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Composites Science and Technology 66 (2006) 1953–1962
COMPOSITES SCIENCE AND TECHNOLOGY
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Flexural and interlaminar mechanical properties of unidirectional liquid crystalline single-polymer composites ☆

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Received 18 November 2005; received in revised form 2 January 2006; accepted 16 January 2006
Available online 3 March 2006

Abstract

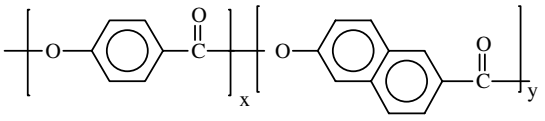
New single-polymer composites were obtained by combining two types of wholly aromatic copolyester liquid crystalline fibres having melting points differing by about 40 °C. Vectran® M and HS fibres were co-wounded on an open square metal frame in order to obtain a unidirectional preform with an equal volume fraction of both fibres. In a second stage, the preform was consolidated under pressure at temperatures ranging from 260 up to 285 °C. Under the selected processing conditions, one component (Vectran® M) formed a continuous matrix while the other one (Vectran® HS) retained its fibrous form and most of the original mechanical properties.

In the longitudinal direction, the bending modulus resulted to be substantially independent of the consolidation temperature (T_c) with an average value of about 39 GPa, while the maximum stress sustained in the outer layer increased from 157 MPa, at $T_c = 260$ up to 259 MPa, at $T_c = 285$ °C. Concurrently, all the matrix related properties such as the transversal bending modulus, the transversal maximum stress in the outer layer, and the interlaminar shear strength (ILSS) markedly improved as the consolidation temperature rose. In particular, both the maximum transversal bending stress and ILSS values increased by a factor of 2.8 as T_c increased from 260 up to 285 °C. Moreover, the consolidation temperature resulted to slightly affect the Charpy impact resistance of the investigated composites that, up to $T_c = 280$ °C, oscillated around an average value of 79 kJ/m^2. On the other hand, the consolidation temperature markedly influenced the energy absorbing mechanisms. In fact, the ductility index showed a maximum value of 9 at $T_c = 265$ °C and then it monotonously decreased down to a minimum value of 4.5 at $T_c = 285$ °C.

Keywords: A. Liquid crystalline polymers; A. Vectran; A. Single-polymer composites; E. Filament winding; B. Mechanical properties

1. Introduction

Single-polymer composites consist of a matrix and fibres of the same chemical composition. Over the past 30 years, this concept has been extensively investigated with polyethylene [1–35]. More recently, some attempts have been also made with other polymers like polypropylene [36–42], poly(ethylene-terephthalate) [43–45], poly(ethylene-naphthalate) [46], and liquid-crystalline copolyesters [47–49]. Copolymers of 4-hydroxybenzoic acid (HBA) and 2-hydroxy-6-naphthoic acid (HNA) with the following formula



are the basis of the liquid-crystal engineering resins commercialized in 1985 by Hoechst Celanese Corporation (USA) under the trade name of Vectra®. Since 1986, Hoechst Celanese and Kuraray Company Ltd. (Japan) have jointly evaluated these materials in fibre applications. Vectran®

☆ Partly presented at the 3rd International Conference on Science and Technology of Composite Materials COMAT 2005, 11–14 December 2005 Buenos Aires, Argentina.

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doi:10.1016/j.compscitech.2006.01.015

high-performance fibre is produced from the Vectra® LCP [50] with a HBA/HNA molar ratio of 73/27 [51–53]. At a present, the only examples of single-polymer composites consisting of liquid crystalline polymer (LCP) available in the scientific literature are the works of Hine and Ward [47,48] and of Stellbrink et al. [49], both focused on the hot-compaction of polyester–polyarylate Vectran® fibres.

In the hot-compaction process, a fraction of the surface skin of an array of oriented polymer fibres or tapes is melted under relatively low contact pressure and the structure is then consolidated by the application of a substantially higher pressure for a short time [48,54]. On cooling, the recrystallized polymer acts as a binder, like the resin matrix in a conventional heterogeneous composite. Ward and Hine firstly reported on the preparation of LCP unidirectional [47] and plane-weave [48] single-polymer composites by hot-compaction of Vectran® HS fibres. For unidirectional hot-compacted LCP single-polymer composites elastic moduli of 97.2 and 3.24 are reported for the longitudinal and the transversal directions, respectively [47]. For plane-weave Vectran® based composites tensile modulus and strength values of 7 and 0.13 GPa, respectively, are reported [48]. The hot-compaction of Vectran® HS filament-wounded preform has been also investigated by Stellbrink et al. [49]. At an hot-compaction temperature of 290 °C they were able to obtain 0/90/0° cross-ply laminates with tensile modulus and strength values as high as 33.3 and 0.616 GPa, respectively. The use of temperature and pressure to control the melting of the outer surface layer of polymeric fibres implies that the processing window for the hot-compaction process is quite narrow and this may constitute a problem for the industrial transfer of this technology. Moreover, with this approach it is very difficult, if not impossible, to preserve the original mechanical properties of the polymeric fibres.

In the first part of this paper, we introduced a new method for the preparation of single-polymer composites based on liquid-crystalline wholly aromatic copolyesters Vectran® fibres [55]. Unidirectional composites have been obtained with two different commercial Vectran® fibres, as-spun or thermally treated, characterized by markedly different melting points. A processing window of about 40 °C allowed us to successfully adopt a co-woven/hot consolidation process for the composites production. Both longitudinal and transversal tensile mechanical properties resulted to be markedly dependent on the consolidation parameters such as temperature and pressure [55].

In this paper, we report on the effects of the consolidation temperature on the flexural and interlaminar properties of Vectran® based LCP single-polymer composites.

2. Experimental

2.1. Materials and composites preparation

Composites were prepared using two different commercially available Vectran® fibres, and namely:

- Vectran® M, linear density of 750 denier (1 denier = 9 g/km), 150 filaments per yarn;
- Vectran® HS, linear density of 1500 denier, 300 filaments per yarn.

These fibres have the same chemical composition, as revealed by the FT-IR spectra reported in Fig. 1, but markedly different properties. A detailed description of the main thermomechanical properties of these fibres is reported in the first part of this paper [55], and some data are briefly summarized in Table 1. Optical micrographs of polished transversal cross-sections of both type of fibres are reported in Fig. 2. Both fibres appear to have an almost circular cross-section. The diameter measured on 250 fibres results to be 25.5 ± 2.1 μm for Vectran® M and 25.1 ± 2.1 μm for Vectran® HS. These values are in good agreement with the microscopic observation previously performed along the fibre axis [55].

The preparation of the composites is carefully described in the first part of this paper [55], and it can be briefly summarized as follows. Both Vectran® M and HS fibre were co-wounded on a open metal frame (see Fig. 3a). The adopted winding sequence, that is represented in Fig. 3b, consisted of twelve winding passages purposely chosen in on order to reach an equal volume fraction of both Vectran® M and HS fibres. The wounded preform was then inserted between the plates of a Carver Laboratory Press

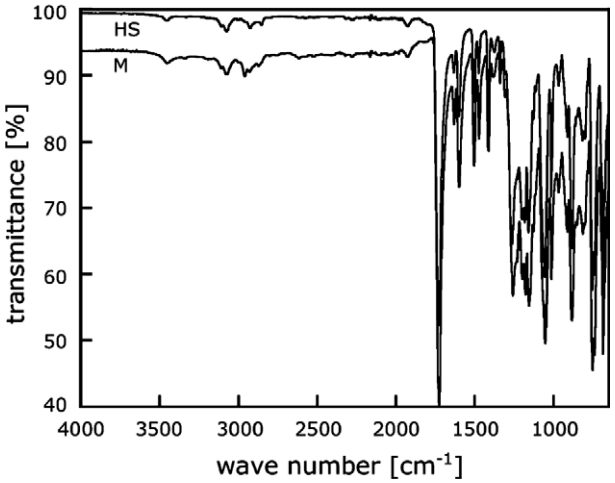


Fig. 1. FT-IR spectra of Vectran® M and HS fibres.

Table 1
Some properties of Vectran® M and HS fibres (taken from [55])

Property	Vectran® M	Vectran® HS
Melting temperature [°C][a]	276	315
Tensile modulus [GPa][b]	83.7	88.8
Weibull scale parameter [MPa][c]	1309	3374
Weibull shape parameter	8.28	6.13

[a] Measured by DSC analysis.
[b] Values extrapolated from data obtained on single fibres tested at various gage lengths.
[c] Referred to a 25 mm gage length.

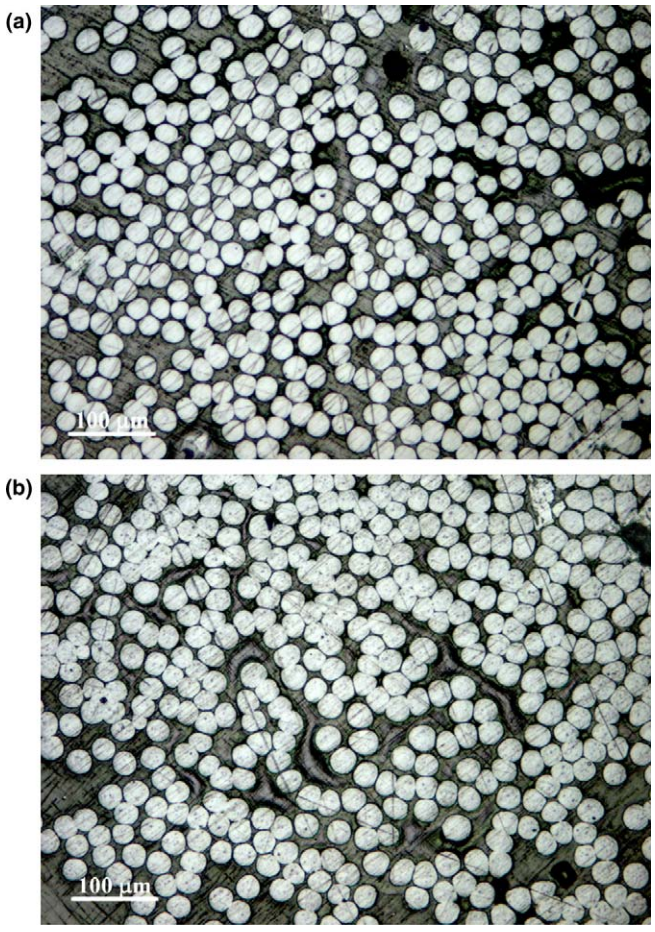


Fig. 2. Optical micrographs of the un-etched polished cross-sections of: (a) Vectran® M; and (b) Vectran® HS fibres.

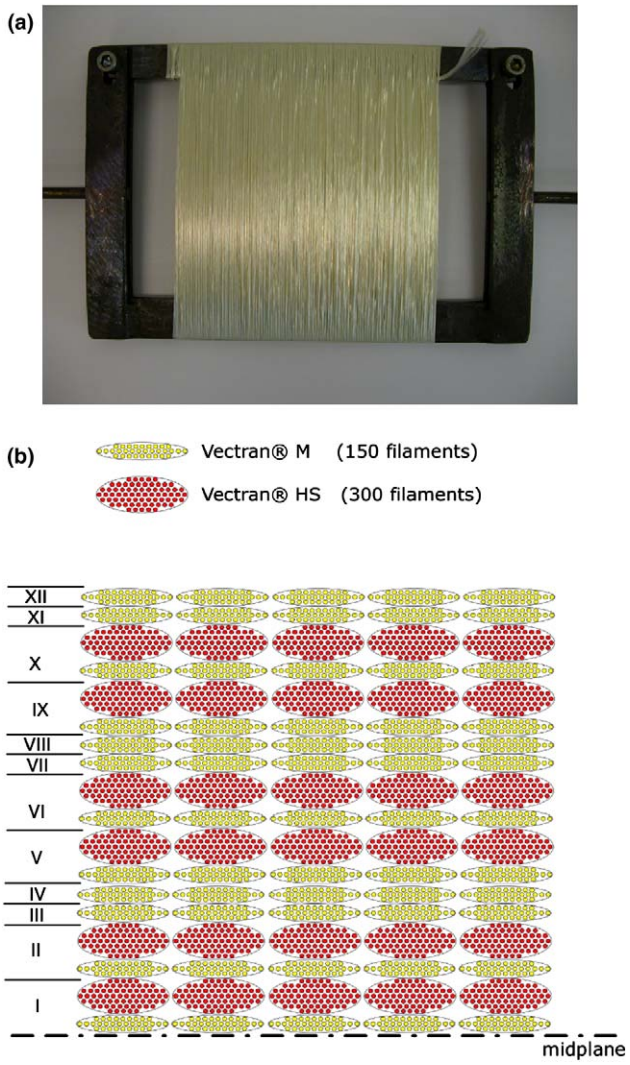


Fig. 3. Schematic of the manufacturing process of the co-woven perform by filament winding: (a) collapsible flat open square frame; (b) sequence of fibres deposition.

and consolidated according to the processing scheme described in Fig. 4. When a consolidation temperature T_c was reached, the pressure was rapidly increased up to 4.4 MPa for a short period of 30 s. In this work the consolidation temperature was changed in the range from 260 up to 285 °C and the resulting composite sheets presented thickness values in the range from 2.45 to 1.89 mm, depending on the consolidation temperature.

2.2. Testing procedures

Three point bending tests were conducted in accordance to the ASTM standard D790 on bars of rectangular cross-section resting on two supports and centrally loaded by means of a loading nose. Specimens 90 mm long and 15 mm wide were obtained along both the longitudinal and the transverse directions. A span length of 76 mm assured a span-to-depth ratio of at least 30, and a cross-head speed of 32 mm/min was adopted. Tests were performed at room temperature with an Instron 4502 universal testing machine on at least three specimens for each sample. Longitudinal specimens were tested with a 1 kN load cell, while transversal specimens were tested with a 0.1 kN load cell.

Short beam shear test were performed on small bars of rectangular cross-section. Specimens 36 mm long and 12 mm wide were machined out of the composite plates along the longitudinal directions. A span length of 24 mm assured a span-to-depth ratio lower than 13. Test were performed at room temperature under a cross-head speed of 1 mm/min. The Instron 4502 universal testing machine was equipped with a 1 kN load cell.

Charpy impact tests were performed on tests bars of rectangular cross-section, 90 mm long and 7 mm wide. Thinner specimens for the impact tests were prepared by limiting the winding sequence to the IV step, that provided sheets thickness after consolidation in the range from 0.82 to 0.67 mm [55]. Tests were performed by a Charpy instrumented pendulum CEAST model 6549. Specimens were supported to the machine anvils at a span length of 40 mm and broken by a single swing of the pendulum with the impact line midway between the supports in the flatwise direction. The striking nose of the pendulum was charac-

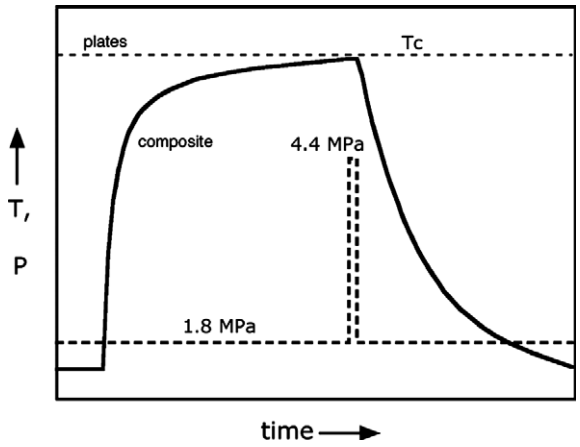


Fig. 4. Schematic of the processing temperature and pressure profiles.

terized by an included angle of 30° and the tip was rounded to a radius of 2 mm. The striking hammer impacted the specimens at a speed of 2 m/s and with a kinetics energy of 1.91 J. Load–time data points were acquired at a sampling time of 0.08 ms over a period of 50 ms. At least six specimens were tested for each experimental condition.

3. Results and discussion

3.1. Composites microstructure

The optical micrographs of un-etched polished cross-sections of composites consolidated at various temperatures are collected in Fig. 5 at various magnification levels. First of all, it is interesting to note that Vectran® HS fibres maintain their fibrous morphology at each of the investigated consolidation temperature. At the same time, it clearly emerges that Vectran® M fibres completely loose their fibrous structure even at the lowest consolidation temperature of 265 °C. On the other hand, the optical micrographs of composites compacted at 260 and 265 °C indicate that the adopted temperature is to low to obtain a satisfactory consolidation process. In fact, a number of macro cracks located inside the original Vectran® HS yarns can be observed (Fig. 5, a1 and a2). At higher magnifications (Fig. 5, b1 and b2) it clearly appears that the matrix made of Vectran® M molten fibres is not able to flow and efficiently bind the Vectran® HS fibres. Moreover, the consolidation temperature is too low to induce any hot-compaction phenomenon among Vectran® HS fibres. At consolidation temperatures of 270 °C or higher, the micro cracks practically disappear and the Vectran® HS fibres seem to be quite homogenously bounded by the Vectran® M matrix. Nevertheless, it is worthwhile to note that Vectran® M matrix is not able to flow in the intertices between the Vectran® HS fibres, but it rather plays as a binder between the individual Vectran® HS yarns. The optical micrographs indicate that a consolidation temperature of 265 °C is enough to melt the Vectran® M matrix but not to force it to flow between the individual Vectran® HS fibres that completely maintain their original shape. At 280 °C Vectran® M matrix partially flows and bind the Vectran® HS fibres that also appear to be slightly deformed in correspondence of the points of contacts.

The observed changes in the microstructure are also accompanied by macroscopic changes in the composite sheets, such as variations of their thickness, that markedly decreases as the consolidation temperature rises (see Fig. 6). Interestingly enough, the sheet thickness appears to be practically independent of the consolidation temperature up to 270 °C, and then it linearly decreases with the consolidation temperature. This behaviour can be interpreted by considering that for temperatures higher than 270 °C the Vectran® M molten fibre assume a viscosity sufficiently low to flow and to be partially squeezed out of the composite plates. The Vectran® HS fibre volume fraction can be estimated by assuming that its value is 0.5 at the lowest consolidation temperature, and that the thickness variations can be attributed to a flow of Vectran® M matrix out of the composite sheets. Under this hypotheses it is possible to compute that Vectran® HS fibre volume fraction is increasing up to 0.65 with the consolidation temperature in the way reported in Fig. 6.

3.2. Three point bending test

The modulus and maximum stress sustained in the outer layer, as measured by three-points bending tests on specimens with the main axis oriented along the fibre direction, are reported in Fig. 7 as a function of the consolidation temperature. It is seen that the bending modulus is substantially independent of the consolidation temperature with an average value of about 39 GPa. Uniaxial tensile tests performed on thinner composite plates of the same composition indicated markedly higher modulus values [55]. In fact, up to 280 °C the tensile modulus resulted to be scarcely affected by the consolidation temperature with an average value of about 59 GPa. This wide discrepancy could be attributed to the following factors. First of all, an anisotropy in the tensile/compressive mechanical behaviour of Vectran® fibres may be assumed. In fact, even if no experimental information are available for Vectran® fibres, there are several experimental evidences that highly oriented fibres behave in a different manner if loaded under tension or compression [56,57]. In fact, by Raman spectroscopy on PAN-based carbon fibres, Melanitis and Galiotis were able to evaluate that the ratio of the compressive to the tensile moduli can change in the range from 0.96 down to 0.68 depending on the fibre type [56]. In a more recent study on Kevlar 49 fibre, Dobb and Ghane reported a value of 0.72 for the ratio of the compressive to tensile moduli [57]. In the bending tests a part of the specimen is actually subjected to compressive loads and, consequently, the estimated modulus could be affected by the fibre anisotropy, if any. Another factor that could account for the lower bending modulus with respect to tensile one is the

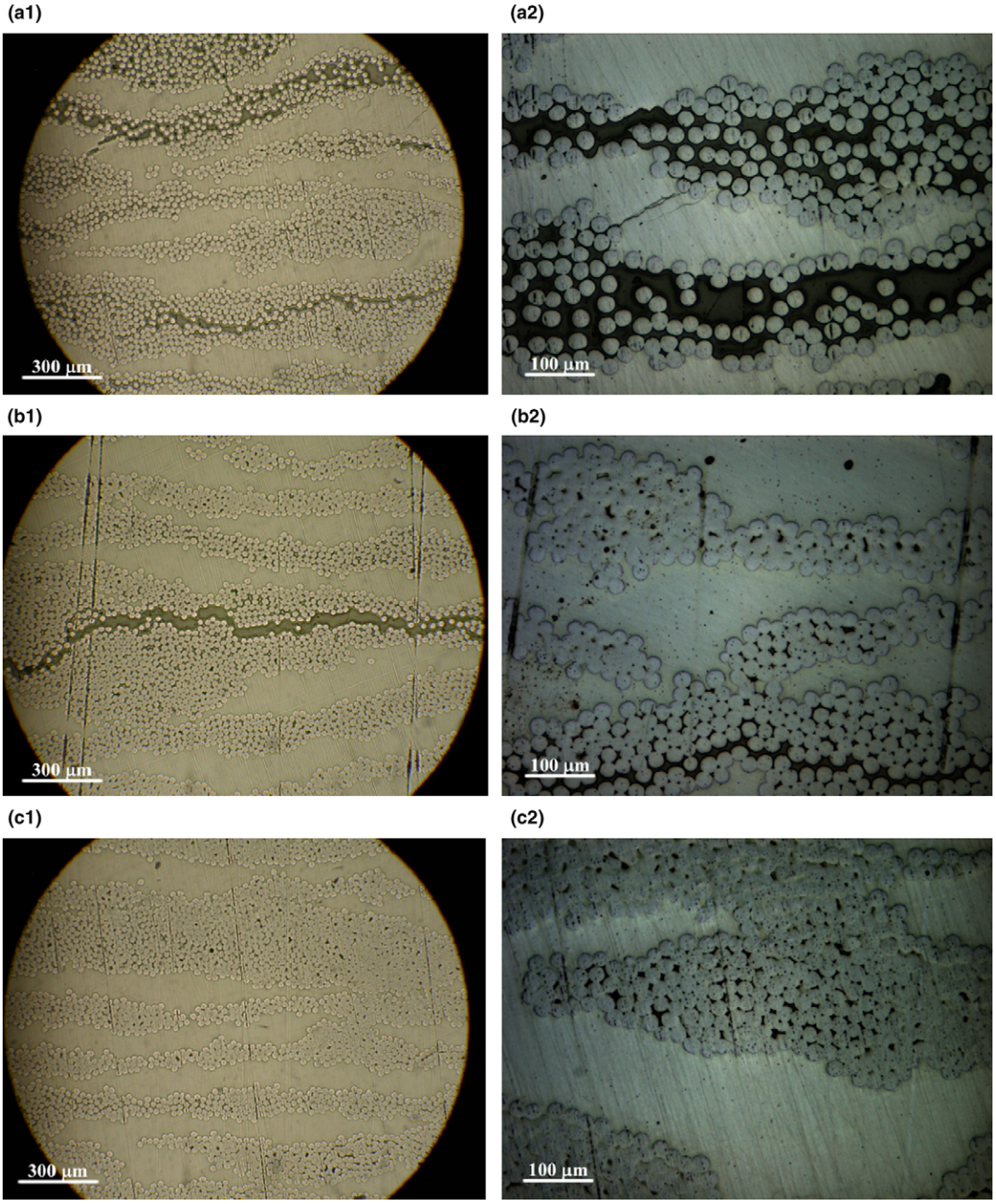


Fig. 5. Optical micrographs of the un-etched polished cross-sections of composites consolidated at 260 °C (a1, a2), 265 °C (b1, b2), 270 °C (c1, c2), 275 °C (d1, d2), 280 °C (e1, e2), and 285 °C (f1, f2).

effect of the shear deformation that is always present in the bending configuration. This component is more and more important as the span-to-depth ratio diminishes and, if neglected, it usually yields to apparent bending moduli lower than those measured under uniaxial tension. In order to overcome this problem, ASTM D790 standard recommends a span-to-depth ratio of at least 16 for homogeneous materials and it also claims that for some highly anisotropic composites, shear deformation can significantly influence modulus measurements, even at span-to-depth ratio as high as 40. In the present case, the span length is 76 mm that corresponds to a span-to-depth ratio in the range from 31 up to 40, depending on the plate thickness.

In the bending tests the maximum normal stress reached in the outer layer is usually considered as a measure of the material strength. The effect of the consolidation temperature on the maximum stress in the outer layer is also reported in Fig. 7. It is important to consider that, in the present case, the bending of composite specimens do not provoke the tensile or compressive failure of the outer layers but a load drop occurs when an interlaminar crack starts and propagates. As a consequence, the reported maximum stress values could be

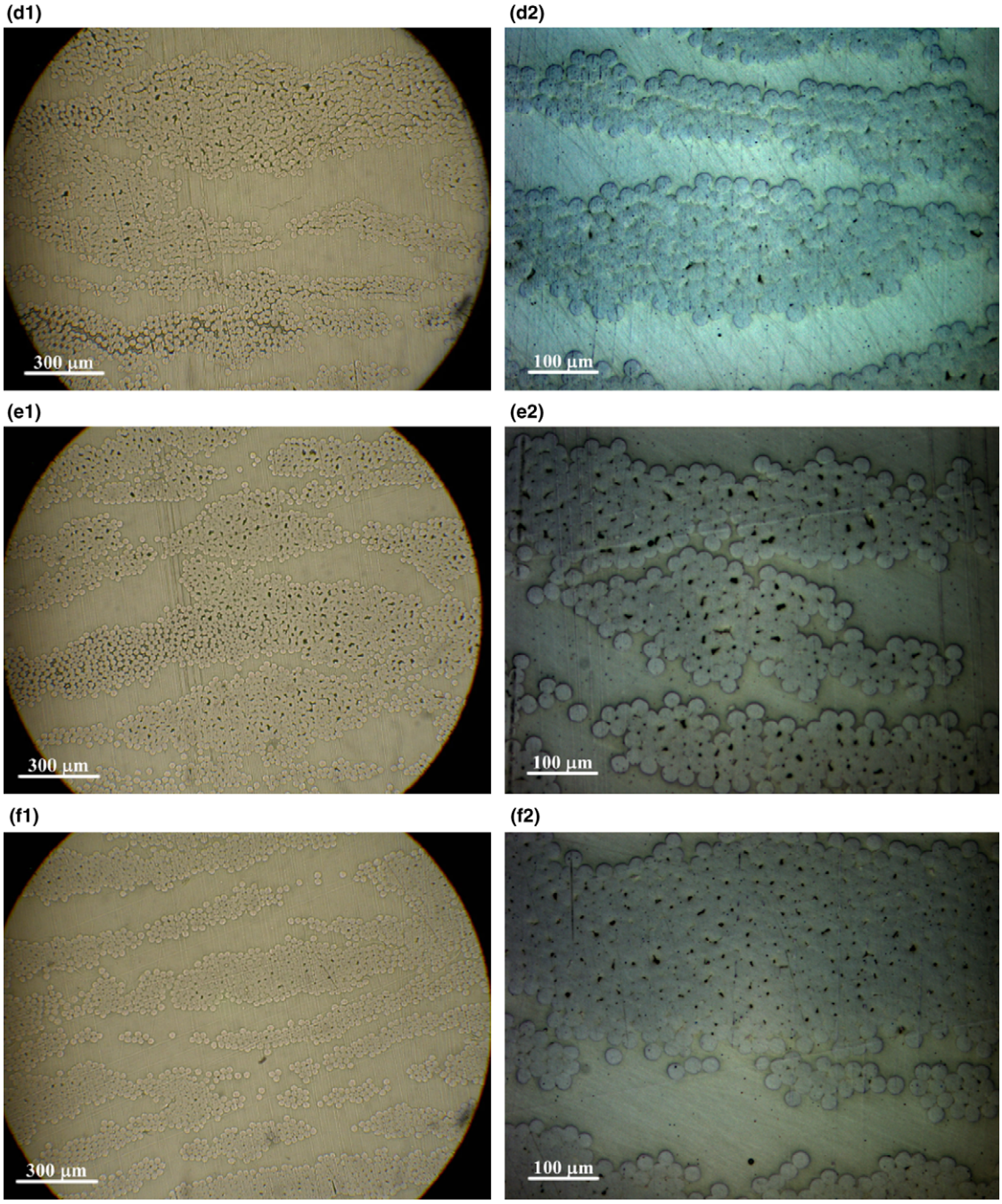


Fig. 5 (*continued*)

related to the interlaminar shear strength rather than the longitudinal tensile strength. In fact, the strength values measured under tensile mode resulted to decreases from 920 to 480 MPa when the consolidation temperature increased from 265 to 285 °C [55]. On the contrary, the maximum bending stress reported in Fig. 7 is increasing with the consolidation temperature, with a trend typical of the matrix related properties, such as the transversal strength [55].

The bending modulus and maximum stress values measured on specimens with fibres transversally oriented are reported in Fig. 8. Similarly to the transversal tensile modulus and strength [55], also modulus and maximum stress values are increasing with the consolidation temperature. It can be noticed that an improvement of a factor 2.8 of the transversal maximum stress is observed when the consolidation temperature is raised from 265 up to 285 °C.

3.3. Short beam shear test

The load–displacement curves obtained from the bending tests of specimens with a low span-to-depth ratio are reported in Fig. 9 for several consolidation temperatures. In all cases, mid-plane interlaminar failure has been clearly observed. Consequently, the strength values determined

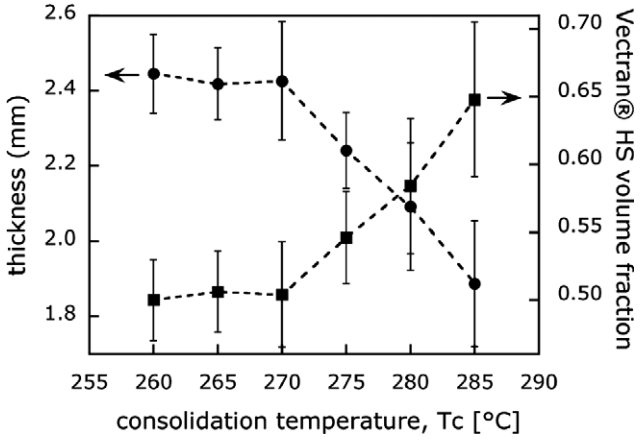


Fig. 6. Effect of the consolidation temperature on the thickness (●) and Vectran® HS fibre volume fraction (■) of composite sheets.

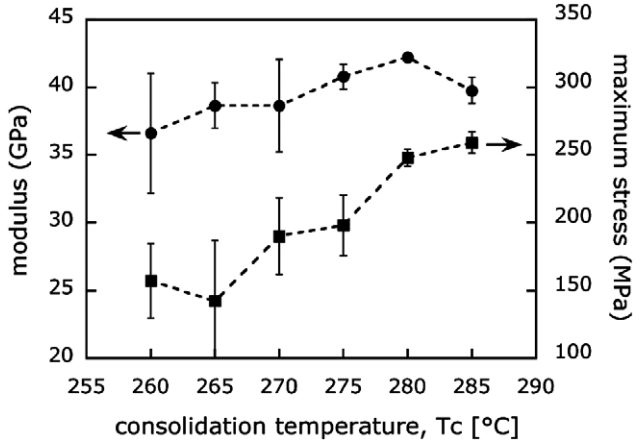


Fig. 7. Effect of the consolidation temperature on the modulus (●) and the maximum stress (■) as measured under the three point bending configuration in the longitudinal direction.

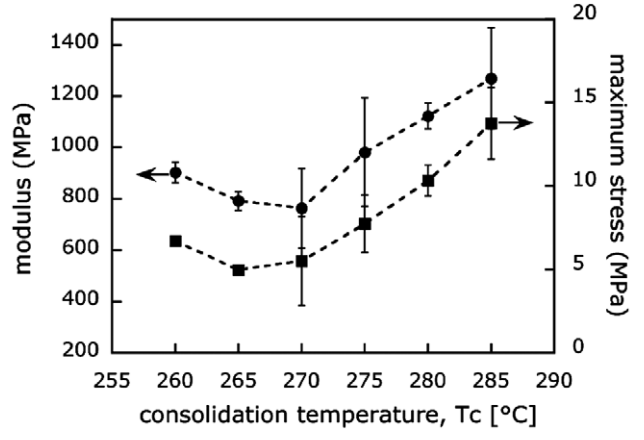


Fig. 8. Effect of the consolidation temperature on the modulus (●) and the maximum stress (■) as measured under the three point bending configuration in the transversal direction.

from this test method can be attributed to the interlaminar shear resistance. In particular, accordingly to the indications of the ASTM standard D2344, an interlaminar shear

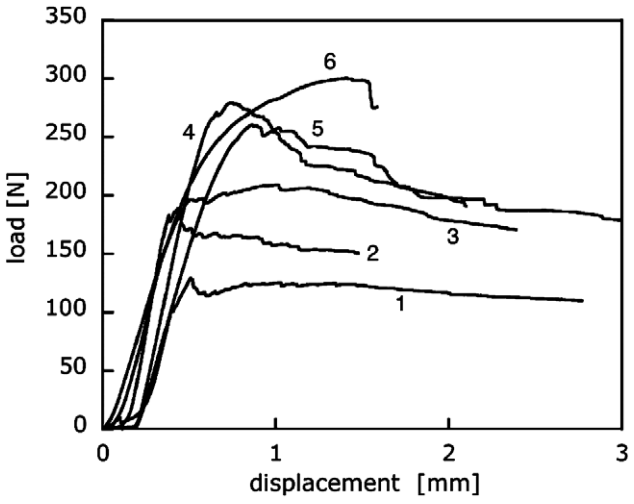


Fig. 9. Load–displacement curves recorded in the short beam shear tests of composites consolidated at various temperatures: (1) 260 °C; (2) 265 °C; (3) 270 °C; (4) 275 °C; (5) 280 °C; (6) 285 °C.

strength (ILSS) parameter has been computed from the maximum load observed during the test, P_m according to the following equation:

$$\mathrm{ILSS} = 0.75\frac{P_m}{bh} \tag{1}$$

where b and h are the specimens width and thickness, respectively. ILSS values evaluated on the basis of Eq. (1) are reported in Fig. 10. The resistance to shear-induced delamination is profoundly affected by the consolidation temperature. In particular, as the consolidation temperature rises the ILSS values markedly increase from 3.9 MPa at 260 °C up to 10.8 MPa at 285 °C. It is interesting to observe that the parameter ILSS increases by a factor of about 2.8, that exactly corresponds to the variation of the maximum stress evaluated in the three-point bending test in the transversal direction.

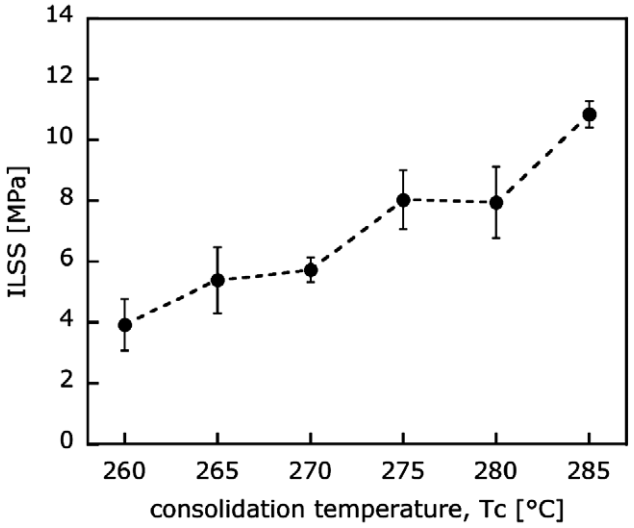
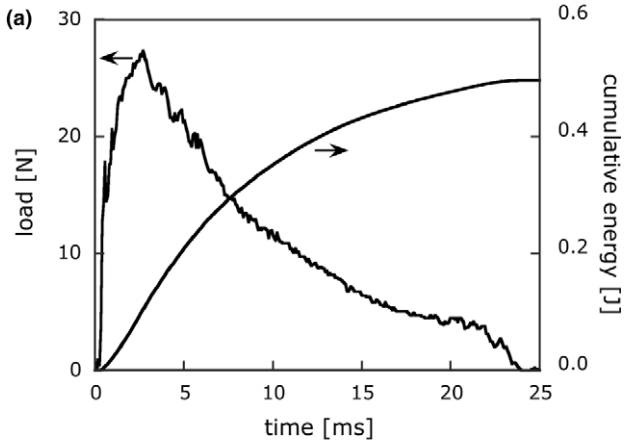


Fig. 10. Effect of the consolidation temperature on interlaminar shear strength (ILSS) values.

3.4. Charpy impact test

A representative load–time curve as obtained from instrumented Charpy impact tests is reported in Fig. 11a. It is seen that the force increases reaching a maximum corresponding to the onset of failure. The fracture is not catastrophic but the crack propagation requires a certain amount of energy. Moreover, the visual inspection of the specimens after the impact test (see Fig. 11b) put in evidence that no complete breakage occurs, and that the energy absorbing mechanisms are related to extended delamination and splitting. A number of reinforcing fibres it also appear to fail under tension on the outer composite layer. The cumulative energy during the impact test is represented on the same Fig. 11a. For each specimen, the Charpy impact resistance could be evaluated by measuring the total energy to fracture (E_t) and normalising it to the specimen cross-sectional area. E_t can be seen as the summation of a crack initiation energy (E_i) and a crack propagation energy (E_p). Beaumont et al. [58] defined a dimensionless parameter called the ductility index (DI), which is found useful for ranking the impact performance of different materials under similar testing conditions. The DI is defined as the ratio between the propagation energy and the initiation energy, i.e.:

$$\mathrm{DI} = \frac{E_p}{E_i} \tag{2}$$



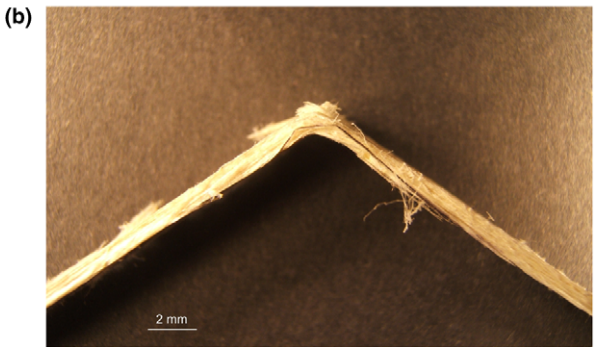


Fig. 11. (a) Load and energy curves recorded during the Charpy impact test of a specimens taken from a composite plate consolidated at 280 °C. (b) Picture of the impacted specimen.

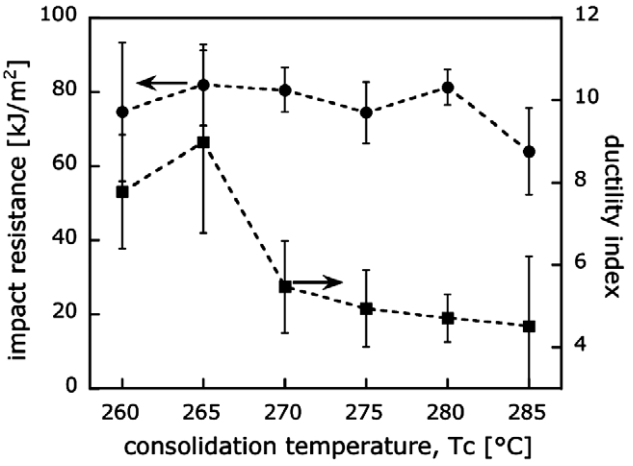


Fig. 12. Effect of the consolidation temperature on the Charpy impact resistance (●) and the ductility index (■) of composites.

High values of DI would mean that most of the total energy is expended for crack propagation. The Charpy impact resistance and the ductility index values are reported in Fig. 12 as a function of the consolidation temperature. The Charpy impact resistance is practically independent of the consolidation temperature up to 280 °C, oscillating around an average value of about 79 kJ/m^2. At a consolidation temperature of 285 °C a slight decrease to 64 kJ/m^2 is observed. These values are quite satisfactory if compared with the typical fracture energy data reported for traditional fibre reinforced polymer composites [59]. On the other hand the ductility index is negatively affected by a rise of the consolidation temperature, showing a maximum value of 9 at $T_c = 265$ °C and a monotonous decrease down to a minimum value of 4.5 at $T_c = 285$ °C. This trend could be tentatively explained by considering that the interlaminar shear strength increases with the consolidation temperature thus limiting the formation of delamination crack paths that are generally responsible of energy dissipation processes.

4. Conclusions

The hot-consolidation of co-wounded preforms offers a method for the manufacture of new single-polymer liquid crystalline composites. The flexural mechanical behaviour under static and impact conditions and the resistance to interlaminar failure of the resulting composites can be optimized by changing the consolidation temperature. In this study, the consolidation temperature has been varied from 260 up to 285 °C by steps of 5 °C. The following conclusions can be drawn:

(i) In the longitudinal direction, the bending modulus is substantially independent of the consolidation temperature with an average value of about 39 GPa, while the maximum stress in the outer layer increases from 157 MPa at $T_c = 260$ up to 259 MPa at $T_c = 285$ °C.

(ii) The transversal bending modulus and maximum stress and the interlaminar shear strength values markedly improve as the consolidation temperature increases. In particular, both the maximum transversal bending stress and ILSS values improve by a factor of 2.8 as T_c varies from 260 up to 285 °C.

(iii) Up to $T_c = 280$ °C the Charpy impact resistance of the investigated composites oscillates around an average value of 79 kJ/m^2 and for $T_c = 285$ °C decreases to 64 kJ/m^2. At the same time, the ductility index presents a maximum value of 9 at $T_c = 265$ °C and then it monotonously diminishes down to a minimum value of 4.5 at $T_c = 285$ °C.

Acknowledgments

The authors thank Dr. Forrest Sloan of Kuraray America Inc., Vectran® Division for the helpful suggestions and comments.

References

[1] Capiati NJ, Porter RS. The concept of one polymer composites modelled with high density polyethylene. J Mater Sci 1975;10:1671–7.
[2] Mead WT, Porter RS. The preparation and tensile properties of polyethylene composites. J Appl Polym Sci 1978;22:3249–65.
[3] Ajji A, Ait-Kadi A, Rochette A. Polyethylene-ultra high modulus polyethylene short fibers composites. J Compos Mater 1992;26(1):121–31.
[4] Marais C, Feillard P. Manufacture and mechanical characterization of unidirectional polyethylene-fibre/polyethylene-matrix composites. Compos Sci Technol 1992;45:247–55.
[5] Bassett DC, Olley RH, Hine PJ, Ward IM. Morphology of compacted polyethylene fibers. J Mater Sci 1993;28(4):1107–12.
[6] Hine PJ, Ward IM, Olley RH, Bassett DC. The hot compaction of high modulus melt-spun polyethylene fibers. J Mater Sci 1993;28(2):316–24.
[7] Olley RH, Bassett DC, Hine PJ, Ward IM. Morphology of compacted polyethylene fibers. J Mater Sci 1993;28(4):1107–12.
[8] Rolel D, Yavin E, Wachtel E, Wagner HD. Experimental study of transcrystallinity in UHMWPE/LLDPE composites. Compos Interface 1993;1(3):225–42.
[9] Teishev A, Incardona S, Migliaresi C, Marom G. Polyethylene fibers polyethylene matrix composites – preparation and physical properties. J Appl Polym Sci 1993;50(3):503–12.
[10] Kabeel MA, Bassett DC, Olley RH, Hine PJ, Ward IM. Compaction of high-modulus melt-spun polyethylene fibers at temperatures above and below the optimum. J Mater Sci 1994;29(18):4694–9.
[11] Teishev A, Marom G. The effect of transcrystallinity on the transverse mechanical properties of single-polymer polyethylene composites. J Appl Polym Sci 1995;50(3):503–12.
[12] Stern T, Teishev A, Marom G. Processing of composites of chopped PE fibre-reinforced PE matrix. Adv Comp Lett 1996;5(4):103–6.
[13] Arazi ZS, Harel H, Marom G, Yavin B. Polyethylene/polyethylene composite materials for ballistic protection. Sampe J 1997;33(4):72–5.
[14] Shalom S, Harel H, Marom G. Fatigue behaviour of flat filament-wound polyethylene composites. Compos Sci Technol 1997;57(9–10):1423–7.
[15] Stern T, Marom G, Wachtel E. Origin, morphology and crystallography of transcrystallinity in polyethylene-based. Composites Part A 1997;28(5):437–44.
[16] Stern T, Teishev A, Marom G. Composites of polyethylene reinforced with chopped polyethylene fibers: effect of transcrystalline interphase. Compos Sci Technol 1997;57(8):1009–15.
[17] Yan RJ, Hine PJ, Ward IM, Olley RH, Bassett DC. The hot compaction of Spectra gel-spun polyethylene fibre. J Mater Sci 1997;32:4821–31.
[18] Bonner MJ, Hine PJ, Ward IM. Hot compaction of crosslinked high modulus polyethylene fibres and fabrics. Plast Rub Compos Pro 1998;27(2):58–64.
[19] Mosleh M, Suh NP, Arinez J. Manufacture and properties of polyethylene homocomposite. Composites Part A 1998;29A:611–7.
[20] Ogawa T, Hiroaki M, Osawa S. Mechanical properties of ultrahigh-molecular-weight polyethylene fiber-reinforced PE composites. J Appl Polym Sci 1998;68:1431–9.
[21] von Lacroix F, Werwer M, Schulte K. Solution impregnation of polyethylene fibre polyethylene matrix composites. Composites Part A 1998;29(4):371–6.
[22] von Lacroix F, Loos J, Schulte K. Morphological investigations of polyethylene fibre reinforced polyethylene. Polymer 1999;40(4):843–7.
[23] von Lacroix F, Lu HQ, Schulte K. Wet powder impregnation for polyethylene composites: preparation and mechanical properties. Composites Part A 1999;30(3):369–73.
[24] Hine PJ, Ward IM, ElMaaty MIA, Olley RH, Bassett DC. The hot compaction behaviour of 2-dimensional woven melt-spun high modulus polyethylene fibres. J Mater Sci 2000;35(20):5091–9.
[25] Pegoretti A, Ashkar M, Migliaresi C, Marom G. Relaxation processes in polyethylene fibre-reinforced polyethylene composites. Compos Sci Technol 2000;60(8):1181–9.
[26] Kazanci M, Cohn D, Marom G. Elastic and viscoelastic behavior of filament wound polyethylene fiber reinforced polyolefin composites. J Mater Sci 2001;36:2845–50.
[27] Levitus D, Kenig S, Kazanci M, Harel H, Marom G. The effect of transcrystalline interface on the mechanical properties of polyethylene/polyethylene composites. Adv Comp Lett 2001;10(2):61–5.
[28] Harel H, Marom G, Kenig S. Delamination controlled ballistic resistance of polyethylene/polyethylene composite materials. Appl Compos Mater 2002;9(1):33–42.
[29] Jacobs O, Kazanci M, Cohn D, Marom G. Creep and wear behaviour of ethylene-butene copolymers reinforced by ultra-high molecular weight polyethylene fibres. Wear 2002;253(5-6):618–25.
[30] Kazanci M, Cohn D, Marom G, Ben-Bassat H. Surface oxidation of polyethylene fiber reinforced polyolefin biomedical composites and its effect on cell attachment. J Mater Sci- Mater Med 2002;13(5):465–8.
[31] Kazanci M, Cohn D, Marom G, Migliaresi C, Pegoretti A. Fatigue characterization of polyethylene fiber reinforced polyolefin biomedical composites. Composites: Part A 2002;33(4):453–8.
[32] Ratner S, Weinberg A, Marom G. Morphology and mechanical properties of crosslinked PE/PE composite materials. Polym Compos 2003;24(3):422–7.
[33] Vaisman L, Gonzalez MF, Marom G. Transcrystallinity in brominated UHMWPE fiber reinforced HDPE composites: morphology and dielectric properties. Polymer 2003;44(4):1229–35.
[34] Ratner S, Weinberg A, Wachtel E, Moret PM, Marom G. Phase transitions in UHMWPE fiber compacts studied by in situ synchrotron microbeam WAXS. Macromol Rapid Commun 2004;25:1150–4.
[35] Ratner S, Pegoretti A, Migliaresi C, Weinberg A, Marom G. Relaxation processes and fatigue behavior of crosslinked UHMWPE fiber compacts. Compos Sci Technol 2005;65(1):87–94.
[36] ElMaaty MIA, Bassett DC, Olley RH, Hine PJ, Ward IM. Hot compaction of polypropylene fibres. J Mater Sci 1996;31(5):1157–63.
[37] Teckoe J, Olley RH, Bassett DC, Hine PJ, Ward IM. The morphology of woven polypropylene tapes compacted at temperatures above and below optimum. J Mater Sci 1999;34(9):2065–73.
[38] Loos J, Schimanski T, Hofman J, Peijs T, Lemstra P. Morphological investigations of polypropylene single-fibre reinforced polypropylene model composites. Polymer 2001;42(8):3827–34.
[39] Hine PJ, Ward IM, Jordan ND, Olley RH, Bassett DC. The hot compaction behaviour of woven oriented polypropylene

fibres and tapes. I Mechanical properties. Polymer 2003;44(4):1117–31.
[40] Jordan ND, Bassett DC, Olley RH, Hine PJ, Ward IM. The hot compaction behaviour of woven oriented polypropylene fibres and tapes. II Morphology of cloths before and after compaction. Polymer 2003;44(4):1133–43.
[41] Li H, Zhang X, Kuang X, Wang J, Wang D, Li L, et al. A scanning electron microscopy study on the morphologies of isotactic polypropylene induced by its own fibers. Macromolecules 2004;37(8):2847–53.
[42] Li HH, Zhang XQ, Duan YX, Wang DJ, Li L, Yan SK. Influence of crystallization temperature on the morphologies of isotactic polypropylene single-polymer composite. Polymer 2004;45(23):8059–65.
[43] Rasburn J, Hine PJ, Ward IM, Olley RH, Bassett DC, Kabeel MA. The hot compaction of polyethylene terephthalate. J Mater Sci 1995;30(3):615–22.
[44] Hine PJ, Ward IM. Hot compaction of woven poly (ethylene terephthalate) multifilaments. J Appl Polym Sci 2004;91(4):2223–33.
[45] Rojanapitayakorn P, Mather PT, Goldberg AJ, Weiss RA. Optically transparent self-reinforced poly(ethylene terephthalate) composites: molecular orientation and mechanical properties. Polymer 2005;46:761–73.
[46] Hine PJ, Astruc A, Ward IM. Hot compaction of polyethylene naphthalate. J Appl Polym Sci 2004;93(2):796–802.
[47] Hine PJ, Ward IM. Measuring the elastic properties of high-modulus fibres. J Mater Sci 1996;31:371–9.
[48] Ward IM, Hine PJ. Novel composites by hot compaction of fibers. Polym Eng Sci 1997;37(11):1809–14.
[49] Stellbrink KKU, Hausser G, Steegmuller R. One-component composites as functionally gradient materials. J Thermoplastic Comp Mat 1999;12(3):188–200.
[50] Beers DE, Ramirez JE. Vectran high-performance fibre. J Text Inst 1990;81(4):561–74.
[51] Menczel JD, Collins GL, Saw SK. Thermal analysis of Vectran(R) fibers and films. J Therm Anal 1997;49(1):201–8.
[52] Taylor JE, Romo-Uribe A, Libera MR. Bimodal orientation defects in main-chain thermotropic liquid crystalline polymer fibers. Macromolecules 2002;35:1751–6.
[53] Taylor JE, Romo-Uribe A, Libera MR. Molecular orientation gradients in thermotropic liquid crystalline fiber. Polym Adv Technol 2003;14:595–600.
[54] Ward IM, Hine PJ. The science and technology of hot compaction. Polymer 2004;45:143–1427.
[55] Pegoretti A, Zanolli A, Migliaresi C. Preparation and tensile mechanical properties of unidirectional liquid crystalline single-polymer composites. Compos Sci Technol, in press, doi:10.1016/j.compscitech.2006.01.012.
[56] Melanitis N, Galiotis C. Compressional behaviour of carbon fibres. Part 1. A Raman spectroscopic study. J Mater Sci 1990;25:5081–90.
[57] Dobb MG, Ghane M. Tensile and compressive moduli of fibres using a two-component beam system. J Mater Sci 1996;31(17):4445–50.
[58] Beaumont PWR, Reiwald PG, Zweben C. Methods for improving the impact resistance of composite materials. in Foreign object impact behaviour of composites. ASTM Spec Tech Publ 1974;568:134–58.
[59] Cantwell WJ, Morton J. The impact resistance of composite materials – a review. Composites 1991;22(5):347–62.