JOURNAL OF MATERIALS SCIENCE **35** (2000) 5091 – 5099

The hot compaction of 2-dimensional woven melt spun high modulus polyethylene fibres

P. J. HINE, I. M. WARD
IRC in Polymer Science and Technology, University of Leeds, Leeds, LS2 9JT, UK

M. I. ABO EL MAATY, R. H. OLLEY, D. C. BASSETT
J. J. Thomson Physical Laboratory, Whiteknights, University of Reading, RG6 6AF, UK
E-mail: d.c.bassett@reading.ac.uk

In this paper we describe the production, properties and morphology of hot compacted 2-dimensional woven high modulus polyethylene fibres. The aims of the work were to establish the optimum conditions for production of the compacted woven PE sheets using a combination of mechanical measurements at Leeds and morphological investigations at Reading. This joint approach had proved very successful in a previous study on the compaction of unidirectional arranged PE fibres, where the optimum compaction temperature was established as 138°C, where ∼10% of the original fibres were melted. Morphological studies clearly showed that the melted material had recrystallised, epitaxially, onto the original fibre backbones, forming a coherent network to bind fibres into a continuous structure. The current studies, using the woven PE material, showed that a higher temperature was needed to fill all the space between the woven polyethylene fibres, and so produce a coherent material. Peel tests, where two layers of cloth are compacted together and then pulled apart, were carried out over a range of compaction temperatures to measure the interlayer bond strength; this increased with increasing compaction temperature. Significantly, reasonable bond strengths were established at the optimum temperature established for the unidirectional samples (138°C measured on the mould or 136°C in the centre of the fibre assembly) which produces ∼10% melted and recrystallised material, although a higher interlayer strength was measured at higher temperatures where more of the melted phase was produced. Morphological investigations of woven samples with ∼10% melted material, showed that while the individual fibre bundles were well bonded, not all of the complicated junctions between the fibre bundles in the woven network were completely filled with melted and recrystallised material, and that a temperature 2°C higher than for 1D compactions was probably optimum. The optimum temperature was found to fall very close to the temperature at which complete melting of the fibre occurred. *© 2000 Kluwer Academic Publishers*

1. Introduction

Recently, technical, commercial and ecological considerations have been combined in the production of "one-polymer composites", in particular those of polyethylene (PE) where a high-modulus polyethylene fibre is bonded with a polyethylene matrix. Normally the fibre is made of a high molecular weight linear PE with a matrix of a lower-melting type of PE, either LDPE or LLDPE [1–5]. However, previous work at Leeds University [6] has shown that unidirectionally arranged high modulus melt spun polyethylene fibres can be compacted into a continuous material using suitable conditions of temperature and pressure, with only the one PE, namely the fibre, being supplied. The critical parameter for the 'hot compaction' process was found to be the compaction temperature, which needed to be much more precisely controlled than the mixed-PE composites studied elsewhere. The optimum value of this parameter, for the unidirectional fibre arrangement, was found to be just inside the melting range of the fibre, such that a small fraction of the surface of each fibre was melted. At this temperature, which was established as 138°C for melt spun polyethylene fibres, sufficient melted material (∼10–20%) was produced to form a 'matrix' phase to bind the structure together, while leaving intact a substantial fraction of the original oriented fibres. The 'hot compacted' material therefore exhibited a high longitudinal stiffness and strength, by virtue of the retention of a substantial percentage of the original oriented fibres (∼80–90%), while the fibre to fibre bonding developed by the recrystallised phase was such that transverse failure occurred within the fibres rather than at the interface between them. The morphological studies carried out at Reading [7, 8], showed clearly that at the optimum temperature of 138°C, sufficient melted material had been produced to fill all the gaps in the structure. At this compaction temperature the distances between the fibres were small enough to allow the recrystallised lamellae to bridge the inter-fibre distance without changing molecular orientation.

One consequence of the unidirectional fibre arrangement was the extremely high level of anisotropy shown by the compacted plates, with a high stiffness and strength in the fibre direction (36 GPa and 90 MPa respectively) and lower values in the transverse direction (1.5 GPa and 25 MPa respectively). While these properties could have potential applications, it is clearly advantageous to be able to provide more balanced properties. In this paper we report on a study of the compaction of woven PE fibres. The fibre used for these studies was the same as that used in the previous work, namely CERTRAN® melt spun high modulus polyethylene fibres (formerly known as TENFOR®) manufactured by Hoechst Celanese, U.S.A. Compacted sheets, made from woven PE cloth, were found to have much more balanced properties, with a lower, but balanced in-plane modulus and in-plane strength. The stiffness of these compacted PE sheets, of about 10 GPa, was still much higher than would normally be possible with any unreinforced, or even oriented, polymeric sheet material. In contrast to the situation in polypropylene, where unidirectional compactions are unsuitable owing to the great retraction force in this material, and two-dimensional compactions are necessary to achieve a useful product [9, 10], the motivation here is the properties of the final product, rather than any limitations imposed by the process itself.

Samples were made at temperatures above and below the optimum compaction temperature established from the previous unidirectional studies, and a combination of mechanical measurements and morphological investigations has been used to investigate the properties of these samples in order to establish the optimum compaction temperature for the woven samples.

2. Experimental

2.1. Compacted sheet production

Woven cloth, produced from multifilament yarns of CERTRAN® high modulus melt polyethylene fibres (∼15 μm diameter), was supplied by Hoechst Celanese, U.S.A. The weight average molecular weight of the fibre was 150,000, the polydispersity was 8.8, and the tensile modulus of the fibre, measured at a strain rate of 10^{-4} s^{-1}, was 42 GPa. The woven cloth weight was 175 g/m^2, and was a plain weave construction. The hot compaction process followed broadly that used for the previous polyethylene studies, but for the woven samples a closed matched metal mould was used rather than the open ended mould used for the unidirectional studies [6]. Pieces of cloth, 125 mm square, were cut and stacked into the mould (4 layers for each 1 mm of compacted sheet thickness). The mould was placed into a hot press set at the required compaction temperature, and a pressure of 0.7 MPa (100 psi) was applied. Once the assembly reached the compaction temperature, it was left to dwell for 2 minutes at which time a higher pressure of 2.8 MPa (400 psi) was applied. The assembly was then cooled to below 110°C, still under pressure, and then removed from the press.

The compaction temperature is normally measured by a thermocouple placed into a drilled hole in the matched metal mould. The optimum temperature quoted above from the previous unidirectional tests, of 138°C, was determined in this way. Recent experiments, carried out by placing a thermocouple in between the woven layers during compaction, have shown that the temperature in the assembly is ∼2°C lower than the mould temperature. Therefore, for a number of samples, a thermocouple was placed between the cloth layers during compaction (one side of the mould was removed to facilitate this) to calibrate this temperature difference.

Henceforth, compaction temperatures will be distinguished according to whether this was measured on the mould or in the centre of the fibre assembly.

2.2. Mechanical tests

2.2.1. Peel tests

Samples for T peel tests, (following ASTM D1876), were made by compacting two layers of cloth together, with a thin layer of foil, 10 mm wide, at one end to act as a subsequent starter crack. The samples were subsequently pulled apart, at a crosshead speed of 50 mm/min, using an RDP tensile test machine, and the average peel load was determined.

2.2.2. Tensile tests

The modulus of the compacted plates was measured under tensile loading. Dumbbell shaped specimens were cut from the compacted sheets using a standard cutter (gauge length 25 mm, width 4 mm). Samples were tested using an RDP Howden tensile test machine and a Messphysik video extensometer for measurement of strain. The tensile tests were carried out at a strain rate of 10^{-4} s^{-1}.

2.3. Differential scanning calorimetry

Differential scanning calorimetery experiments were carried out using a Perkin Elmer DSC-7. Partial melting studies were carried out on the original fibre in order to establish the fraction of melted material produced at various ‘compaction temperatures’. In order to replicate the level of constraint seen during compaction, when the woven fibre assembly is under pressure throughout the process, the fibres were wound around a crumpled DSC pan lid and then knotted to hold them at a fixed length. The partial melting tests involved raising the tied fibre bundle from 25°C to a fixed temperature (the ‘compaction temperature’), at a rate of 60 K/min, holding for a dwell time for 2 minutes, and then cooling back to 25°C. A full melting scan was then run at 10 K/min, to ascertain the percentage of melted material achieved at each temperature. Full melting tests, also at a scan rate of 10 K/min, were carried out on compacted samples to establish the percentage of melted material at each process temperature. Although, in principle, it should be possible to choose an optimum compaction temperature from the partial melting experiments, as described above, there is often an offset between the measured mould temperature and the temperature in the centre of the fibre assembly. The thermocouple experiments were used to calibrate this offset for the particular heated press used.

2.4. Morphological studies

Cut surfaces suitable for examination after etching were made with a diamond knife on a microtome. After cutting, specimens were etched for 2 hours under constant agitation with a permanganic reagent consisting of 1% w/v potassium permanganate in a mixture of 10 vols. concentrated sulphuric acid to 4 vols. orthophosphoric acid (Merck reagent, min. 85%) to 1 vol. distilled water [11]. Etched surfaces were either gold coated and examined under a Philips 515 SEM, or else replicas of the etched surfaces were taken with cellulose acetate softened with acetone for TEM (transmission electron microscopy). The dried cellulose acetate films were then coated obliquely with tantalum/tungsten and backed with carbon, after which the cellulose acetate was dissolved away leaving the final replica for examination under the TEM. Examination of the peel test fracture surfaces (not etched) was carried out using the Phillips 515 SEM.

3. Results

3.1. DSC results

The first experiments to be carried out were the partial melting experiments. Constrained bundles of fibre were taken to a fixed temperature, held for 2 min, and then cooled. Fig. 1 shows the subsequent melting endotherms for these samples. These results are comparable to those published previously [12], in a study of the effects of cross-linking on compaction behaviour: the only difference is that the previous melting results were for unconstrained samples. The constrained samples show a shift to higher temperatures, due to the superheating effects of the constraint, but otherwise the curves are very similar.

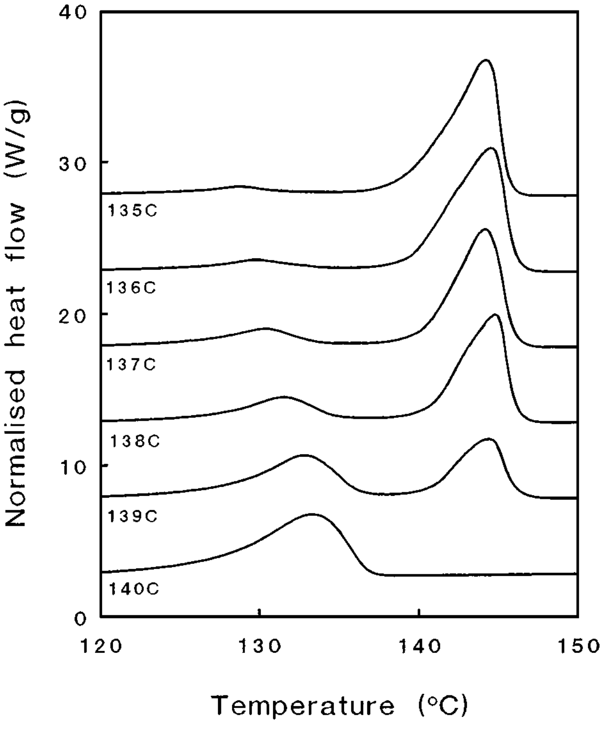
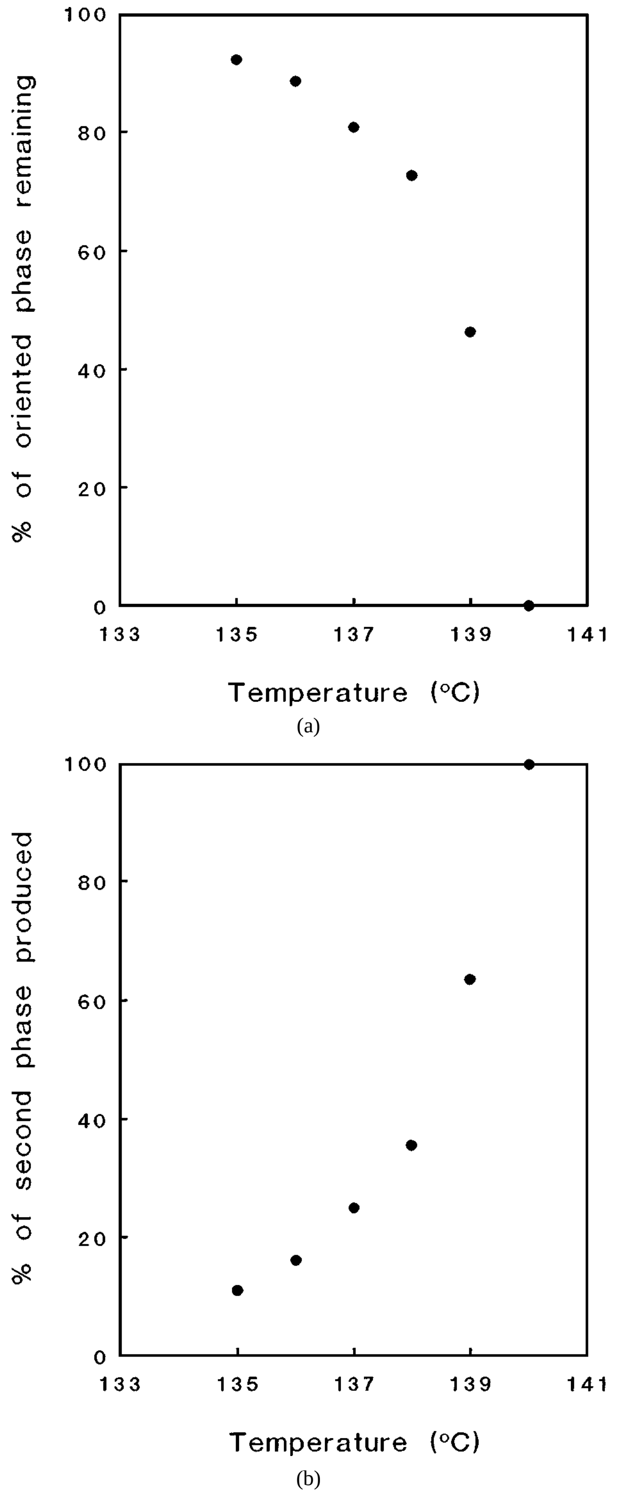


Figure 1 DSC traces for partial melting experiments.

The series of scans in Fig. 1 show that, with increasing temperature, the fraction of melted and recystallised material increases at the expense of the original oriented fibre phase. Whereas the position of the peak due to the original oriented phase, at a temperature of ~144°C, is unaffected by the partial melting, the lower temperature peak, due to the melted and recrystallised material shifts up in temperature with increasing soak temperature. If we attribute the position of the peaks to crystal size, then we can surmise that as the amount of melted material increases, so the crystal size increases. However, the peak position can also be affected by constraint, and so further work would be required to confirm the mechanism for this shift in the lower peak.

Interestingly the crystallinity of the melted material (completely melted at 140°C) is lower than the crystallinity of the original fibre, with values of the enthalpy ΔH of 164 and 237 J/g respectively. We can therefore express the changes seen in Fig. 1 in two ways: either as a percentage decrease in the original oriented phase (Fig. 2a), or as a percentage increase in the melted and recrystallised phase (Fig. 2b). These two relationships were formed by normalising the percentage of the oriented phase to 237 J/g and the melted and recrystallised phase to 164 J/g. Both show essentially the same information, that there is a non-linear increase in the melted and recrystallised phase with increasing temperature. Although there is a roughly linear decrease in the oriented phase up to 138°C, above this there is a sharp transition and by 140°C the fibre is completely melted after a 2 minute soak. This transition has important implications, for whereas the temperature required for optimum compaction of unidirectionally arranged fibres (~10% melted or 135–136°C) is well away from this transition, the temperature needed to produce the higher fraction of melt required to fill the gaps in a woven structure is bound to be closer to the transition. The closer to the transition the optimum temperature is, the better the temperature control over the required compaction area will need to be, for if the temperature passes the transition, complete melting of the sample will occur. It is worth a comment that in our work on the effect of crosslinking on compaction behaviour [12], it was established that the crosslinked materials did not show this sharp transition in melting behaviour, but rather a monotonic decrease in the fraction of the oriented phase (and the corresponding increase in the melted and recrystallised phase) with increasing temperature, and an associated larger processing window.

There is an issue here on the quoted value of the optimum compaction temperature. In our previous published work on unidirectional fibre arrangements, where we measured the temperature of the mould during processing, optimum properties were obtained at a temperature of 138°C, and this gave ~10% melted and recystallised material. However the DSC studies shown



(a)

(b)

Figure 2 (a) Percentage of the oriented fibre phase remaining after partial melting tests; (b) Percentage of the melted and recystallised phase formed vs temperature.

above in Fig. 1, suggest a lower temperature is required to get 10% melted material (135/136°C). Trials carried out by placing a thermocouple in the centre of the fibre assembly during compaction confirmed both sets of results, for when the mould temperature was 138°C, the inner temperature was measured at 136°C (similar to the DSC measurements), and this sample gave ∼10% melted and recystallised material. It is therefore more consistent to consider the fraction of melted and recrystallised material produced, rather than the compaction temperature.

3.2. Mechanical results

3.2.1. Interlayer adhesion

In the compaction process there is always a trade-off between the loss of the oriented phase, and the associated loss of stiffness and strength, and the development of inter-fibre bonding due to the increase in the melted and recrystallised phase. Peel tests were carried out for samples made over a range of compaction temperatures to assess this trend. After testing, the samples were analysed using the DSC to establish the percentage of melted material. The choice is whether to plot the results against the loss in the oriented phase (as Fig. 2a), or the increase in the melted phase (as Fig. 2b). It is perhaps more appropriate to plot the peel strength values vs the amount of the recrystallised phase, as it is this factor which controls the development of the interlayer bonding.

Fig. 3 shows the results of the peel tests. The peel load traces always showed a sawtooth appearance, with the load rising to a peak and then dropping to a lower value, most likely due to the vagaries of the contact of the two woven surfaces (see Fig. 4 later). The error bars shown on the figure, therefore indicate the maximum and minimum values measured, corresponding to the peaks and troughs of the peel load traces.

It appears that the peel strength increases quite rapidly initially, but then levels out at ∼30% of the melted phase. These results mirror, to some extent, the results from the unidirectional tests [6], where the transverse strength (the inter-fibre strength), initially rose quickly, then levelled off, and then rose again when the sample was completely melted. The point where the peel load levels out, is very close to the sudden transition seen in Fig. 2, suggesting that to get the best interlayer bonding one needs to get as close as possible to the upper limit temperature (138°C in the fibre assembly).

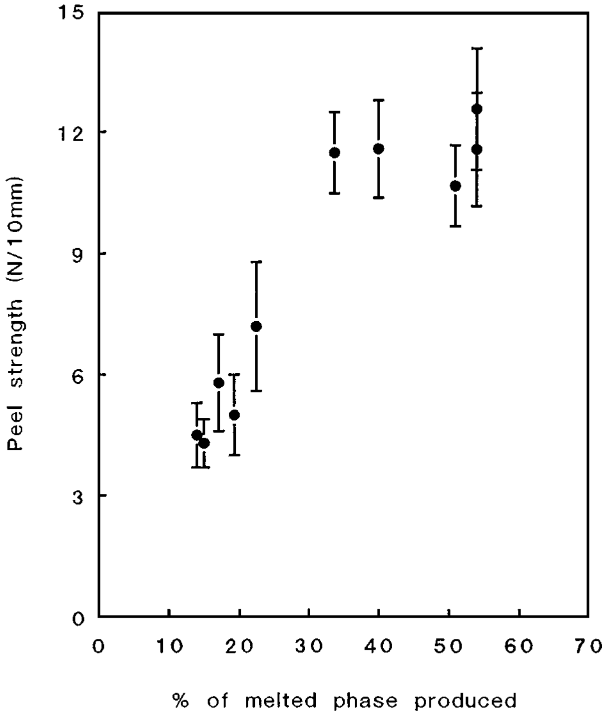


Figure 3 Peel strength for a 10 mm strip vs % of the melted phase produced.

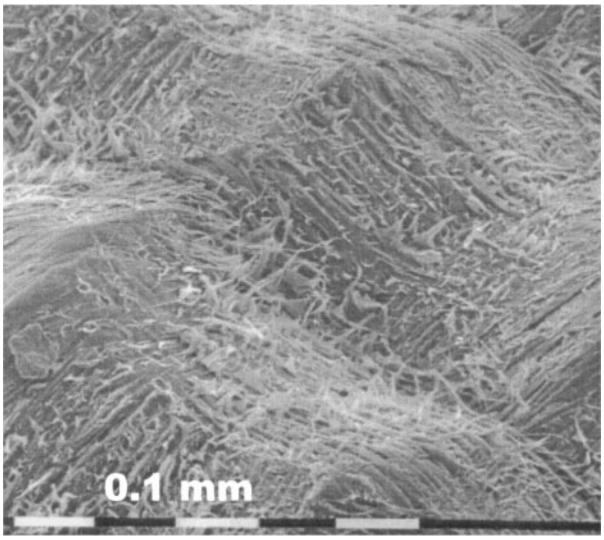


Figure 4 Fracture surface for typical peel samples.

The key question is what level of bonding is required? The interlayer is liable to be the weakest link in a compacted woven material, because there is only a thin layer of melted and recrystallised material to form the bond. It is clear that ∼20–30% of melted material develops a good interlayer bond. The level of bonding seen at 25% melted and recystallised material, 7 N for a 10 mm strip, is lower than that we have obtained with compacted woven polypropylene samples [13] at ∼10 N for a 10 mm strip, but very reasonable. The values seen with the higher percentages of the melted material, at around 11 N for a 10 mm strip, are very similar to the polypropylene results. It is likely that the mechanical properties of the melted and recrystallised material are also an important factor in controlling the interlayer peel strength.

Fig. 4 shows a typical failure surface from one side of a peeled sample (23% melted). The 'bumpy' nature of the woven surface is very clear, with hills and valleys at least 300 μm apart. The failure surface shows clearly that the melted and recrystallised material has been deformed significantly during the peel test. This evidence of stress transfer, confirms the excellent bond that had been developed between the melted material and the oriented fibres. There is little, if any, fibre disturbance or lifting, which suggests that the peel strength is purely governed by the percentage and strength of the melted and reformed phase. Obviously, although we have 23% melted material in this composite, only a small proportion of this is present at the interface between the woven layers (basically the amount of melted material that is produced around each fibre). If we assume an average fibre diameter of 15 μm [7], and a volume fraction of melted material of ∼25%, then the layer of melted material would be 2 μm on each fibre, or a layer 4 μm thick between fibres. This is a very small layer if all the stress is concentrated there, as suggested by Fig. 4.

Another important issue in the development of interlayer bonding could be the flatness of the weave. If only a thin film of melted material is produced, the flatter the weave, the more likely a good bond will be developed. Although only one weave style has been investigated here, work on woven polypropylene tapes has suggested that flatter weaves give a higher bond strength, and that for rougher weaves a higher compaction pressure can increase bond strength, presumably by bringing the interlayer surfaces into closer contact and closing up internal spaces.

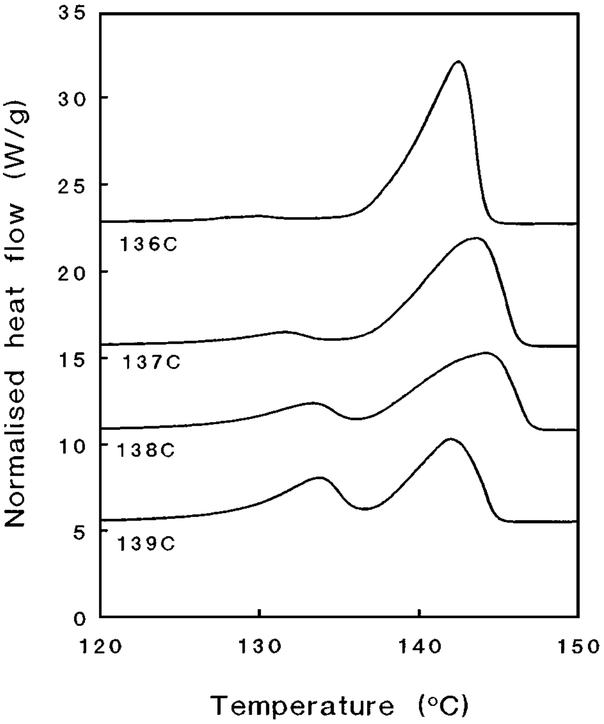


Figure 5 DSC melting endotherms for tensile samples.

3.2.2. Tensile modulus measurements

Samples were compacted for the tensile tests at 136, 137, 138 and 139°C (measured in the centre of the fibre assembly), and as with the peel tests, DSC measurements were carried out to determine percentage of melted material produced in each sample. Fig. 5 shows the DSC traces for these four samples: the percentage of melted material was 6, 14, 32 and 49% for 136, 137, 138 and 139°C respectively. The general trend is as seen in Fig. 1, for the partial melting studies, with increasing melted material produced with increasing compaction temperature. There are, however, a couple of interesting differences. Firstly, it is seen that the higher melting peak, due to the original oriented phase, is at a lower temperature than the corresponding peak from the partial melting studies carried out in the DSC (Fig. 1). Secondly it is seen that, as opposed to Fig. 1, the higher melting peak shifts up with increasing temperature for the first three compaction temperatures. The difference in the two sets of data is due to the effects of constraint. In the partial melting studies, the fibres were constrained by winding them around a former, whereas here the compacted samples were tested in the DSC unconstrained. Therefore for the unconstrained samples, as the percentage of melted material increases, the constraint increases and so the melting peak of the oriented peak shifts to higher temperatures. A similar, albeit much larger, effect was seen in the work on compaction of woven polypropylene tapes [9].

Fig. 6 shows the tensile modulus measured for these four samples. Also shown for comparison, is

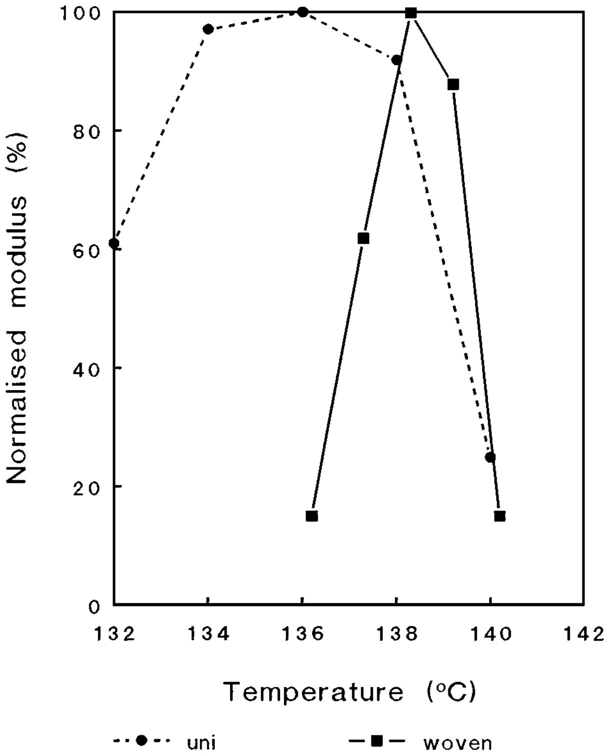


Figure 6 Normalised tensile results for unidirectional and woven samples.

the longitudinal modulus for unidirectionally arranged fibres [6]. To allow a direct comparison, the results for the two fibre arrangements have been normalised to the maximum modulus measured, which was 9.9 ± 0.3 GPa for the woven fibre materials from the current study, and 36 ± 4 GPa for the previous unidirectional work [6]. The compaction temperature for the unidirectional samples made previously has been adjusted by the 2°C offset between the measured mould temperature and the assembly temperature: it is the assembly temperature which is used as the *X* axis on Fig. 6. The first impression is that for the woven fibre materials, there is a much smaller temperature range over which good materials can be made. This is a confirmation of the peel test results, which showed that the best bonding is produced at the highest possible temperature before the fibre melts. This will also be confirmed by the following morphology studies.

As the temperature window for optimum compaction is narrow, it is important to achieve an even temperature distribution through the woven polyethylene layers, as a through thickness temperature gradient could lead to regions of either incomplete compaction, or complete melting of the fibres. Morphological investigations showed an even distribution of melting through the sample thickness, suggesting that an even temperature had been achieved.

3.3. Morphology

In the work on unidirectional specimens, the morphology developed at the optimum temperature of 138°C (temperature measured on the mould - ∼10% melted phase) was found to have the following features as displayed in Fig. 7. The fibre in the centre of the picture is typical in that it is touching its neighbours on all sides, but there is sufficient melted material to fill the gaps, which has recrystallised so as to retain the same overall molecular orientation as the fibres themselves. At lower compaction temperatures, fibres are deformed into polygonal cross section in order to fill the space, and there is insufficient melt formed to bind the composite to give good transverse strength. At higher compaction temperatures, a much higher proportion of the melted and recrystallised material was produced, leaving the fibre cross-sections circular. All the fibres touched and some had started to melt internally in regions of free volume. The recrystallised melt developed banded structures but remained in crystallographic register with the fibres at the mutual interface [8]. The internal structure of the fibre is etched into craters where the permanganic reagent has penetrated longitudinal density deficient regions in the fibres [14].

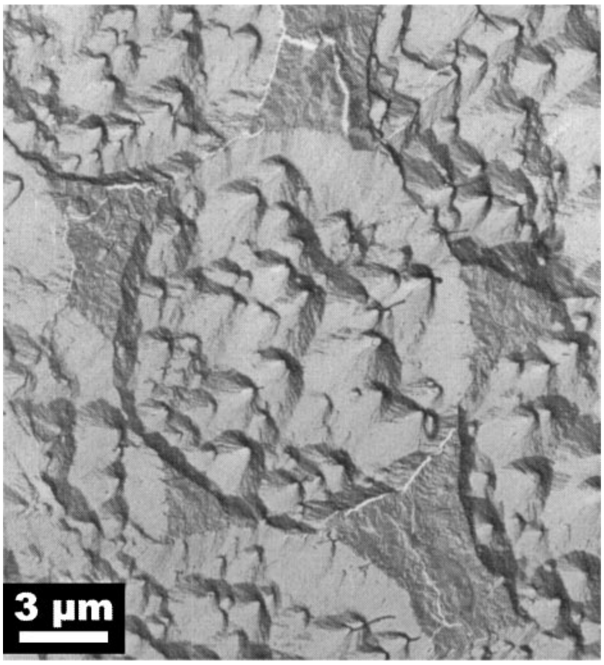


Figure 7 TEM of transverse section of an optimal (138°C in mould) unidirectional sample, ∼10% melted.

The woven nature of the material compacted at 138.5°C on the mould (∼15% melted) is apparent in Fig. 8a, where bundles of transverse fibres appear light and the longitudinal fibres appear darker. This structure and appearance is very similar to the 2-dimensional polypropylene compactions. The transverse bundles display sharp tips in the horizontal direction, suggestion that the bundles as a whole have been considerably re-shaped during the compaction process, but more detail is needed to show to what extent this occurs by relocation of fibres within bundles and how much by deformation of the fibres themselves.

The more detailed structure of this compaction is far from uniform. A portion of the specimen containing a variety of features is shown in Fig. 8b. One thing that becomes apparent is that the orientations of the two sets of fibres are far from uniform. For example at A a bunch of transverse fibres is seen emerging at the normal angle, giving circular cross sections while at B a group of fibres has been moved sideways, perhaps as alternating bundles of fibres are moved against one another during

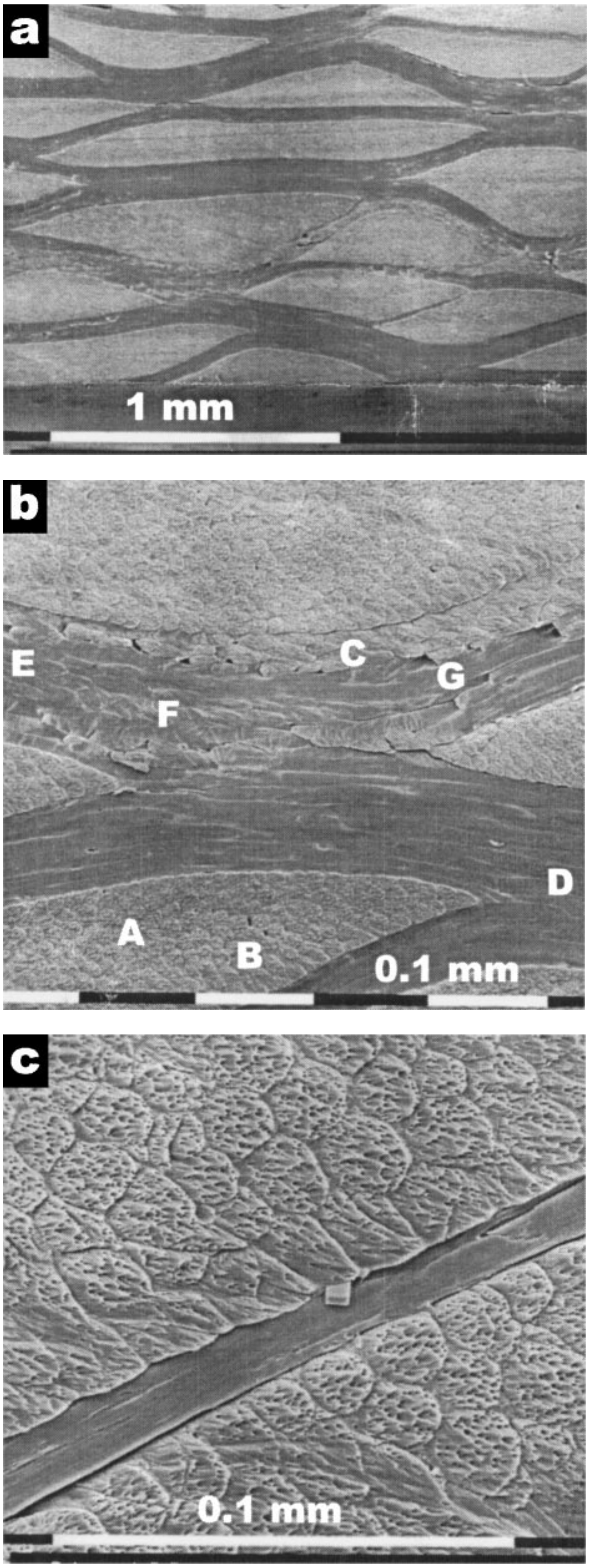


Figure 8 SEM pictures of 2D compaction, ∼15% melted (a) general view showing woven nature of material; (b) more detailed picture with annotations, see text; (c) showing polygonal sections of transverse fibres, with distortion where crossed bundles of fibres meet.

the compaction process. They therefore show elliptical cross sections. In some cases, as at C, they become grossly deformed in the process. Corresponding features are seen in the longitudinally displayed fibres, where those at D are at the normal angle showing their full length, at E they are moved sideways and display long elliptical cross-sections, while at F they have undergone severe deformation evidenced by kink bands within the fibres themselves.

Incomplete compaction is also evidenced by the voiding at G. The occurrence of this voiding in the two-dimensional specimens implies that the geometry of this compaction, in particular the mismatch where two orthogonal bundles of fibres meet, will lead to a greater proportion of vacancies so that the ∼10% of melt is insufficient to fill these, contrary to the one-dimensional situation. However, the total deficit does not appear in terms of voids in the compaction: rather than the rather few voids as at G in Fig. 8b, most of it is taken up by deformation of fibres as at the lower compaction temperatures in one dimensional systems [8]. In many areas the circular fibre sections are collapsed into polygons as at top left in Fig. 8c, though in addition to this mode of deformation the two dimensional structure allows for sideways movements and kinking and shearing of the fibres, which tends to occur most where two orthogonal bundles of fibres meet.

Many of these features can be seen in greater detail in the TEM pictures in Fig. 9. In Fig. 9a there

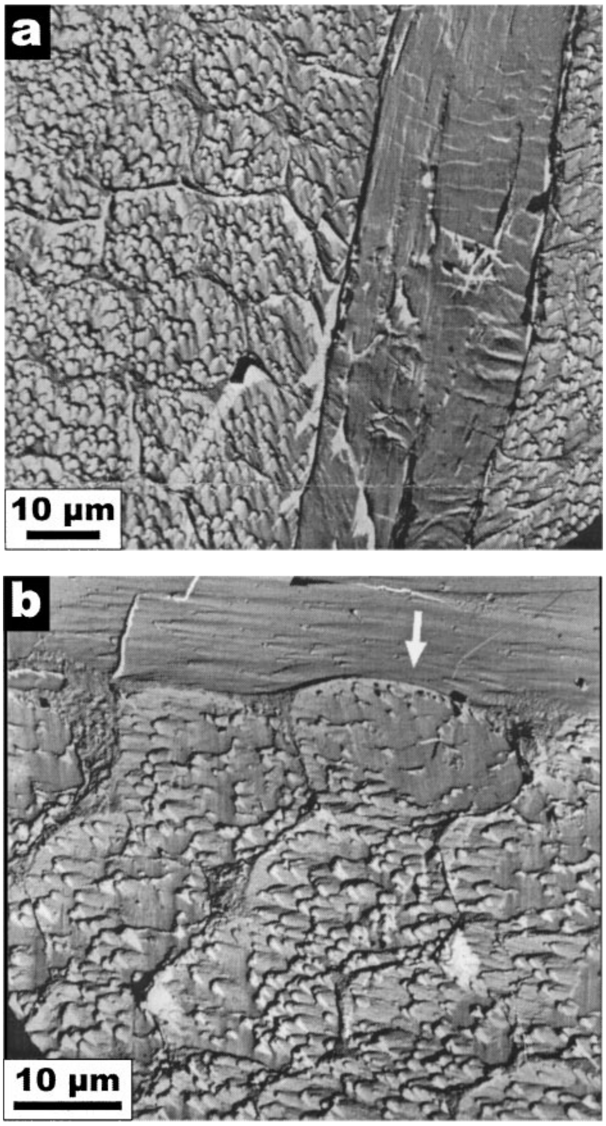


Figure 9 (a) TEM picture of 2D compaction, ∼15% melted. (a) region with poor melt filling between 90° bundles; (b) with better melt filling. For details see text.

is displayed a region where there is insufficient melt formed to fill the gaps between the fibres, and the transverse fibres at the left of the figure have been squashed into polygonal cross sections, a feature also observed in one-dimensional compactions below the optimum, for example at 136°C [8]. As one moves right towards the longitudinal fibres, the transverse ones become increasingly distorted, and at the boundary itself there is no actual welding of the fibres, so that the etched surface contains a deep narrow groove. The replication material has penetrated this and casts the long white "shadows" visible at the boundary. The longitudinal part appears to consist of two fibres, and the one on the right has been heavily stressed resulting in the numerous bands running across it. Fig. 9b shows a junction between two bundles in a region where there is more melt filling visible between the transverse fibres, but here their structure appears different to the classic appearance in Fig. 7, largely due to their being pushed off angle and so displaying elliptical cross-sections. According to the etching mechanism, the craters becomes less prominent as the angle increases. Some deformation of the fibres has occurred where a transverse fibre has to some extent indented a longitudinal one (arrowed).

The compaction at 138°C (measured in the fibre assembly - $\sim$25% melted material) shows much more melt between the fibres: however, this is not uniform, and as Fig. 10a shows, there are regions which have not filled well with melt, and have undergone considerable stress, leading to the kink bands in the longitudinal fibres visible at top right of picture. However, most regions are well melt filled: the transverse fibres in Fig. 10b resemble those in Fig. 7, though there are some voids, such as those at the left and right of picture, which are probably formed as the melt crystallises, reduces in specific volume, and retracts from certain regions. Similar voids are observed in longitudinal section as in Fig. 10c, formed in regions of melt which has recrystallised in the form of lamellae growing outwards from the fibre (arrowed). Such voiding has almost never been observed in one-dimensional compactions. Looking more closely at such regions, the lamellae are observed to grow epitaxially from the fibre surface as in the one-dimensional compactions, but this orientation is not maintained to more than about 2 μm from the fibre surface. Nevertheless, in regions where melt is found between longitudinal and transverse fibres, a melt pocket such as the left-most one observed in Fig. 9b can be seen to be divided into two regions with the lamellae seen edge-on next to the longitudinal fibre and flat-on next to the transverse ones. However, the fibres at these junctions are generally so distorted that the ideal appearance of two orthogonal sets of lamellae is not always observed

We can therefore summarise the morphological and the mechanical results by concluding that at the optimum temperature previously established for the unidirectional samples, where $\sim$10% melted material is produced, good bonding is achieved within the aligned fibre bundles, but insufficient melted material is produced to give good interlayer bonding. Optimum bonding and modulus is achieved in the woven samples at $\sim$2°C above this temperature, where $\sim$25% of melted material is produced. The drawback is that the temperature range over which good materials can be made from the woven PE fibre cloth is quite narrow, as this temperature is very close to the point where the fibre melts completely.

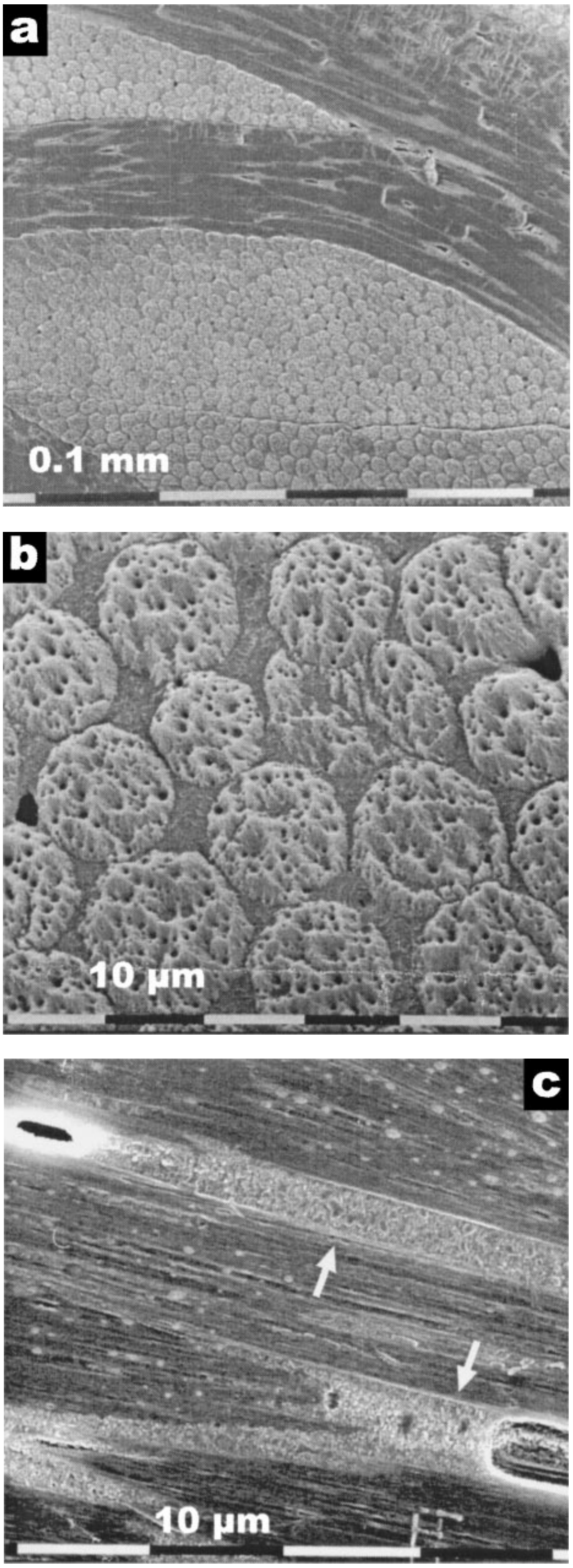


Figure 10 SEM picture of 2D compaction, $\sim$25% melted (a) general view; (b) transverse morphology in detail; (c) longitudinal morphology in detail.

4. Conclusions

The hot compaction of woven 2D high-modulus PE fibres produces materials which have a lower in-plane modulus but a higher in-plane strength compared to compacted unidirectionally arranged fibres. The stiffness of these compacted woven PE sheets is considerably higher than is normally possible with any unreinforced, or even oriented, polymeric sheet material.

In the previous studies on unidirectional fibres, a compaction temperature of 138°C on the mould (136°C in the fibre assembly) was established as the optimum temperature by producing ∼10% melted and recystallised material. For the woven samples investigated here, this was found to be insufficient, for while the individual fibre bundles were well compacted, the interlayer region required more melt. Morphological analysis showed there was also a degree of variability in melt filling over the sample area.

The optimum temperature for compaction of woven 2D samples was found to be ∼2°C higher than for the unidirectional samples: the downside is that this temperature is close to the upper limit where significant melting occurs.

The interlayer region of a compacted woven composite is the weakest region, since it only contains a thin layer of melted and recrystallised polyethylene.

References

1. G. HINRICHSEN, S. KREUZBERGER, Q. PAN and M. RATH, *Mech. Compos. Mater.* **32** (1996) 719.
2. C. MARAIS and C. P. FEILLARD, *Compos. Sci. Technol.* **45** (1992) 247.
3. D. ROLEL, E. YAVIN, E. WACHTEL and H. D. WAGNER, *Compos. Interf.* **1** (1992) 225.
4. A. TEISHEV, S. INCARDONA, C. MIGLIARESI and G. MAROM, *J. Appl. Polym. Sci.* **50** (1003) 503.
5. F. V. LACROIX, M. WERWER and K. SCHULTE, *Composites Part A* **29** (1998) 371.
6. P. J. HINE, I. M. WARD, R. H. OLLEY and D. C. BASSETT, *J. Mater. Sci.* **28** (1993) 316.
7. R. H. OLLEY, D. C. BASSETT, P. J. HINE and I. M. WARD, *ibid.* **28** (1993) 1107.
8. M. A. KABEEL, R. H. OLLEY, D. C. BASSETT, P. J. HINE and I. M. WARD, *ibid.* **29** (1994) 4694.
9. P. J. HINE, I. M. WARD and J. TECKOE, *ibid.* **33** (1998) 2725.
10. J. TECKOE, R. H. OLLEY, D. C. BASSETT, P. J. HINE and I. M. WARD, *ibid.* **34** (1999) 2065.
11. M. M. SHAHIN, R. H. OLLEY and M. J. BLISSETT, *J. Polym. Sci. Polym. Part B: Polym. Phys.* **37** (1999) 2279.
12. M. BONNER, P. J. HINE and I. M. WARD, *Plastics, Rubber and Composites, Processing and Applications* **27** (1998) 58.
13. P. J. HINE, M. BONNER, B. BREW and I. M. WARD, *ibid.* **27** (1998) 167.
14. M. I. ABO EL-MAATY, R. H. OLLEY and D. C. BASSETT, *J. Mater. Sci.* **34** (1999) 1975.

*Received 1 February
and accepted 23 February 2000*