Available online at www.sciencedirect.com
SCIENCE DIRECT®
Polymer 44 (2003) 5993–6002
polymer
www.elsevier.com/locate/polymer

The influence of yarn-processing parameters on the tensile properties and structure of poly(*l*-lactic acid) fibres

J. Suesat[a], D.A.S. Phillips[a], M.A. Wilding[a,*], D.W. Farrington[b]

[a]*The Department of Textiles, UMIST, P.O. Box 88, Manchester M60 1QD, UK*
[b]*7, The Common, Quarndon, Derby DE22 5JY, UK*

Received 24 March 2003; received in revised form 6 May 2003; accepted 8 May 2003

Dedicated to Prof. Ian M. Ward on the occasion of his 75th birthday

Abstract

This paper examines the influence of processing parameters on the physical properties and structure of yarns constructed from poly(*l*-lactic acid) (PLLA) fibres. Commercially produced spun- and false-twist texturised (FTT) PLLA yarns, and knitted fabrics derived there from were characterised in terms of their tensile properties, and structurally using differential scanning calorimetry (DSC) and wide angle X-ray diffraction. The effects of pre-dye heat-setting at 130 °C for varying times was assessed in terms of the resultant tensile properties of the yarns. The as-received FTT yarns (and hence their derived fabrics) differed in properties and fibre microstructure as compared to the spun yarns (and fabrics). More significantly, for both FTT and spun materials, differences in fibre properties and structure were observed between yarns removed from the fabrics and their respective feed-yarns. We associate this with possible thermomechanical influences experienced by the fibres during the knitting process. The duration of heat-setting influenced the tensile properties and DSC spectra for both types of yarn. Scouring following heat-setting was also carried out, and this produced no measurable additional effect on the spun yarns, but FTT yarns heat-set for less than ca 45 s showed instability to scouring.

Keywords: Poly(*l*-lactic acid); Heat-setting; Morphology

1. Introduction

Over recent years, fibres based on poly(lactic acid) (PLA) have attracted increasing interest owing to the fact that they lend themselves to manufacture from renewable resources; in particular, from corn-starch. Two alternative chemical routes have been exploited in this respect: the first makes use of the polycondensation of appropriate monomers; the second entails so-called 'ring-opening polymerisation' of a cyclic dimer intermediate of lactic acid [1–4]. In both cases, the starting chemicals are derived from fermentation of the raw material. Attention has focused mainly on the ring-opening route, since it involves milder conditions than the polycondensation process.

The stereochemistry of lactic acid gives rise to two optically active forms: *laevo*-rotatory (L-form) and *dextra*-rotatory (D-form). This fact is reflected in the chemistry of the PLA polymer itself, and provides the possibility of generating PLA fibres containing monomers of the two isomers in varying proportions. Although fibres representing both extremes (ie all-L and all-D), as well as copolymers of the two forms, may be produced, those consisting of essentially the pure L-form (PLLA) have been most widely studied. PLLA is a semi-crystalline thermoplastic polymer which can be processed in a similar way to conventional polyesters such as poly(ethylene terephthalate) (PET). Fibres in which there is an increasing concentration of the D-form tend to be proportionately less crystalline, owing to the disruptive effect on the geometrical regularity of the chemical repeat units along the polymer chain.

The physical properties and structure of PLLA have been studied by a number of researchers [1–13], from whose work one may conclude that this polymer has significant commercial potential as a textile fibre. Its mechanical properties are reported to be broadly similar to those of conventional PET [1], although its lower melting and

* Corresponding author. Tel.: +44-161-200-4145; fax: +44-161-955-8160.
E-mail address: mike.wilding@umist.ac.uk (M.A. Wilding).

0032-3861/03/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0032-3861(03)00547-0

softening temperatures clearly present a limitation on its use. Further, the equilibrium conformation of the PLLA molecule is helical [5], whereas in PET the crystalline chain segments are almost fully extended. This will certainly have a bearing on the tensile properties of PLLA; for example, a lower intrinsic tensile modulus would be indicated. According to Dorgan et al. [6] the mechanical properties of PLLA are comparable to those of polystyrene, and its melt-rheology enables it to be processed readily into fibre form.

Schmack et al. [7] investigated the physical properties of PLA generated by reactive extrusion. This material was also used as the basis for studying the effect of high-speed melt spinning and spin-draw conditions on the fibre structure and properties. Other researchers [8–13] have also contributed to understanding the relationship between fibre-spinning parameters and physical properties.

2. Aims and methodology

Given the potential textiles applications of PLLA, it is clearly appropriate to elucidate as far as possible the interrelationships between fibre microstructure, morphology and physico-chemical properties; more specifically, it is important to gain an understanding of how the material performs with respect to such textile production processes as yarn/fabric formation, heat-setting, dyeing and finishing. Ideally, one would wish to be able to identify the optimum conditions of temperature, time and other influential parameters.

In the knitwear industry it is common practice to heat-set fabrics prior to down-stream wet-processing, in order to impart a degree of dimensional stability. This operation is generally carried out using a stenter, in which the fabric is maintained at constant width as it passes through appropriate heating and cooling zones, and at a rate chosen to ensure prescribed residence times.

Another industrial process generally applied prior to dyeing of fabrics is that of scouring to remove finishes and surface contaminants. Whilst heat-setting is intended to provide structural and dimensional stability, it is nonetheless conceivable that scouring could have an additional influence on the fibre structure and properties—and hence on subsequent performance in dyeing—since it involves aggressive wet conditions (albeit carried out at a significantly lower temperature than that of heat-setting.)

Our research focuses on a set of commercially produced PLLA yarns and knitted fabrics. These materials are characterised in terms of their tensile properties and structure, based on differential scanning calorimetry (DSC) and wide angle X-ray diffraction (WAXD). Attention is focussed on property and structure differences which we have observed, not only between the two types of as-received yarn, but (more significantly) also between the feed-yarns and fabric-yarns of the same type.

The effects of simulated processing operations, viz. heat-setting and scouring, on the fibre tensile properties is investigated, in an attempt to identify the minimum treatment time needed to confer stability. We have also carried out a DSC study which was aimed at identifying any morphological changes accompanying these processes, and which we had originally planned to include in this paper. However, it has become clear to us that the unambiguous interpretation of such data, as applied to pre-annealed materials, is fraught with problems: not least, the fact that the DSC technique itself subjects the test sample to annealing influences. We have therefore decided to omit this aspect, pending further consideration.

We have simulated the stentering process on a laboratory scale using yarn samples. The use of fabric would, of course, have provided a closer match to what is done commercially, but would also have introduced a number of complications: for example, a weft-knitted fabric is intrinsically an unstable structure; and there will be inter-yarn friction at yarn cross-over points. Factors such as these would have given rise to a large element of uncertainty as to the exact conditions experienced by the yarns (and component fibres) themselves. It was therefore in the interest of maintaining scientific clarity that we adopted this approach.

Clearly, the temperature of heat-setting will be an influential factor determining the subsequent morphology and properties of the fibres. In the interest of keeping the number of parameters to a minimum, we have at this stage fixed the temperature of heat-setting and investigated, rather, the influence of treatment time. The temperature we have chosen matches that used in the commercial stentering process. Our continuing work does, however, include the setting temperature as a variable.

In addition to studying the effects of heat-setting and scouring on the substrate itself, it is important to evaluate the extent to which these processes either assist or inhibit performance in operations carried out further downstream. To this end, the physical study described here was conducted in parallel with an investigation of the performance in dyeing of the same set of PLLA yarn samples [14].

3. Experimental

3.1. Materials and characterisation

A set of staple-spun yarns, false-twist texturised (FTT) continuous filament yarns and their respective weft-knitted fabrics was provided by Cargill-Dow LLC, USA. In each case the fibre content was 100% PLLA. The yarn specifications were as follows:

Spun yarn: 20 Ne (29.5 tex); delustred;
FTT yarn: 70 denier (7.78 tex); bright; 68 filaments.

The fabric specifications were as follows:

FTT fabric: single jersey knit; 32.8 in. (83.3 cm) per course; 24 needles per inch (ca 9.5 needles per cm); needle gauge = 54.

Spun fabric: single jersey knit; 41.6 in. (105.7 cm) per course; 24 needles per inch (ca 9.5 needles per cm); needle gauge = 54.

3.2. Assessment of fabrics

All the data presented in this paper relates either to fibres or yarns: the fabrics were not assessed directly, but rather in terms of their component yarns, samples of which were carefully removed for the purpose. Thus, where we refer to, for example, 'fabric derived from the FTT yarns', this should be interpreted as being based on the component yarns, and not on the fabric as a whole.

3.3. Tensile measurements

All tensile measurements on the yarns were carried out in accordance with British standard EN ISO 2062:1995, using an Instron Model 1122 tensile tester, under standard laboratory conditions (20 ± 2 °C; 65 ± 2% r.h.), with a gauge-length of 500 mm and at an applied strain rate of 1 min^{-1}. 10 replicates were tested for each nominally equivalent sample.

3.4. WAXD studies

WAXD data pertaining to the as-received PLLA yarns and those derived from the fabrics was obtained both as equatorial intensity vs 2θ diffractometer scans and as whole-pattern photographs.

The Diffractometry was conducted using a Philips XPERT MPD machine employing Cu K_α ($\lambda = 0.154$ nm) radiation. The generator was operated at 50 kV and 40 mA.

Photographic flat-plate diffraction patterns were recorded using a Philips 1120/80 Commazon instrument, again with Cu K_α radiation. The sample-film distance was 50 mm and the exposure time was 2 h.

All experiments were carried out on yarn bundles in which the nominal fibre axis was vertically disposed, and lying in a plane normal to the input X-ray beam.

3.5. DSC studies

The DSC data was gathered using a TA Instruments Model Q100 Modulated DSC (MDSC®) with refrigerated cooling system (RCS). 5-mg samples were scanned in the temperature range 20–220 °C at a heating rate of 10 °C min^{-1}.

3.6. Heat-setting procedure

Heat-setting of the spun and false-twist texturised PLLA yarns was carried out using a Werner Mathis steamer/baker. We have chosen to use a constant-length (nominally at zero pre-tension) treatment employing dry air (no steam), at a fixed temperature of 130 °C. According to Cargill-Dow [15], this is the optimum temperature for stabilising PLLA fabrics. The samples, consisting of lengths of yarn wound by hand on aluminium formers, were heat-set for durations of 15, 30, 45 and 60 s.

3.7. Scouring procedure

Samples of the heat-set yarns were scoured for 10 min at 60 °C in an aqueous solution containing 1.0 g/l of 'Neutracon' (a blend of anionic and non-ionic detergents, supplied by Decon Laboratories Ltd.). This procedure was carried out in a beaker at a liquor-to-goods ratio of 10:1 (ie 100 ml of liquid to 10 g of fabric), and with continuous stirring.

4. Results and discussion

4.1. Characterisation studies

Data relating to the as-received materials is presented in Figs. 1–4 and Tables 1 and 2.

4.1.1. Spun yarn vs FTT yarn, as-received

Fig. 1 presents averaged tensile stress–strain curves obtained for the as-received yarns (Fig. 1a) and those derived from the fabrics (Fig. 1b), while Table 1 summarises their measured tensile parameters.

The observed tensile properties of the as-received spun and false-twist texturised PLLA yarns clearly differed. In particular, both the tenacity and initial modulus were higher for the FTT yarn than for the spun yarn, whereas the elongation to break was marginally lower.

The most tempting explanation for these differences is that they reflect the differing thermomechanical experiences of fibres processed via the two yarn production routes. This, if true, would not be surprising, but one does need to exercise caution in comparing fibre properties based on measurements conducted on yarns: not least because in a staple-spun yarn there is the potential for inter-fibre slipping, which is prevented in continuous filament yarns. There is also likely to be some inequality of load-sharing by the fibres in the yarn cross-sections, regardless of which type of yarn is under consideration. The nature of this will depend on the actual yarn structure (e.g. high twist in the case of spun yarn vs little or no twist in FTT yarn). Furthermore, especially for the FTT yarns, added uncertainty arises from the implicit assumption that all the fibres were initially straight, and yet at the same time under zero

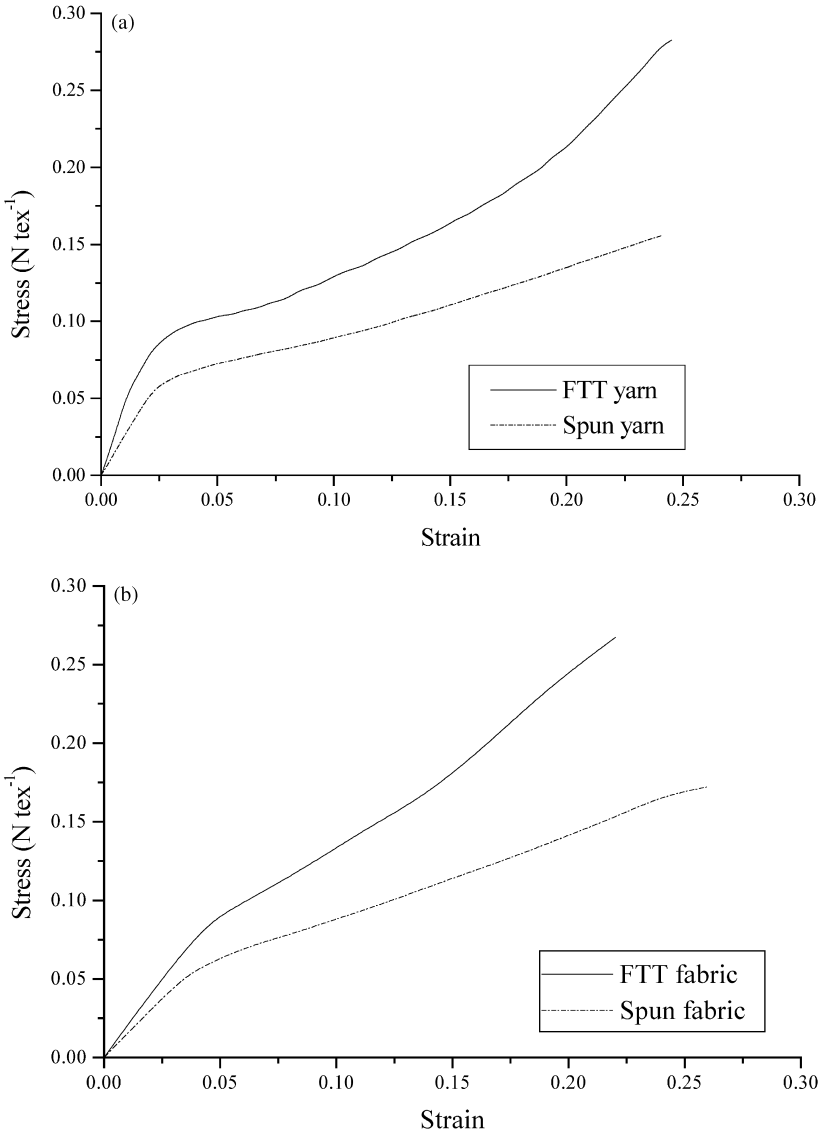

Fig. 1. Tensile stress vs strain curves of as-received: (a) PLLA yarns; (b) yarns ex-derived fabrics.

tension. This is significant because FTT yarns, almost by definition, contain crimped fibres.

The proposition that the two yarn processes do in fact subject the fibres to different thermomechanical influences is, however, supported by the DSC and WAXD data appearing in Figs. 2a, 3a, 4a and c, and in Table 2. Whilst the melting endotherms (Fig. 2a) are complex (e.g. each involving at least two components), there is little doubt that the spun and FTT yarn spectra differ markedly. Perhaps the most obvious distinction is that both the onset and completion of melting occurs approximately 5 °C higher for the spun yarn than for the FTT yarn. More subtle differences are also evident: for example, the endotherm for the FTT yarn is narrower than that for the spun yarn and, as discussed later, may actually feature three components. (Having said this, the possibility of several overlapping

Table 1
Tensile properties of as-received spun and FTT PLLA yarns and their respective fabrics. Figures in parentheses are approximate standard deviations calculated from the 10 replicate measurements

Sample identification	Elongation at break (%)	Tenacity (Ntex^{-1})	Initial modulus (Ntex^{-1})
FTT yarn	24.6 (±0.5)	0.28 (±0.01)	3.9 (±0.1)
Spun yarn	25.3 (±0.5)	0.16 (±0.01)	2.4 (±0.2)
Fabric derived from FTT yarn	23.0 (±1)	0.28 (±0.01)	2.9 (±0.5)
Fabric derived from spun yarn	25.0 (±1.5)	0.16 (±0.01)	1.4 (±0.2)

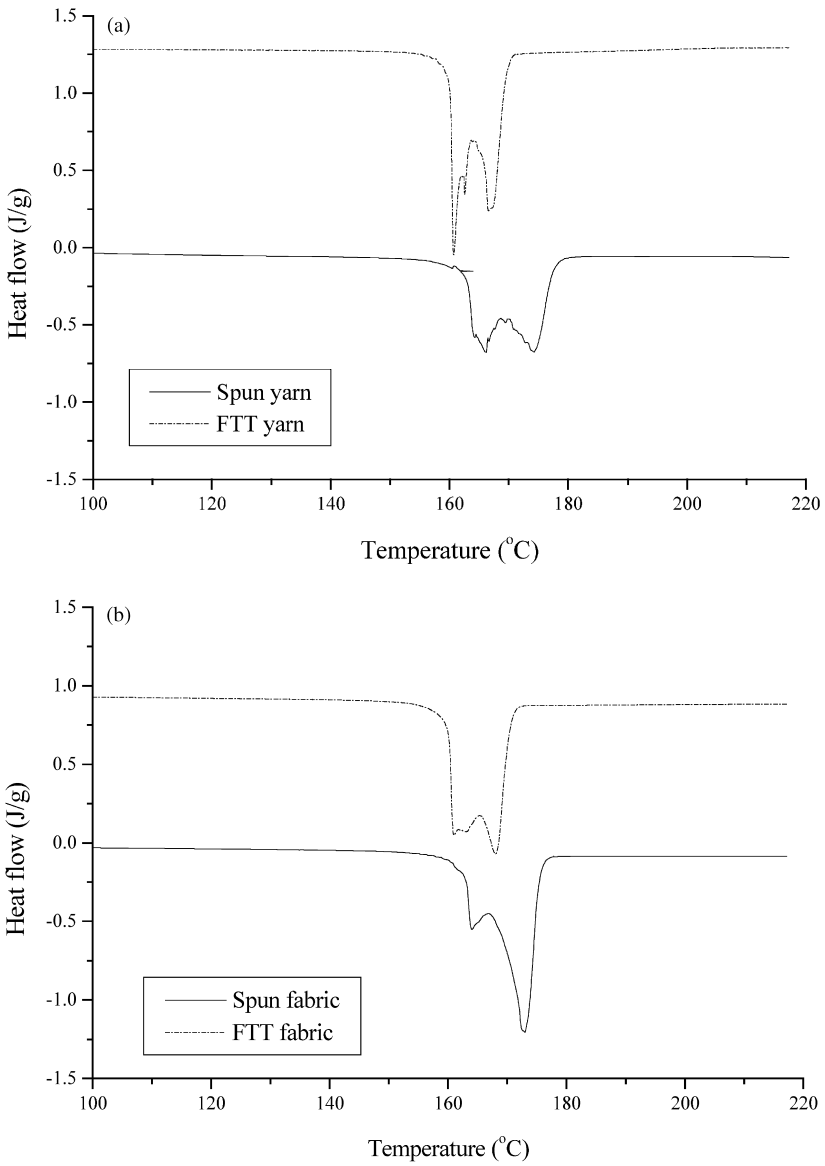

Fig. 2. DSC scans of as-received: (a) PLLA yarns; (b) yarns ex-derived fabrics.

peaks even for the spun yarn cannot be ruled out owing to the broader shape of the feature).

The lower melting temperature seen for the FTT yarn suggests the possibility that the fibre morphology is less-well developed, and/or that it comprises smaller crystalline entities, than that corresponding to the spun yarns. On the other hand, the fact that the feature is narrower would suggest a more uniform texture—that is, a narrower distribution of crystallite sizes. Moreover, Table 2 shows the FTT material to be significantly more crystalline overall than the spun yarn (ca 63% cf 47%).

Table 2
Crystallinity values for spun and FTT PLLA yarns and derived fabrics, determined from WAXD measurements

Sample	Crystallinity (%)
FTT yarn	62.7
Spun yarn	47.3
Fabric derived from FTT yarn	62.7
Fabric derived from spun yarn	41.9

For both yarn types, the melting endotherm is clearly multi-modal, leading one to suspect that the fibre morphologies are made up of at least two distinct populations. Similar 'multiple melting' phenomena have been reported in other melt-spun fibres [16,17]. It has often been found that the position of one component of the endotherm could be influenced by progressive annealing treatments, whereas the other remained relatively fixed in temperature.

A closer inspection of the DSC data of Fig. 2a reveals that the (two) melting peaks for the spun yarn are at about 166 and 174 °C, whereas in the FTT yarn, the (three) peaks are at approximately 161, 163, and 167 °C. It can be postulated that these double and triple melting peaks are due

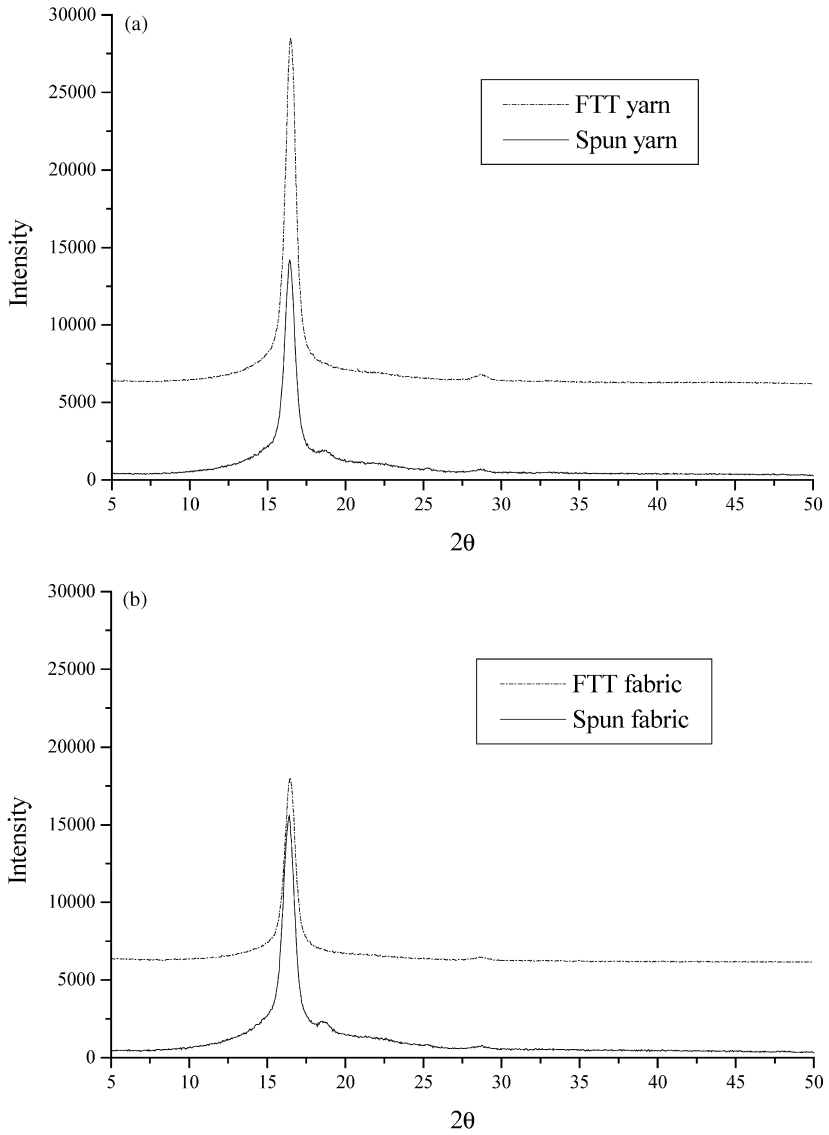

Fig. 3. WAXD intensity vs 2θ (equatorial) diffractograms of as-received: (a) PLLA yarns; (b) yarns ex-derived fabrics.

to the presence of distinct crystal populations initially present in the yarn samples, as already indicated. On the other hand, the possibility cannot be ruled out that they reflect annealing processes taking place during the DSC scan itself [18,19]. This, of course, highlights a potential drawback of the DSC technique, but does not of itself detract from the conclusion that very real differences exist between the thermal responses of the two differently processed yarns.

The equatorial diffractometer scans of both as-received yarn types (Fig. 3a) exhibit an intense peak at a 2θ value of about 16.5°, which can be assigned to the (200) crystallographic planes [20]. In the case of the spun yarn, a weak additional peak appears at around 18°. This reflection is also observed in the spectrum of the spun yarn removed from fabric (Fig. 3b), suggesting that it is a real feature, and not merely an experimental artefact. One might speculate this to be an indication of polymorphism, with the spun yarn possibly exhibiting more than one crystal form. The whole-pattern photographs of Fig. 4a and c highlight the better-developed crystalline structure of the FTT yarn as compared to the spun yarn. If anything, the spun yarn displays marginally lower crystalline orientation, which could provide an alternative, and perhaps more likely, explanation for the appearance of the 18° reflection: that it is, in reality, an off-axis reflection which becomes smeared across the equator.

4.1.2. Feed-yarns vs fabric-yarns

Given the observations already discussed, it stands to reason that the component yarns of the two derived fabrics would also differ in properties and structure. This is indeed borne out by the data of Figs. 1b, 2b, 3b, 4b and d, and by Table 1. More interestingly, however, is the fact that all the techniques used point to significant property and structure

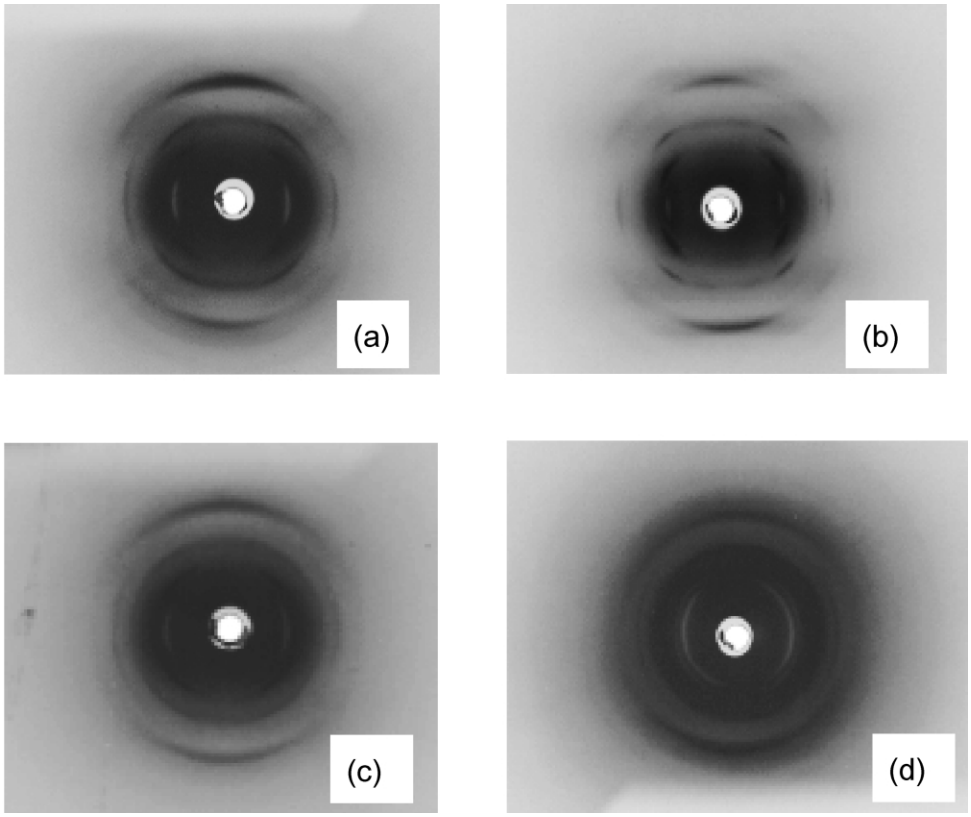

Fig. 4. Flat-plate WAXD patterns of as-received: (a) FTT yarn; (b) FTT yarn ex-derived fabric; (c) spun yarn; (d) spun yarn ex-derived fabric.

differences between the feed-yarns and those removed from their equivalent fabric.

From Table 1, for example, it is observed that for both yarn types, a significant drop in initial modulus occurs when the yarns are knitted, albeit their respective ultimate properties (extensibility and tenacity) are virtually unaffected.

Further, Fig. 2a and b clearly indicate different DSC responses for the feed-yarns and fabric-yarns of a given type, the melting endotherms being very different in shape following conversion to fabric in both cases. In particular, it would appear that the different crystal populations have been modified, as indicated by changes in the relative intensities of the various component peaks. Accompanying this, there may also be changes in crystallinity, crystalline perfection, crystallite size and distribution.

The WAXD diffractograms of Fig. 3a and b do not appear to differ markedly, and the measured crystallinity values for the feed and fabric-yarns are similar (Table 2), but the diffraction patterns themselves certainly do reveal differences (compare Fig. 4a with Fig. 4b and Fig. 4c with Fig. 4d). In particular, for the FTT yarn it would seem that conversion into fabric has resulted in a more fully oriented fibre structure, indicated by the sharper reflections and narrower arcs. By contrast, for the spun yarn, the pattern has become more diffuse and suggests, if anything, a less well-oriented fibre structure.

Taken overall, the tensile and analytical results strongly suggest that the fibres in the yarns have been subjected to thermomechanical influences at some stage during the fabric production process. The fabrics were supplied to us in greige (untreated) form, and would not have been given any deliberate processing that could produce these differences. We are therefore led to the conclusion that they are side-effects of the knitting process, possibly arising from high tensions combined with frictional heating at needles, guides, etc. The melting point and T_g of PLLA are considerably lower than, for example, regular PET, which may well make it more prone to such unintended effects in processing.

If the above is the case, then it is somewhat mystifying as to why the FTT structure should become more oriented while in the spun yarn the opposite is true. There may be a clue in the fact that the individual fibres are present in the spun yarn as short staple, and it is in reality only inter-fibre friction which maintains them in a state of constant length when the yarn itself is under tension. Thus, at elevated temperatures they could still shrink, through inter-fibre slippage, even though the yarn does not. In the FTT material, fibre slippage cannot occur, and if the yarn is under tension at high temperature the result is more likely to be improved crystalline texture and orientation through annealing effects. This is not an insignificant point in the context of our study, because it leaves open the disturbing possibility that in the nominally constant length heat-setting procedure there could be some fibre shrinkage in the case of the spun yarns.

Table 3
Measured tensile parameters of heat-set-scoured and heat-set-unscoured PLLA yarns-setting and scouring

Setting time (s)	FTT yarn						Spun yarn					
	Elongation at break (%)		Tenacity (Ntex^{-1})		Initial modulus (Ntex^{-1})		Elongation at break (%)		Tenacity (Ntex^{-1})		Initial modulus (Ntex^{-1})	
	Unscoured	Scoured	Unscoured	Scoured	Unscoured	Scoured	Unscoured	Scoured	Unscoured	Scoured	Unscoured	Scoured
0	25.5 ± 0.9	32.0 ± 1.0	0.28 ± 0.01	0.25 ± 0.01	3.88 ± 0.14	1.50 ± 0.06	27.5 ± 1.0	29.0 ± 1.6	0.16 ± 0.01	0.15 ± 0.01	2.43 ± 0.20	1.35 ± 0.13
15	32.0 ± 1.0	38.0 ± 1.0	0.27 ± 0.02	0.26 ± 0.01	4.55 ± 0.18	2.85 ± 0.23	30.0 ± 1.6	28.0 ± 1.7	0.15 ± 0.01	0.15 ± 0.01	2.04 ± 0.10	1.51 ± 0.15
30	32.0 ± 1.0	34.0 ± 1.4	0.27 ± 0.01	0.28 ± 0.01	4.28 ± 0.07	3.70 ± 0.24	31.0 ± 1.2	30.0 ± 1.3	0.15 ± 0.01	0.16 ± 0.01	2.08 ± 0.19	1.85 ± 0.28
45	31.0 ± 2.0	35.5 ± 1.8	0.25 ± 0.03	0.28 ± 0.01	4.17 ± 0.25	3.81 ± 0.24	31.0 ± 1.5	29.0 ± 1.4	0.15 ± 0.01	0.15 ± 0.01	2.06 ± 0.6	1.76 ± 0.26
60	35.0 ± 1.3	34.0 ± 2.5	0.28 ± 0.02	0.27 ± 0.03	4.53 ± 0.16	4.31 ± 0.13	32.0 ± 1.2	31.0 ± 1.6	0.16 ± 0.01	0.17 ± 0.01	2.02 ± 0.16	2.49 ± 0.11

4.2. Influence of heat-setting and scouring

The effects of heat-setting and of scouring on the tensile properties of the spun and FTT yarns are summarised in Table 3 and Fig. 5.

4.2.1. Heat-setting alone

As stated earlier, the as-received yarn samples were heat-set at 130 °C for durations of 15, 30, 45 and 60 s. Referring to Table 3, it is observed that the ultimate properties of both types of (unscoured) yarns are virtually unaffected by heat-setting. At most, there is a slight increase in the extensibility of the two yarns initially on heating, but this remains fairly constant with respect to longer treatments. The fact that the tenacity and extensibility are essentially unchanged is not particularly surprising because while one would expect the heat treatment to influence the detailed fibre fine-structure, this latter is likely to be largely irrelevant once the fibres have been stretched to breaking point. On the other hand, the initial modulus will certainly be sensitive to structure modification. Interestingly, for the FTT yarn this parameter shows an increase of about 15%, whereas for the spun yarn a decrease of some 16% is indicated. This could be associated with the possibility of fibre shrinkage in the spun yarn, as discussed earlier. Fig. 5 shows that the effect on initial modulus occurs quite quickly on heat-setting, with little further change taking place for longer treatment times.

4.2.2. Scouring alone

The purpose of scouring a yarn or fabric is to remove spin finish using detergent in warm water. For PLLA yarns, the conditions used are 60 °C for 10 min. However, the glass transition temperature (T_g) of PLLA is about 60 °C, and so it is very likely that scouring could bring about morphological changes, especially as it is carried out under wet alkaline conditions. Generally, scouring of fabrics is not performed without prior stentering. Nevertheless, it is instructive to examine what effect it could conceivably have on otherwise untreated material. Data relating to this is included in Table 3 (shown as 'setting time' of 0 s; 'scoured'), and it is clear that once again, there is a clear influence on initial modulus, which is dramatically reduced for both yarn types.

4.2.3. Heat-setting combined with scouring

As previously stated, the commercial purpose of heat-setting is to provide fabrics with stability towards downstream processing treatments, such as dyeing and finishing. We have shown that scouring (a necessary precursor to dyeing) in the absence of heat-setting can bring about changes in the PLLA fibres. The question remains as to whether heat-setting is able in fact to confer structural resistance to scouring, and if so, what duration is required. Table 3 and Fig. 5 include tensile data relating to the as-received yarns that have been scoured following heat-setting. As before, there is little to comment on as regards

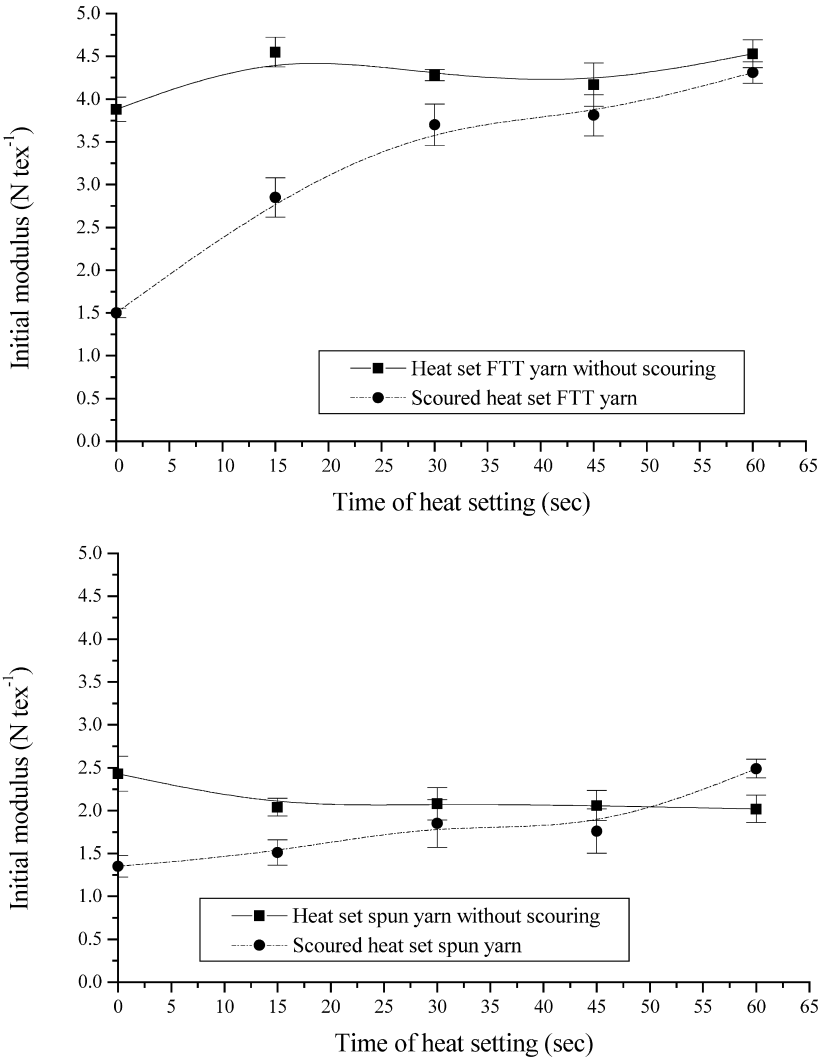

Fig. 5. Initial modulus as a function of heat-setting time, comparing scoured yarns with unscoured yarns: (a) FTT yarn; (b) spun yarn.

the ultimate properties, and therefore the data is confined to tabular form. However, it is clear that if the time of heat-setting is short, then scouring definitely does affect the initial moduli of both yarn types. For example, in the FTT case, heat-setting for 15 s without scouring gives a modulus of about 4.6 $Ntex^{-1}$, but scouring reduces it to around 2.9 $Ntex^{-1}$. Similarly, for the spun yarn, the modulus falls from about 2 $Ntex^{-1}$ to approximately 1.5 $Ntex^{-1}$.

It would appear that in order to minimise the destabilising effects of scouring it is necessary first to heat-set the yarns at 130 °C for a period of at least 45 s.

5. Conclusions

The main conclusions to be drawn from this limited study are:

1. the as-received spun and false-twist texturised PLLA yarns displayed differences in both tensile properties and morphology which we attribute to their quite different yarn-formation routes;
2. yarns taken from the fabrics derived from the spun and false-twist texturised PLLA yarns displayed different physical properties and morphology, as would be anticipated;
3. the tensile properties and morphology of the as-received yarns differed from those of yarns removed from the respective fabrics; this applied to both FTT and spun materials, and is provisionally attributed to unintended thermomechanical influences experienced by the fibres during the knitting process;
4. varying the time of heat-setting at 130 °C has little influence on the ultimate properties (extensibility and tenacity), but a measurable effect on the initial modulus; heat-setting for times shorter than about 15 s produces an increase in modulus of the FTT yarn and a decrease in modulus of the spun yarn; heating for longer times has little additional effect;
5. scouring alone at 60 °C causes a significant drop in the initial modulus of both PLLA yarn types;

6. yarns of both types (FTT and spun) may be stabilised to scouring by means of heat-setting at 130 °C, but this process must be continued for at least 45 s.

This last point is an important one which impinges on the energy-consumption, and hence the economics, of PLLA fabric production. In fact, studies such as our own do point up wider issues concerning the low softening and melting temperatures of PLLA, which may impose limitations on both the processing and subsequent end-usage of textile products based on the polymer.

Acknowledgements

The authors are indebted to Cargill-Dow Polymers for provision of materials. In addition, we would like to acknowledge helpful discussions held with Messrs J. Lunt, S. Sandukas, E. Young, S. Jones (Cargill-Dow), J. Bone and S. Dervan (DyStar).

References

[1] Lunt J, Bone J. Properties and dyeability of fibers and fabrics produced from polylactide (PLA) polymers. Proc. AATCC International Conference and Exhibition, Winston-Salem, NC, USA; September 17–20, 2000.
[2] Jacobsen S, Degée Ph, Fritz HG. Polym Engng Sci 1999;39(7):1311.
[3] Jacobsen S, Fritz HG, Degée Ph, Dubois Ph, Jérôme R. Ind Crops Products 2000;11:265.
[4] Gruber P, O'Brien M. Biopolymers, vol. 4: polyester III—applications and commercial products. Weinheim: Wiley-VCH; 2002. p. 235–239; ISBN: 3527302255.
[5] Hoogsteen W, Postema AR, Pennings AJ, Brinke GT. Macromolecules 1990;23:634.
[6] Dorgan JR, Lehermeier HJ, Palade LI, Cicero J. Macromol Symp 2001;175:55.
[7] Schmack G, Jehnichen D, Vogel R, Tändler B, Beyreuther R, Jacobsen S, Fritz H-G. J Biotechnol 2001;86:151.
[8] Mezghani K, Spruiell JE. J Appl Polym Sci 1998;36:1005.
[9] Kalb B, Pennings AJ. Polymer 1980;21:607.
[10] Horáček I, Kalíšek V. J Appl Polym Sci 1994;54:1751.
[11] Horáček I, Kalíšek V. J Appl Polym Sci 1994;54:1759.
[12] Horáček I, Kalíšek V. J Appl Polym Sci 1994;54:1767.
[13] Eling B, Gogolewski S, Pennings AJ. Polymer 1982;23:1587.
[14] Phillips DAS, Suesat J, Wilding MA, Farrington DW, Sandukas S, Bone J, Dervan S. Coloration Technology 2003;119(3):128.
[15] Lunt J, Sandukas S. (Cargill-Dow LLC). Private communication.
[16] Bell JP, Slade PE, Dumbleton JH. J Polym Sci A-2 1968;6:1773.
[17] Hearle JWS, Greer R. Text Prog 1970;2(4):68.
[18] Sarasua JR, Prud'homme RE, Wisniewski M, Borgne AL, Spassky N. Macromolecules 1998;31:3895.
[19] Lowe NE, Negulescu II. Thermal Behaviour of poly(lactic acid) related to the application of disperse dyes. Proc. AATCC International Conference and Exhibition, Winston-Salem, NC, USA; September 17–20, 2000.
[20] Miyata T, Masuko T. Polymer 1997;38(16):4003.

Glossary of terms

False-twist texturising (FTT): an in-line bulking process often applied to thermoplastic filament yarns; entails rapid heating of yarn to a temperature between T_g and T_m, followed by twisting, cooling and untwisting.
Tex: the standard unit of linear density, applied to textile fibres and filament yarns; the weight in g of a 1-km strand.
Ne: 'New English Cotton Count'; a measure of a yarn's 'fineness' or inverse linear density; effectively the number of 1693-metre lengths per kg weight of yarn (officially, the number of 840-yard 'hanks' per lb weight); used mostly for staple-spun yarns; Ne is equivalent, approximately, to 590/tex.
Liquor-goods ratio: used in wet processing of textiles to indicate the relative abundance of liquid and solid constituents; strictly speaking it is calculated on a mass:mass basis, but where the liquor is aqueous it amounts approximately to (volume of liquid in ml)/(mass of goods in g).