly influenced by the presence and orientation of the glass fibres in the moulding. It is known from these earlier investigations and from commercial experience with such materials [5] that distortion of glass-fibre filled thermoplastic structural foams is commonly encountered, sometimes creating problems in their subsequent application. However, the reasons for this distortion and the parameters influencing it require explanation.

The aim of this paper, therefore, is to provide an insight into the mechanism for distortion behaviour, the magnitude of the effects and the influence of selected formulation and processing variables. The work reported is part of a wider investigation by the authors to consider structure–property relationships in mineral-filled and short glass-fibre reinforced polypropylene structural foam made by a short-shot injection moulding route and incorporating a chemical expansion system.

2. Experimental procedure

2.1. Materials and moulding conditions

Propathene HW60SF30 (ICI (Petrochemicals and Plastics Division) plc), a polypropylene homopolymer containing 30% by weight of coupled short glass fibres, was used in this investigation. For comparison, structural foam mouldings were also made from Propathene 121C40H, a copolymer grade of polypropylene containing 40 wt % of surface-treated calcium carbonate. These materials were foamed by incorporating Genitron EPB azodicarbonamide chemical blowing agent (FBC plc, Hauxton, Cambridge, UK), at three levels of addition: 0.1%, 0.5% and 1.0% by weight of compound.

Plaque mouldings with dimensions 250 mm × 400 mm and thickness 8 mm were prepared by ICI on a purpose-build Krauss-Maffei TSG 100 structural foam moulding machine. In all cases a short-shot moulding procedure was employed [1]. A number of panels with thicknesses of 12 and 20 mm were also produced. Mouldings were made at three injection speeds: fast (0.8 sec), medium (1.3 sec) and slow (2.7 sec), using three different shot weights chosen to give approximate density reductions of 10, 15 and 25%, relative to unfoamed solid material.

2.2. Measurement of distortion

The amount of distortion in the structural foam panels was measured approximately four weeks after moulding, by means of the Moiré shadow fringe technique developed by Thomas and Dawson [6] to observe the flatness of injection-moulded discs and trays.

The method involved positioning a 12 in. by 10 in. (~ 305 mm × 254 mm) grating containing 150 lines per in. (~ 5.9 per mm) just above the surface of a moulded panel. The panel was obliquely illuminated

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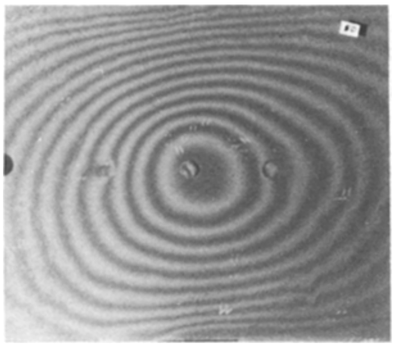

Figure 1 Moiré fringe pattern produced by domed distortion of a moulded structural foam plaque.

from one side by a horizontal line source shining down through the grating at an angle of about 45°. It was found that this arrangement gave 5 fringes per mm of height difference when viewed orthogonally to the surface of the grating. The fringes became less distinct the further the panel surface was positioned from the grating, the maximum useful distance being about 10 mm. The distortion of a panel was quantified by counting the total number of fringes across a moulding in two directions mutually perpendicular to each other, and starting from the mid-points of two adjacent sides. Fringe patterns were also recorded photographically.

2.3. Determination of fibre orientation

The anisotropy in material properties which can result from the flow orientation of fibres suspended in a thermoplastic matrix was expected to be of fundamental importance to the distortion observed in moulded panels. Such fibre orientation was observed on the fracture surfaces of impact specimens, produced as part of a comprehensive study of the impact behaviour of reinforced structural foam mouldings to be reported in a subsequent paper. Apart from observations of fracture surfaces by scanning electron microscopy, fibre orientation was studied by examining thin sections taken from the mouldings.

These were prepared by first cutting a flat surface on the specimen using a low-speed diamond saw. The cut surface was then fixed to a microscope slide using a low-viscosity epoxy resin with excellent optical clarity (EPO-TEK 301M, supplied by Logitech Ltd). Once the resin had cured, the specimen was lapped down to a thickness at which the orientation of the glass fibres

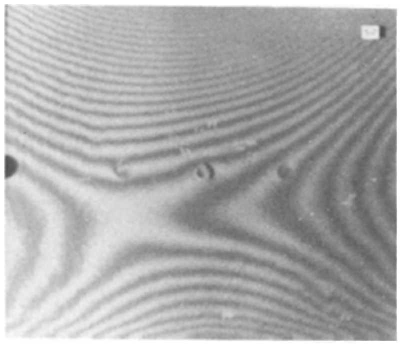

Figure 2 Moiré fringe pattern produced by anticlastic distortion of a moulded structural foam plaque.

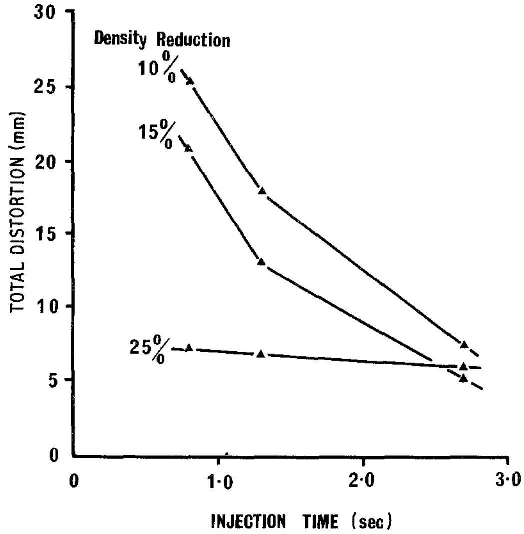

Figure 3 The effect of injection time and moulding density on distortion of 8 mm thick short glass-fibre reinforced polypropylene structural foam plaques. Blowing agent concentration 0.1 wt %.

could be easily seen using a transmission light microscope. The specimen was then capped with a coverslip using further epoxy resin as the mounting medium. This method of thin-section preparation had the advantage that relatively large sample areas (e.g. 1000 mm^2) could be examined from only one specimen.

3. Results and discussion

Two basic forms of panel distortion were observed as shown from the Moiré fringe patterns in Figs 1 and 2. In Fig. 1 the panel has deformed into a dome shape, whereas in Fig. 2 anticlastic curvature has resulted in the formation of a saddle shape. The approach adopted for quantifying distortion, discussed earlier, was kept the same for both shapes.

The greatest distortion measured (25.4 mm) was found in 8 mm thick panels, where a low level of blowing agent had been combined with a fast injection speed. However, the extent of this distortion could be greatly reduced by lowing the injection speed (Fig. 3), particularly in the case of foams with high apparent density.

The level of distortion obtained at a slow injection speed was similar to that found in calcium carbonate-filled polypropylene structural foam mouldings (Fig. 4), at the same plaque thickness and blowing agent concentration (0.1 wt %). It is significant that substitution of a fibrous additive by a particulate filler

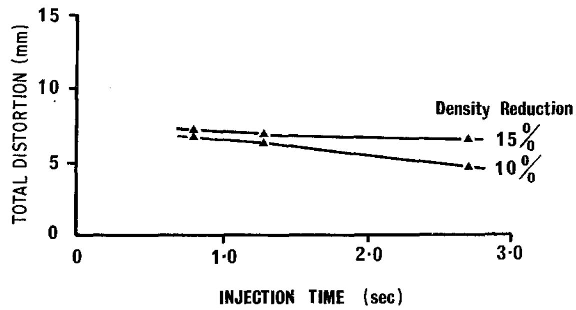

Figure 4 The effect of injection time and moulding density on distortion of 8 mm thick mineral filled polypropylene structural foam plaques. Blowing agent concentration 0.1 wt %.

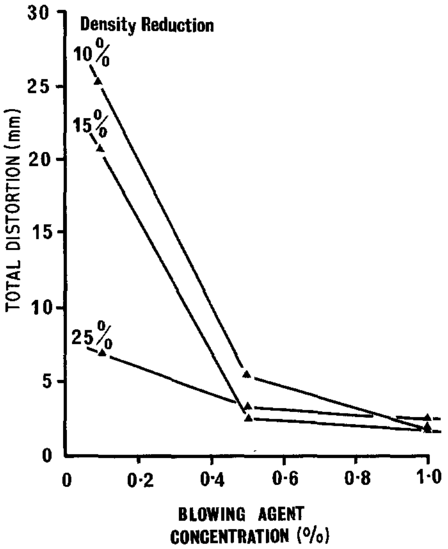

Figure 5 The effect of blowing agent concentration on distortion of 8 mm thick short glass-fibre reinforced polypropylene structural foam plaques produced at a fast injection speed.

minimizes the sensitivity of plaques to distortion due to changing injection speed.

From earlier work, however, it has been demonstrated that slow injection speeds (and low structural foam densities) result in a greatly increased surface roughness, originating from enhanced cell rupture at the flow front during injection and expansion of melt into the mould cavity [4]. Since occurrence of this surface irregularity may prove unacceptable in some potential applications, it is generally considered desirable to employ very rapid rates of injection. Fig. 5 shows that by increasing the initial concentration of blowing agent it is possible to produce panels with very little distortion, even when using very fast injection conditions. It was notable that the lowest level of distortion obtained from all of the 8 mm thick samples examined occurred with a blowing agent concentration of 1.0 wt %, together with a fast injection speed, at density reductions of 10 and 15%. However, at slower injection speeds the degree of panel distortion was not always reduced by increasing the blowing agent concentration, in fact under some conditions the distortion actually increased. This is evident from Fig. 6, which summarizes the effects on distortion in glass-reinforced polypropylene structural foams for the three principal variables considered in this study, namely injection speed, blowing agent concentration and level of density reduction. Analogous results are presented in Fig. 7 for distortion of mineral-filled polypropylene foams.

As mentioned earlier, structural foam panels were manufactured at three different thicknesses (8, 12 and 20 mm). Distortion was greatly reduced by increasing the plaque thickness from 8 to 12 mm at equivalent density reductions and injection speeds, but there was no significant further reduction in distortion by increasing thickness from 12 to 20 mm (Fig. 8).

The distortion of unconstrained mouldings on ejection from their mould cavity may be assumed to be due to an imbalance of stresses within the mouldings [7–9]. Such non-uniform distribution of stresses may be the direct result of the moulding process, for example, if the platens on either side of the cavity had different heat transfer rates, or indirectly, due to the forming process, as in the case of flow-induced orientation of molecules, crystallites, fillers or fibres [10]. Here, shrinkage anisotropy can lead to distortion as the part cools and contracts. The saddle shape or anticlastic curvature observed in this work could be explained if, after moulding, the cooling had produced a significant stress in one direction in the plane of the board relative to the other direction, due to oriented fibres resisting contraction by varying amounts in different directions. The distortion of the panels could then be compared to the buckling of a plate, where such anticlastic curvature is well known, with the ratio between the curvature of adjacent sides being exactly minus Poisson's ratio at the free edges [11, 12].

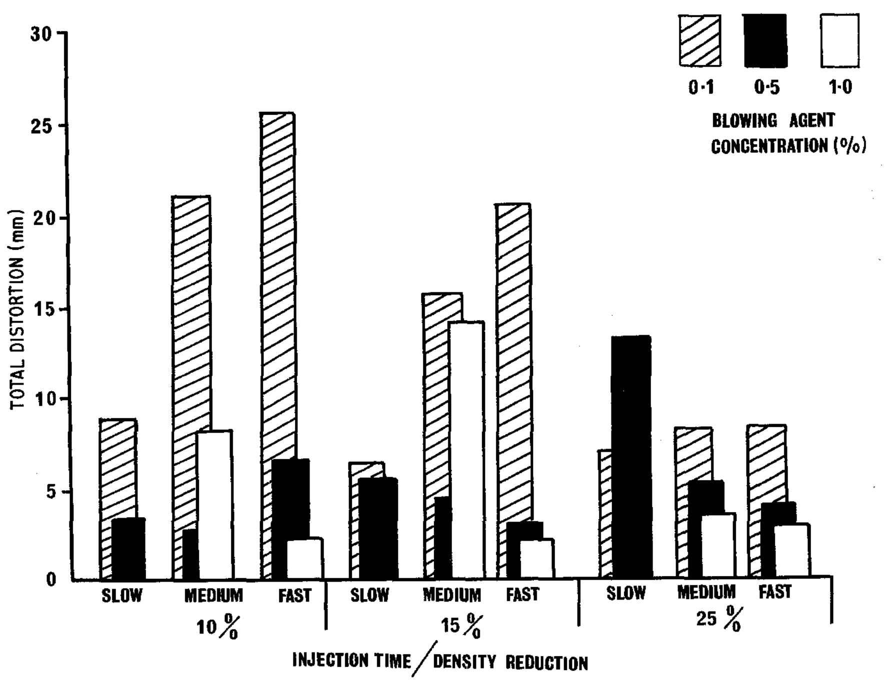

Figure 6 The relationship between distortion and processing variables for 8 mm thick short-fibre reinforced polypropylene structural foam plaques.

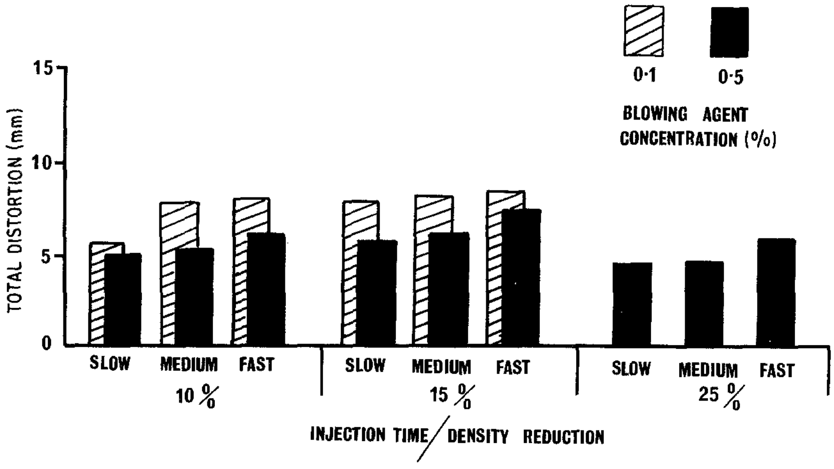

Figure 7 The relationship between distortion and selected processing variables for 8 mm thick mineral-filled polypropylene plaques.

Thomas *et al.* [9] examined distortion in solid polypropylene injection mouldings and found that there was an increase in residual stress in mouldings containing short glass fibres compared with unfilled material, and that specimens reinforced with fibres also exhibited increased distortion. In addition, the rate of relaxation of residual stresses was found to be greater in unfilled polyproylene.

In structural foam mouldings, the influence of fibres on warping was found to be similar to that described above, with unreinforced mouldings having only low levels of distortion. The density of the structural foam mouldings, the proportion of skin to core material as well as the unequal thicknesses of top and bottom skins were found to have little influence on the degree of distortion observed. The overriding influence was, as in the case of solid mouldings, the presence of fibres.

The diverging flow of the melt from the central sprue gate produced predominantly transverse-to-flow orientation in the core of the specimens, while the fibres closer to the surface tended to be aligned in the flow direction. Fibres located at the surface were more randomly positioned in the plane of the surface (Fig. 9). The highest distortion was found to be associated with the greatest degree of fibre alignment described above. Where distortion was less pronounced, the fibre orientation, particularly in the core of the mouldings, was more random (Fig. 10).

The observed differences of fibre alignment in reinforced structural foam mouldings resulted from the changing processing conditions used. Highest fibre alignment, and hence greatest distortion, was associated with fast injection speeds, low levels of blowing agent addition and low density reductions. During expansion of the thermoplastic melt, the fibres tend to remain within the polymer matrix surrounding the cells rather than bridging them. Larger or increased numbers of cells therefore reduce fibre alignment by randomizing the position of the fibres around the cells, thereby reducing distortion (Fig. 11).

4. Conclusions

A Moiré fringe technique has been successfully used to compare distortion between a series of injection-moulded polypropylene structural foam plaques containing either short glass-fibre reinforcement or calcium carbonate filler. The greatest distortion was observed in 8 mm thick plaques made using a fast injection moulding speed and a low level of blowing agent addition. However, distortion was reduced to a much lower level, comparable to that obtained using mineral-filled variants of this material, by increasing the time taken to inject the material. Since this action increases the surface roughness on the moulding, a more acceptable approach to reducing distortion in parts made using high injection speeds is either to lower the moulding density (by reducing shot weight) if this can be tolerated from other property considerations, or alternatively to significantly increase the concentration of blowing agent present. However, the possible consequences of increased cooling times resulting from greater internal pressure generation and subsequent post-blowing effects were not

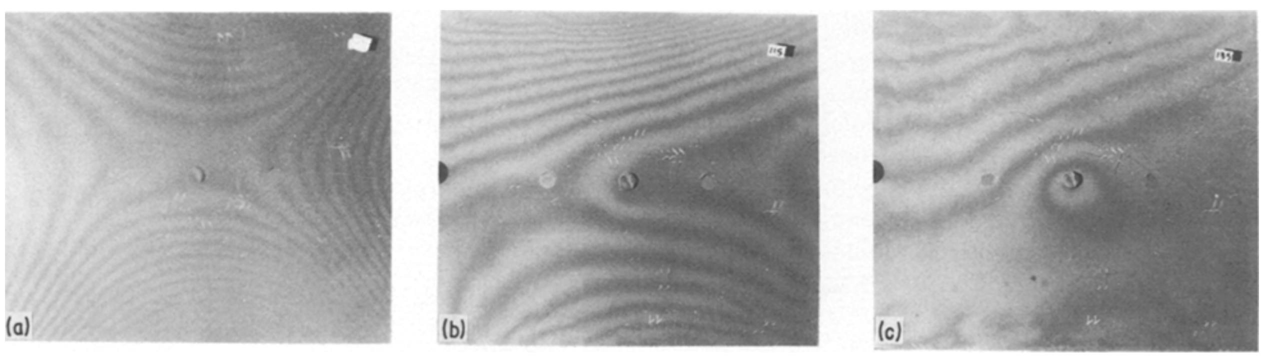

Figure 8 Moiré fringe patterns for (a) 8, (b) 12 and (c) 20 mm thick short-fibre reinforced structural foam plaques produced using similar processing conditions and the same blowing agent concentration (0.1 wt %).

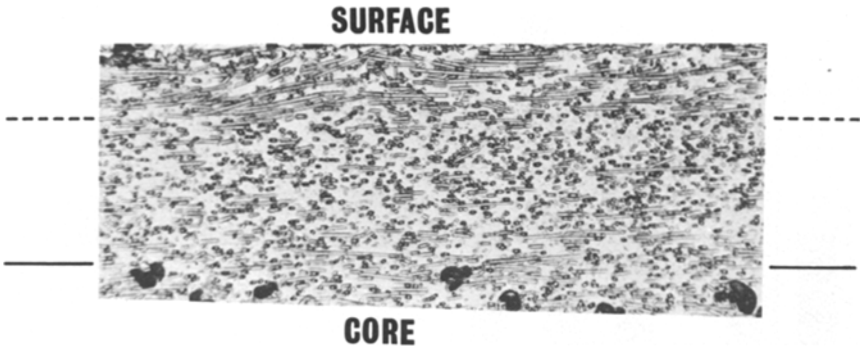

Figure 9 Transmitted light micrograph indicating fibre orientation in the surface region of a structural foam moulding (viewed normal to flow direction). × 50

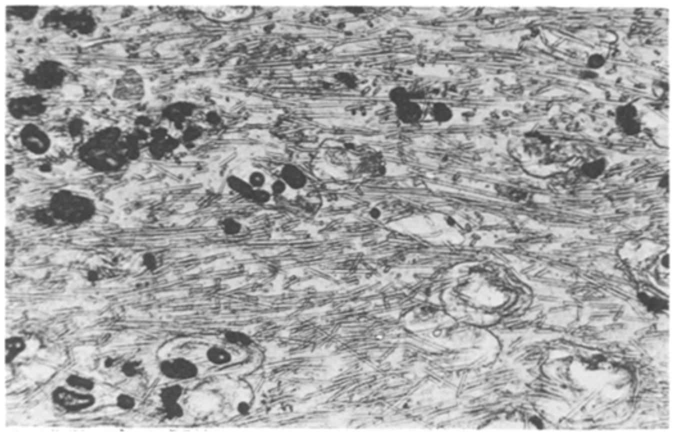

Figure 10 Transmitted light micrograph showing random orientation of fibres in the core of a structural foam moulding. × 50

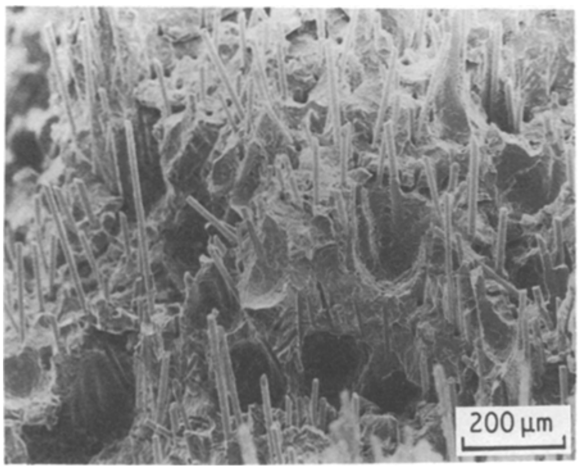

Figure 11 Fibre alignment around the cells in the core region of a short glass-fibre reinforced polypropylene structural foam.

considered although, in this study, all mouldings were subjected to similar times and rates of cooling without the incidence of post-blowing.

Distortion in short-fibre reinforced polypropylene structural foams was found to depend primarily on the orientation of fibres in the moulding. Formulation and processing conditions which tended to reduce the level of fibre alignment (low injection times, high levels of density reduction and high concentrations of blowing agent) generally resulted in mouldings with lower distortion.

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