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A study of the effect of injection speed on fibre orientation in simple mouldings of short glass fibre-filled polypropylene

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The pattern of fibre orientation in injection moulded strips of glass fibre reinforced polypropylene has been studied using the technique of contact micro-radiography. It has been found that the fibre orientation in the core of the mouldings is very dependent on injection speed. High injection speed gives alignment of fibres transverse to the flow direction, while for very low speeds the fibres align parallel to the flow. The associated changes in topography of the mouldings have been studied using scanning electron microscopy. The rheological properties of both glass fibre-filled and unfilled polypropylene have been studied in a capillary rheometer. At low shear rates, the fibres cause a significant increase in viscosity, but at the shear rates likely to be encountered in injection moulding, the filled and unfilled melts have very similar viscosities. The rheological data can be used to interpret the pattern of fibre orientation in the mouldings.

1. Introduction

Short glass fibre-reinforced thermoplastics (SFRTP) are an increasingly important class of engineering materials. Significant improvements in tensile strength and stiffness can be obtained relative to the matrix material, as well as a raising of the maximum working temperature.

The most widely used process for manufacturing articles from SFRTP is injection moulding. For a given unfilled thermoplastic the properties of the moulding depend on the particular morphology developed as a result of the processing conditions. In the case of fibre-filled thermoplastics the situation is more complicated in that the properties of the moulding will depend not only on the matrix properties, but also on the fibre concentration, fibre orientation and fibre length distribution.

If these materials are to be used efficiently in load-bearing engineering applications, it is desirable that the mechanical properties of a moulding, however complex, be predictable at the design stage. Although there are many theories for predicting the properties of a uniaxial long fibre composite, the problem becomes formidable in the case of practical mouldings in SFRTP due to the short length of the fibres and the complex pattern of orientation. At this stage, detailed studies are being conducted on simple geometry mouldings in an attempt to provide a basic foundation for the processing–property relationships in more complex mouldings.

Much experience has been gained with these materials by commercial moulders, and empirical procedures for obtaining good quality mouldings have been developed [1–5]. In addition, systematic research has been carried out showing the extent to which mechanical properties can be affected by processing conditions [6, 7]. During the moulding process the fibres may become oriented in a complex manner, often forming layers of differing orientation [8, 9]. This can produce marked anisotropy of mechanical properties [10]. It has been shown for short glass fibre-filled thermosetting materials

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that flow geometry has a major effect on fibre orientation [11, 12], and also that melt viscosity and shear rate can significantly alter the proportions of the oriented regions [11]. Orientation that is unfavourable with respect to the loads encountered in service can lead to component failure both in thermosetting and thermoplastic materials [13].

A considerable amount of attention has been devoted to the rheology of this class of materials [14–21] but only in a few cases have attempts been made to relate this to the behaviour of the material under commercial processing conditions [22–24].

The work presented in this paper is part of a programme aimed at predicting the pattern of fibre orientation in a simple moulding from a knowledge of the basic rheological properties of the material, the moulding conditions, and the mould geometry. The experimental approach in the main programme has been to study the fibre orientation of mouldings over a wide range of processing conditions, and to try to relate it to the flow behaviour during mould filling. This demands a knowledge of the flow properties in both simple and complex flows. In this paper only the effect of injection speed is investigated.

In our early studies of mould filling behaviour a striking change in the fibre orientation was observed at very low injection speeds. These were below the speeds normally employed in practice, but it was thought important to study this effect in detail because although the injection speeds were low, the levels of shear rate obtained will occur in practice when moulding articles containing thick cross-sections.

Injection speed also affects the surface finish of the moulding. In many applications a glossy finish is required, in which case a high injection speed is essential. The effects of injection speed on surface finish have been studied in addition to the effects on structure with a view to understanding the physical changes which give rise to a gloss or matt surface.

For a given mould geometry other factors may affect the orientation and length of fibres and this is the subject of a comprehensive set of experiments, now underway, covering the range of typical moulding conditions.

2. Experimental

2.1. Moulding equipment

The injection moulding machine used in this work was a BIPEL 130/25 model with a 130 tonf. (~ 1.3 MN) clamping force and 6.6 oz. (~ 187 g) maximum shot weight. A special feature of this machine was the closed loop control of the injection process using a Bosch SPR 200 adaptive control system. This allowed close control of the speed of injection and the pressure in the mould cavity through a servo-hydraulic value, and ensured good repeatability of mouldings from shot to shot.

The mould was a two cavity bar mould (Fig. 1) of dimensions 190 mm × 30 mm × 1.5 mm, with a semicircular gate of 1 mm radius. This was chosen to help develop an understanding of the flow behaviour in a simple geometry. One cavity was drilled to take a flush mounted pressure transducer which fed a signal back to the controller.

2.2. Moulding conditions

Mouldings were produced under three sets of conditions:

(1) Fast constant speed injection (injection time = 0.2 sec).

(2) Slow constant speed injection (injection time = 11 sec).

(3) Stepped injection, starting slowly and abruptly changing to fast after 50% of the shot had been injected.

Other machine conditions were:

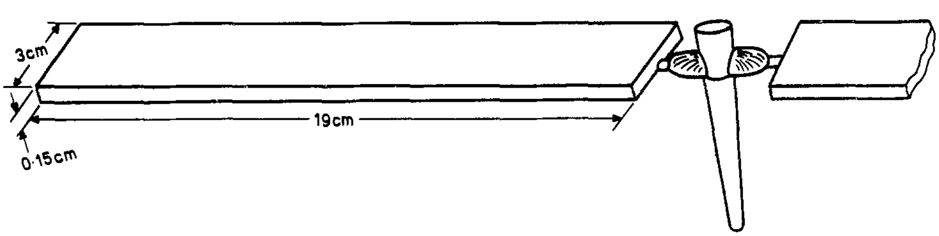


Figure 1 Simple strip moulding used for fibre orientation studies.

Barrel temperature	240° C on all zones
Screw speed	100 r.p.m.
Back pressure	100 p.s.i. (689 kN m^{-2})
Mould temperature	30 to 35° C

For run 3 the control system would not permit a change from the slow speed of run 2 to the fast speed of run 1, an increase of about 50 times. The speed profile used gave an increase of 20 times from the initial slow speed level.

2.3. Structural examination
The examination of fibre orientation in the mouldings was performed using the technique of contact micro-radiography (CMR). The application of this technique to the study of fibre-reinforced thermoplastics has been described by Darlington and McGinley [25]. A thin section, approximately 100 μm thick, is cut from the moulding using a low speed diamond saw. This is laid onto a fine grain photographic plate and exposed to a beam of X-rays, which casts "shadows" of the fibres onto the plate.

The surface of mouldings was also examined by scanning electron microscopy, using a Cambridge Stereoscan 600 electron microscope.

2.4. Rheological examination
Characterization of the rheological behaviour of the material was performed using a Davenport capillary rheometer. A range of dies with diameters of 0.5 mm to 4.0 mm gave a range of apparent shear rates of 0.2 sec^{-1} to 15 000 sec^{-1}. The use of smaller dies to obtain higher shear rates was limited by the onset of pressure fluctuations. These have been found to occur when the fibre length is comparable with or greater than the die diameter.

2.5. Materials
The injection moulding was carried out using I.C.I. Propathene HW60GR/20/001, a polypropylene containing 20% by weight of glass fibres of modal length 600 μm and diameter 10 μm. This material was also used for most of the capillary rheometry, but for purposes of comparison a small amount of work was carried out using Propathene HW60GR/30/001 which contains 30% by weight of the fibres. A third material, Propathene GXM43, which is unfilled and closely resembles the matrix of the two filled materials, was also used.

3. Results
In the studies described here the mould always filled uniformly from the gate. Under a wide range of moulding conditions jet-filling was not observed with glass fibre-filled polypropylene.

3.1. Structure of the mouldings
Using the CMR technique described above, sections cut from the sprue, runners, and the main body of the moulding were examined.

3.1.1. Fibre orientation within the moulding: Fast injection
Contact microradiographs showing fibre orientation within the moulding are given in Fig. 2 for the fast injection case. Fig. 2a shows the plane perpendicular to the major flow direction at a distance of 10 cm from the gate; only the central

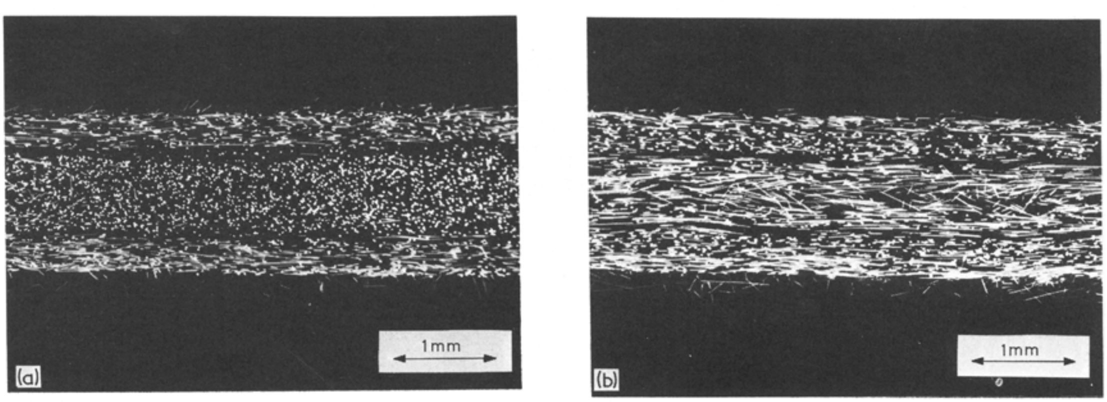


Figure 2 (a) Contact micro-radiograph of a section cut perpendicular to the major flow direction for fast injection. (b) Contact micro-radiograph of a section cut in the plane containing the major flow direction and the thickness direction for fast injection.

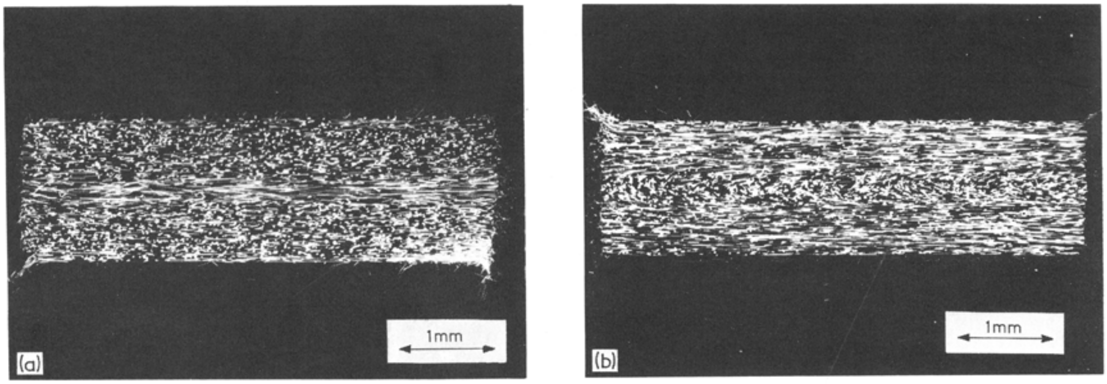


Figure 3 (a) Contact micro-radiograph of a section cut in the plane perpendicular to the major flow direction for slow injection. (b) Contact micro-radiograph of a section cut in the plane containing the major flow direction and the thickness direction for slow injection.

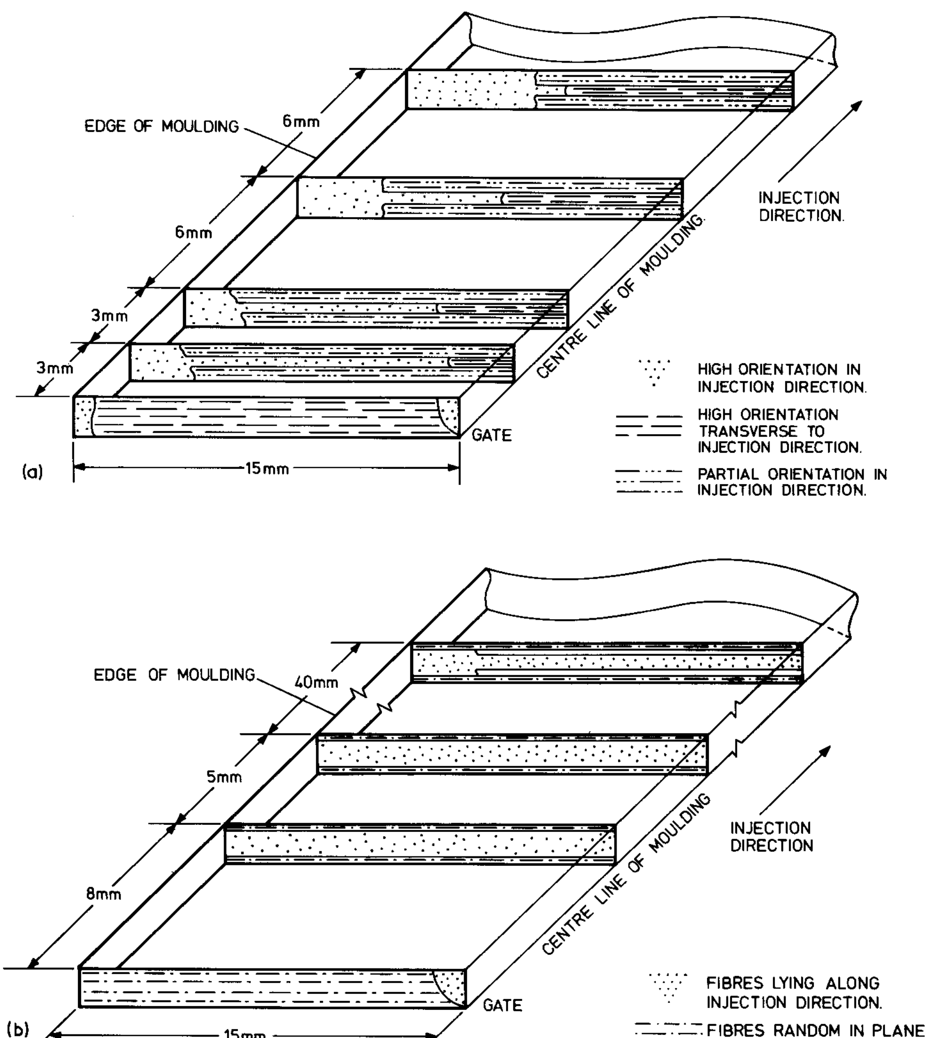


Figure 4 Schematic diagrams of transverse sections through a simple bar moulding; (a) fast injection, (b) slow injection.

portion of the moulding is included. Fig. 2b shows the plane containing the major flow direction and thickness direction, injection being from right to left. The orientation shows a layered structure. The central region contains fibres mainly aligned transversely to the flow direction. Above and below this are regions with the predominant fibre orientation in the flow direction. Very few fibres have any component in the thickness direction. Fig. 4a shows schematically the development of the pattern of orientation obtained from a large number of CMR sections.

The fibre orientation changes only slightly with distance along the moulding, after the first two centimetres, but in this region the orientation changes fairly rapidly, and close to the gate fibre-free zones have been observed. At the edges of the moulding, not shown in Fig. 2a, there is high alignment of fibres in the direction of injection.

3.1.2. Fibre orientation within the moulding: Slow injection

Contact micro-radiographs for the slow injection case are shown in Figs. 3a and b. The sections were cut from a similar position in the moulding to those shown in Figs. 2a and b. The orientation pattern is markedly different from the fast injection case. The central region is of greater thickness and contains fibres highly aligned in the flow direction. The skin layers above and below this region contain fibres with a fairly random orientation in the plane of the moulding. Between the "skin" and the "core" regions there appears to be a fibre free layer.

The development of this pattern of orientation is shown schematically in Fig. 4b.

3.1.3. Fibre orientation in the sprue and runners

A brief study of the sprue and runners was undertaken in order to ascertain the state of fibre orientation as the material enters the mould. Fig. 5 shows the plane perpendicular to the flow direction at the narrow end of the sprue for a slowly injected specimen. In the outer regions the fibres are strongly aligned in the flow direction, but the alignment is much less pronounced near the centre of the sprue. Close to the outside there is a fibre-free ring. This ring is not present at the wide end of the sprue, and does not occur for fast injection. Fig. 6 shows the plane perpendicular to the flow direction for slow injection for a specimen cut about 300 μm from the gate. The centre of the picture reveals that fibres emerging from the gate are very strongly aligned in the major flow direction. This is also true for fast injection.

3.1.4. Fibre orientation within the moulding: Stepped injection

Fibre orientation was examined in the mouldings produced with a slow initial injection, abruptly changing to fast. At the end of the moulding nearest the gate the pattern of orientation was similar to that obtained for a moulding injected slowly throughout. At the far end the pattern was similar to that obtained by fast injection. The orientation changed from one state to the other approximately half-way along the bar, over a distance of 2 to 3 cm.

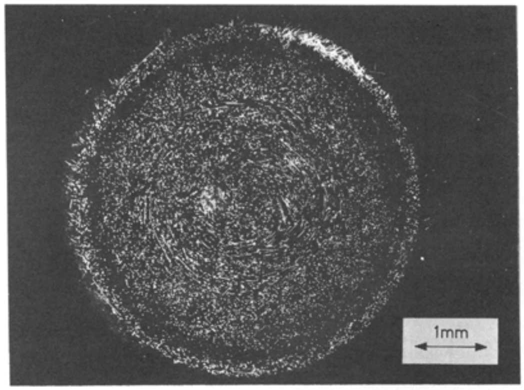


Figure 5 Contact micro-radiograph of the plane perpendicular to the major flow direction at the narrow end of the sprue for slow injection.

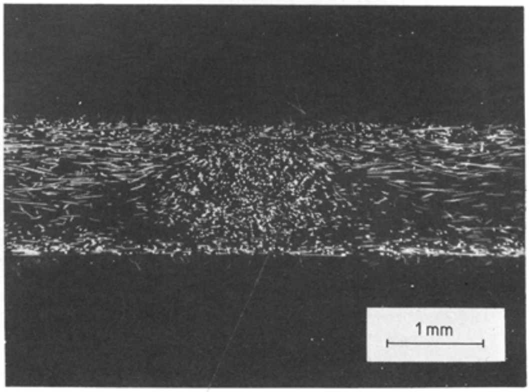


Figure 6 Contact micro-radiograph of a section cut in the plane perpendicular to the major flow direction for slow injection. The section was cut 300 μm from the gate.

3.2. Surface finish

Surface finish of the mouldings was studied visually, and using the scanning electron microscope. Mouldings produced by fast injection always had a very glossy surface, whilst slowly injected mouldings had a matt finish.

The surface of the mouldings produced by stepped injection showed a very sharp transition of surface finish. The end nearest the gate had a matt surface and rough texture; this changed abruptly to give a smooth glossy surface over the rest of the moulding. The surface finish transition was slightly "upstream" of the transition in fibre orientation. Fig. 7a shows an electron micrograph of the change in surface finish. The glossy region is very smooth with no fibres apparent. The matt region contains many ridges which appear to be individual fibres coated with polypropylene. This is shown at greater magnification in Fig. 7b.

3.3. Capillary rheometry

In order to try to understand the difference in fibre orientation at different injection speeds, the rheological properties of the material were determined in capillary flow. Measurements of the pressure drop along a capillary were made, for a series of flow rates, and from this data curves of apparent viscosity versus shear rate were plotted for each of the three materials used here. The die used was 1 mm in diameter and 20 mm long. The effect of the die entrance region was eliminated by taking a set of flow rate versus pressure drop readings on a zero length die of the same diameter, and subtracting the curve from that obtained on the long die. Shear rate data were corrected using the Rabinowitsch correction [27], and the results are shown in Fig. 8. In this diagram the viscosity and shear rate values obtain at the capillary wall. From Fig. 8 it is apparent that the presence of the fibres causes a considerable increase in viscosity at low shear rates, but that at high shear rates the viscosities of the three materials are almost identical. One of the most commonly used models for the flow behaviour of polymer melts is the Ostwald–de Waele or power law model

$$\tau = C\dot{\gamma}^n,$$

where

τ = shear stress
$\dot{\gamma}$ = shear rate
C = constant
n = constant = power law index

Using this model the apparent shear viscosity, $\eta = \tau/\dot{\gamma}$ is given by:

$$\log \eta = \log C + (n-1)\log \dot{\gamma}$$

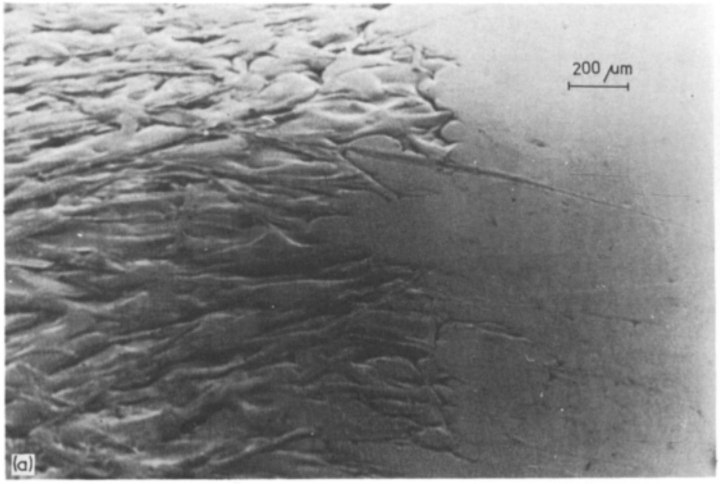
Thus the power law index may be determined from the slope of a plot of log η against log $\dot{\gamma}$. An examination of Fig. 8 reveals that the gradient is not constant, and thus the power law model is not entirely appropriate for a description of these materials over a wide range of $\dot{\gamma}$. The model nevertheless has some use in this context. The power law index is related to the velocity profile, and for Newtonian materials ($n = 1$) the profile is parabolic. For pseudoplastic materials ($n < 1$) the profile is blunter, and approaches plug flow as n tends to zero.

The most striking conclusion to be drawn from Fig. 8 is that at shear rates above about 10 000 sec^{-1} the presence of the glass fibres has very little effect on the shear viscosity in capillary flow. This observation is in agreement with the work of Yarlykov *et al.* [15] on glass fibre-filled polypropylene, and Chan *et al.* [16, 17] on glass fibre-filled polyethylene and polystyrene. Thomas and Hagan [14] have found that the presence of fibres reduces the viscosity at high shear rates in polypropylene, whilst Charrier and Rieger [18], and Ivanyukov *et al.* [19] see very little change in viscosity due to incorporation of fibres in polypropylene, even at low shear rates.

In injection moulding shear rates are often higher than 10 000 sec^{-1}, and this may indicate why it is possible to process highly-filled materials at pressures no higher than those needed for the unfilled materials provided that the shear rates are high enough [4]. One explanation for the lack of the effect of filler on shear viscosity is that the fibres may migrate away from the wall of the die and leave a fibre free layer [28]. Since the velocity profile at high shear rates is very blunt, all the shear will take place in this thin layer. The measured viscosity would therefore be similar to that of the unfilled material.

4. Discussion

The general problem of predicting fibre orientation in complex mouldings from a knowledge of processing conditions and mould geometry is an extremely difficult one. However, considerable progress has been made towards an understanding of the development of the fibre orientation in



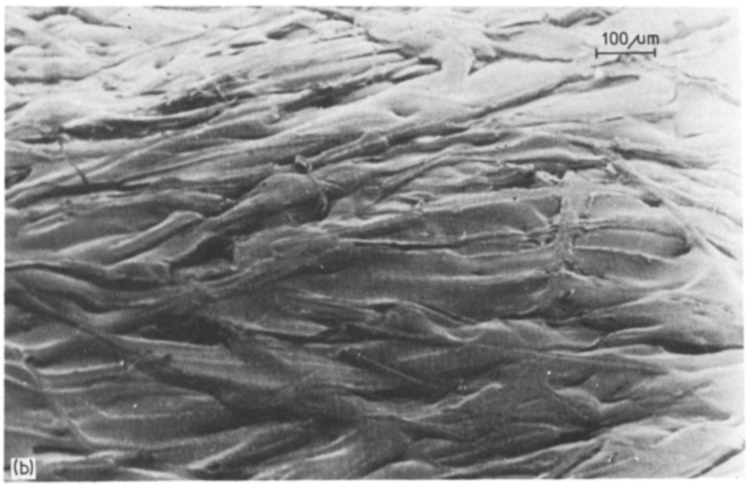


Figure 7 (a) Scanning electron micrograph of the matt-to-gloss transition on the surface of a moulding. (b) Scanning electron micrograph of the matt surface region.

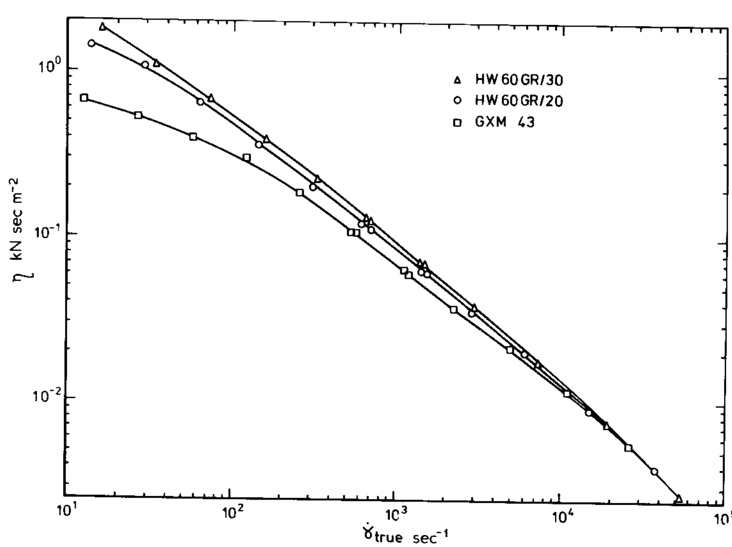


Figure 8 Plot of viscosity η versus shear rate $\dot{\gamma}$ for three polypropylenes containing different amounts of glass fibres. The scale on both axes is logarithmic.

the simple double strip mould. Using information gained from the capillary rheometry many of the fibre orientation effects may be qualitatively explained.

4.1. Effect of injection speed on fibre orientation

Contact micro-radiographs showing the effect of injection speed on orientation of the fibres within the moulding have been shown in Figs. 2 and 3. When the material enters the mould the fibres are already strongly aligned in the injection direction (see Fig. 6). At the gate the sudden increase in dimensions of the channel in which the material flows produces a deceleration which is accompanied by a compressive force along the flow direction. A fibre which is slightly inclined away from the axis will tend to rotate into an orientation transverse to the flow direction under the action of the compressive force. The subsequent development of the fibre orientation in the moulding may be explained using the "fountain" model described by Rose [29], and used by Tadmor [24]. In this model shearing flow takes place everywhere except in the vicinity of the flow front, where the flow is predominantly extensional. The presence of this extensional flow in the flow front has been used by Tadmor to explain the high degree of molecular orientation along the major flow axis which is present in the skin of mouldings in unfilled thermoplastics. The same reasoning accounts for the strong fibre alignment observed in the skins of mouldings in the present study.

In the core of the moulding shearing flow is predominant, and the fibre orientation in the final moulding depends on the flow processes to which fibres are subjected as they pass through the gate, and on the velocity profile in the core. From the shape of the flow curve (Fig. 8) it is evident that at high injection rates the velocity profile in the region of shearing flow is considerably blunter than at low injection rates. Thus at high injection speeds the material will flow almost like a plug, without shearing, except in the outermost regions close to the frozen skin, where the shear rate is highest. The fibre orientation present in the core in the final moulding will therefore be very similar to the transverse orientation which is set up at the gate. Similar transverse fibre orientation patterns following the flow from a small gate into a large mould have been seen by Goettler [11] in a short glass fibre-filled epoxy moulding compound, and by Darlington and McGinley [25] in a short glass fibre-filled thermoplastic. The observation is consistent with that of Owen and Whybrew [12] who showed that converging sections lead to axially aligned fibres, and diverging sections lead to transversely aligned fibres in polyester dough moulding compounds.

At low injection rates at the beginning of the mould filling process the material enters the mould and is subjected to a deceleration as experienced in the fast injection case. Consequently the fibres rotate and take up a transverse alignment. In the shearing flow which occurs behind the flow front in the core the velocity profile is less blunt than for fast injection. This means that the transverse fibre orientation set up at the gate is affected by the shearing flow as the mould fills. The behaviour of concentrated suspensions of fibres in non-Newtonian elastic fluids in shearing flows is not well documented. The case of dilute suspensions has received more attention, and Goldsmith and Mason [30] have shown that in Newtonian matrices, rigid fibres describe a complex orbit in tube flow, and this orbit is in agreement with the theoretical work of Jeffery [31]. The fibres spend 90% of their time aligned to within $\pm 4^\circ$ of the flow axis. For less dilute suspensions the problem will be complicated by fibre–fibre interactions, but for such a case it has been shown experimentally for a short fibre-filled thermoplastic that in shearing flow the fibres align along the flow direction [32]. However the shearing flow may be only secondary in aligning the fibres.

An alternative mechanism is provided by the geometry of the molten core. At the beginning of the slow injection cycle the material entering the mould suffers a deceleration because of the sudden increase of cross-section at the flow front and a core of transversely aligned fibres will be produced. By the time the mould is nearly full the skins of the moulding will have frozen, leaving only a narrow tunnel of still-molten material. Consequently the material which enters the mould at the end of the mould-filling process will not experience the large deceleration which was present at the beginning. The fibres thus remain aligned along the flow direction as they flow through the tunnel formed by the frozen skins. In the course of this flow the original transverse core is destroyed, and the end result is a moulding with a core of material aligned in the flow direction.

Comparison of Figs. 2 and 3 shows that if one associates the change in fibre orientation through the thickness of the moulding directly with the skin/core ratio, then it would appear that the fast injected specimen has a thicker skin than its slowly injected counterpart. The reason for this is probably as follows. In the slow injection case the transition from longitudinal to random fibre orientation occurs at the skin/core boundary. In the case of fast injection the change in fibre orientation does not occur at the skin/core boundary. The central region of transverse alignment represents only the blunted portion of the velocity profile in the flowing core. On either side of this transversely aligned zone there is a region of high shear rate, and the effect of this high shear rate is to realign the transverse fibres in the flow direction. Thus the skin in the fast injection case is considerably thinner than it appears.

4.2. Fibre orientation in stepped injection speed mouldings

The fibre orientation in the moulding produced by stepped injection speed may be explained using the reasoning of Section 4.1. By the time the injection speed is stepped from slow to fast the half of the mould nearest the gate is already full, and the skins in this region are already frozen. This means that the new material, which is injected at high speed into the mould, will not suffer a large deceleration until it reaches halfway down the mould, where no skin has yet formed. Thus the core of the moulding will contain axially aligned fibres near the gate, and transversely aligned fibres at the far end of the mould.

4.3. The effect of injection speed on surface finish

The effects seen are believed to be related to the time taken for a significant pressure to develop in the mould cavity. It is assumed that the material laid down on the cavity wall during injection has initially an appearance similar to that shown in Fig. 7b, with individual melt covered fibres protruding from the surface. For this to be transformed to a smooth gloss surface sufficient pressure must be available in the mould cavity to push this material firmly into contact with the wall, and to force polymer melt into the gaps between surface fibres. Significant pressure will only develop once the cavity has been filled. If this occurs before the material at the wall has fully solidified a glossy surface will result. If solidification occurs before the build up of pressure the original matt surface will remain.

5. Conclusions

A study has been made of the pattern of fibre orientation in simple end-gated mouldings of glass fibre reinforced polypropylene. It has been found that the fibre orientation, particularly in the core of the mouldings, is very dependent on the speed of injection. High injection speeds, as would normally be used commercially, give a transverse alignment of fibres in the core. Very slow injection speeds give longitudinal alignment of the fibres in the flow direction. With the facilities of a programmed injection stroke it is possible to vary the fibre orientation along the bar. A change in injection speed also modifies the surface finish of the mouldings, there being a relatively sharp transition from a gloss to a matt surface when the injection speed changes from fast to slow. This fact may be explained in terms of mould cavity pressure.

The rheological properties of both glass fibre filled and unfilled polypropylene have been studied in capillary flow. At low shear rates, the fibres cause considerable resistance to flow, but at high shear rates the filled and unfilled melts have very similar viscosities. This may explain why glass fibre filled thermoplastics may be processed relatively easily. The rheological results can be used to provide a qualitative explanation for the fibre orientation pattern observed in the mouldings.

Acknowledgements

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References

1. J. E. THEBERGE, *Plast. Des. Process* **13** (1973).
2. J. MAXWELL, *Plastics Today* **22** (1964) 9.
3. O. W. LUCIUS, *Kunststoffe* **63** (1973) 367.

4. T. P. MURPHY, *Mod. Plast.* (US) **42** (1965) 127.
5. W. A. HUNTER, *Plast. Eng.* **31** (1975) 24.
6. W. R. SCHLICH, R. S. HAGAN, J. R. THOMAS, D. P. THOMAS and K. A. MUSSELMAN, *Soc. Plast. Eng. J.* **24** (1968) 43.
7. W. C. FILBERT, *ibid.* **25** (1969) 65.
8. V. KARPOV and M. KAUFMAN, *Brit. Plast.* **38** (1965) 498.
9. G. KALISKE and H. SEIFERT, *Plaste u. Kaut.* **20** (1973) 837.
10. M. W. DARLINGTON, P. L. McGINLEY and G. R. SMITH, *J. Mater. Sci.* **11** (1976) 877.
11. L. A. GOETTLER, *Mod. Plast.* (US) **47** (1970) 140.
12. M. J. OWEN and K. WHYBREW, *Plast. Rubb.* **1** (1976) 231.
13. E. M. ROWBOTHAM, S. A. E. Automotive Engineering Congress, Detroit, Michigan, 740264 (1974).
14. D. P. THOMAS and R. S. HAGAN, S. P. I. Reinforced Plastics Division Conference, Chicago, Illinois (1966).
15. B. V. YARLYKOV, M. L. FRIDMAN, Yu. G. YANOVSKII, E. I. FRENKIN, E. V. ZHIGANOVA, V. V. AMERIK and V. F. PETROVA, *Int. Polymer Sci. Tech.* **4** (1977) T/7.
16. Y. CHAN, J. L. WHITE and Y. OYANAGI, Polymer Science and Engineering Report No. 96, University of Tennessee (1977).
17. *Idem,* Polymer Science and Engineering Report No. 102, University of Tennessee (1977).
18. J. M. CHARRIER and J. M. RIEGER, *Fibre Sci. Technol.* **7** (1974) 161.
19. D. V. IVANYUKOV, V. V. AMERIK, E. V. ZHIGANOVA, N. P. SAMSONOVA, V. F. PETROVA, and A. V. KONYSHEVA, *Soviet Plastics* (1972) 53.
20. J. BELL, *J. Composite Mater.* **3** (1969) 244.
21. S. NEWMAN and A. TREMENTOZZI, *J. Appl. Polymer Sci.* **9** (1965) 3071.
22. L. R. SCHMIDT, *Polymer Eng. Sci.* **14** (1974) 797.
23. *Idem, Advances in Chemistry* **142** (1975) 415.
24. Z. TADMOR, *J. Appl. Polymer Sci.* **18** (1974) 1753.
25. M. W. DARLINGTON and P. L. McGINLEY, *J. Mater. Sci.* **10** (1975) 906.
26. R. O. MASCHMEYER and C. T. HILL, *Advances in Chemistry* **134** (1973) 95.
27. J. M. McKELVEY, "Polymer Processing" (John Wiley & Sons, Inc., New York and London, 1962).
28. H. L. GOLDSMITH and S. G. MASON, "Rheology", Vol. 4, edited by F. R. Eirich (Academic Press, New York, 1967) p. 216.
29. W. ROSE, *Nature* **191** (1961) 242.
30. H. L. GOLDSMITH and S. G. MASON, *J. Colloid Sci.* **17** (1962) 448.
31. G. B. JEFFERY, *Proc. Roy. Soc.* **102** (1922) 161.
32. M. J. FOLKES and P. LEECH, to be published (1978).

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