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Formation of and Coalescence from the Inclusion Complex of a Biodegradable Block Copolymer and α-Cyclodextrin: A Novel Means To Modify the Phase Structure of Biodegradable Block Copolymers

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ABSTRACT: A well-defined biodegradable block copolymer (PCL-*b*-PLLA, $M_n = 1.72 \times 10^4$, $M_w/M_n = 1.37$) of poly(ϵ-caprolactone) (PCL) and poly(L-lactide) (PLLA) was synthesized by a two-step ring-opening polymerization of ϵ-caprolactone and L-lactide. Furthermore, we found that α-cyclodextrin (α-CD) molecules may simultaneously thread onto both PLLA and PCL blocks of PCL-*b*-PLLA to form an inclusion complex (IC). Washing the copolymer−α-CD IC with hot water removed the α-CD, and the copolymer chains were coalesced. Very interestingly, the coalesced copolymer sample shows a great suppression in microphase separation, compared with the as-synthesized copolymer. In contrast to the significant decrease in crystallinity of ca. 50% and up to 79% for PCL and PLLA blocks, respectively, the melting points (T_m's) and the cold crystallization temperatures (T_{cc}'s) of both PCL and PLLA blocks of the coalesced sample increased in DSC measurements. These results may imply that only small amounts of more extended crystals, with less chain folding, were produced during the process of copolymer coalescence. Fourier transform infrared (FTIR) spectra, differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and wide-angle X-ray diffraction (WAXD) measurements were employed to demonstrate formation of the block copolymer−α-CD IC as well as to gauge the suppression of the microphase separation in the coalesced sample.

Introduction

Cyclodextrins (CDs) are cyclic oligomers of amylose, consisting of 6, 7, or 8 glucose units, and are named α-, β-, and γ-cyclodextrin.[1] Supramolecular inclusion complexes (ICs) organized by noncovalent interactions can be formed by threading CD molecules onto polymer chains. The driving force for the threading process is due to intermolecular hydrogen bonding between neighboring CDs as well as steric compatibility and hydrophobic interactions between host and guest molecules.[2−4] Since the discovery by Harada et al. that α-CD may form a crystalline IC with poly(ethylene glycol) in aqueous solution,[5] many kinds of linear polymeric guests with either hydrophilic or hydrophobic natures were found to have the ability to form ICs with different types of CDs. For instance, an IC of α-CD with the biodegradable poly(ϵ-lysine) was obtained recently by Yui et al.,[6] and according to literature reports, ICs of CDs and aliphatic polyesters have been studied by several groups.[7−9]

Aliphatic polyesters are biodegradable and biocompatible, and therefore constitute a very important class of biomaterials of growing interest in the field of biomedical applications, especially as matrices for controlled drug delivery systems.[10] In the biodegradable polyester family, poly(ϵ-caprolactone) (PCL) and poly(L-lactide) (PLLA) are two well-known representatives, whose syntheses and properties[11−13] have been extensively studied. PLLA has a high tensile strength and high melting point (ca. 160 °C) but low elongation at break due to the brittleness that results from its high crystallinity and a glass transition temperature above room temperature. In addition, the thermal processing window of PLLA is narrow, because it undergoes thermal degradation above its melting point. In contrast, PCL has high flexibility while its tensile strength and melting point (ca. 60 °C) are low. Therefore, these two polyesters are found to fall short of the required properties for many applications when they are used individually. To gain biomaterials of optimized properties from PLLA and PCL, two different approaches, blending and block copolymerization, are usually adopted. However, PCL and PLLA have been found to be incompatible. Phase separation exists in both block copolymer[12,13] and blend systems,[14] and high crystallinity for both components is detected.

We have reported an attempt to blend polymers by first forming their inclusion complex (IC) with cyclodextrin as the host and then coalescing the guest polymers from their CD−IC crystals by washing them with hot water. In this manner, we obtained an intimately mixed blend of PCL and PLLA,[9] which are normally incompatible. We believe that PCL and PLLA reside proximally at the molecular level in their common IC, and subsequent coalescence of PCL and PLLA from their common α-CD−IC crystals may yield an intimate mixing of PCL and PLLA chains, which turns the inherently immiscible PCL/PLLA pair into a compatible blend. For the coalesced PCL/PLLA blend, PCL chains did not show any crystallinity, and only a very small fraction (∼5%) of the PLLA was crystalline. Annealing the PCL/PLLA blend coalesced from their common IC crystals at 200 °C, which exceeds the melting point of

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both PCL and PLLA, did not induce any further phase separation as demonstrated by DSC and microscopic observations.

These results led us to attempt the formation of similar blends with amorphous polymer pairs, such as polycarbonate (PC)/poly(methyl methacrylate).[15] Again, intimately mixed blends were obtained via coalescence from their common CD−IC. On the basis of these results, we hoped that this method may also apply to block copolymer systems, thereby serving to lower the degree of microphase separation normally obtained. In this paper, we first describe the synthesis of PCL-*b*-PLLA by a step, ring-opening polymerization of ϵ-CL and L-lactide, then the formation of the IC of α-CD with PCL-*b*-PLLA, and finally the coalescence of the block copolymer from the α-CD IC crystals in the hope of reducing the phase separation and crystallinity of both PCL and PLLA blocks. To our knowledge, this is the first report in which the phase structure of a block copolymer is modified by coalescing the copolymer from its CD−IC.

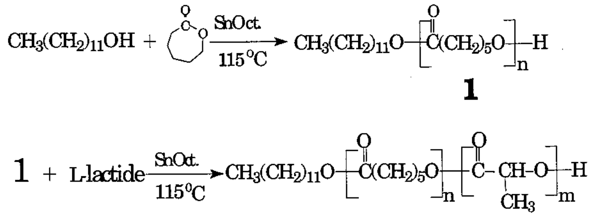
PCL-*b*-PLLA was selected for this study, not only because PCL and PLLA homopolymers may simultaneously form ICs with α-CD[9] and microphase separation exists in this copolymer system, but also because PCL-*b*-PLLA is a very useful biomaterial. It is well-known that the morphology of biodegradable polymers greatly affects their material performance, especially their biodegradation and permeability, which are of decisive importance in the controlled release of drugs. Crystallization usually leads to rough surfaces and porous structures. Furthermore, crystalline domains do not accommodate foreign molecules. Both of these factors favor the rapid release of drugs.[16] In contrast, amorphous polymers usually yield matrices with smooth surfaces and uniform structure.[17] Therefore, suppression of crystallinity should help improve the capacity of PCL-*b*-PLLA to encapsulate drugs and allow a more stable and more gradual release of drugs from their polymeric matrix.

Experimental Section

Materials. ϵ-Caprolactone and L-lactide (both from Aldrich) were purified as described in the literature.[13] Toluene (from Fisher) was dried over CaH_2 and distilled under dry argon. Stannous(II) octoate (SnOct, from Aldrich), α-CD (from Cerestar Co.), and methanol (from Fisher) were used as received. 1-Dodecanol (from Aldrich) was dried under high vacuum for 24 h at 60 °C, and then it was further dried by azeotropic distillation in dry toluene.

Synthesis of the Diblock Copolymer. Diblock copolymer was synthesized by a method similar to that reported previously.[13] Monohydroxyl PCL was first synthesized by using 1-dodecanol as an initiator and was subsequently used as a macroinitiator of polymerization of L-lactide to yield the diblock copolymer (Scheme 1). Typically, ϵ-CL, SnOct (ca. 0.1% of ϵ-CL in molar amount), and 1-dodecanol were weighed into a round-bottomed flask equipped with a magnetic stirring bar. The flask was sealed under argon and was immersed in an oil bath at 115 °C for 24 h. The product was purified by precipitating into cold methanol from dichloromethane solution. After being vacuum-dried for 48 h at 40 °C, the prepolymer was further dried by repeated azeotropic distillation in toluene before serving as the macroinitiator of polymerization of L-lactide. Under dry argon atmosphere, the polymerization of L-lactide catalyzed by SnOct (0.1% of L-lactide in molar amount) was performed at 115 °C for 24 h in toluene solution. To purify the copolymer, it was precipitated into cold methanol from toluene solution and subsequently from dichloromethane solution. The purified copolymer was dried for 48 h at 40 °C in a vacuum oven.

Scheme 1



Preparation of Samples. To prepare the inclusion complex, α-CD (15 g as received) was dissolved in distilled water (60 mL) and heated to 60 °C in a flask equipped with a condenser. PCL-*b*-PLLA (0.7 g) was dissolved in acetone (150 mL) and heated to 50 °C. Then the polymer solution was added dropwise to the α-CD solution. After stirring for 3 h at 60 °C, the solution was allowed to cool to room temperature while continuously stirring overnight. A white powder was collected by filtration and then washed repeatedly with dichloromethane and water to remove free polymer and uncomplexed α-CD, respectively. Finally, the IC was dried in a vacuum oven at 40 °C for 48 h. The coalesced sample was prepared by the same method we reported previously.[9]

Sample Characterization. Gel permeation chromatography (GPC) analysis was carried out using a Waters Styragel HR4 × 10^4 Å WAT044225 column with THF as an eluent and PMMA standards (Waters and American Polymer Standards) for column calibration. The eluent was analyzed with a differential refractometer R401 (Waters) together with a model 730 data module (Waters).

^1H NMR spectra were recorded on a Bruker 300 MHz DPX spectrometer in $CDCl_3$ at room temperature.

DSC measurements were performed at a heating rate of 10 °C/min on a Perkin-Elmer differential scanning calorimeter (DSC-7) calibrated with indium.

The thermal stabilities of as-synthesized copolymer, α-CD−copolymer IC, and coalesced copolymer samples were measured with a Perkin-Elmer Pyris 1 thermogravimetric analyzer (TGA) at a heating rate of 20 °C/min.

Powder X-ray diffraction analysis was conducted with a Seimens type-F X-ray diffractometer (30 kV, 20 mA) using Ni-filtered Cu Kα radiation. The specimens were mounted on aluminum frames and scanned from 5° to 40° (2θ) at a speed of 1.2°/min.

The FTIR spectral studies were carried out in a Nicolet 510P FTIR spectrometer in the range between 4000 and 750 cm^{-1}, with a resolution of 2 cm^{-1}. All powder samples were pressed into KBr pellets for the FTIR measurements.

Results and Discussion

Characterization of the Block Copolymer. The ^1H NMR spectrum shown in Figure 1 agrees well with the expected block structure of the copolymer. It is noteworthy that no peak at 3.65 ppm corresponding to the $HOCH_2-$ methylene proton signal of the PCL prepolymer[12,13] can be detected in the spectrum of the copolymer. Moreover, the GPC curve of the copolymer exhibits a unimodal distribution and an increase in molecular weight after copolymerization. Therefore, ^1H NMR and GPC measurements confirm that a well-defined diblock copolymer of PCL and PLLA was synthesized successfully. We are also able to calculate the copolymer composition (i.e., block lengths) from integration of characteristic peaks attributed to the PLLA block (e.g., methine carbon peak d at 5.15 ppm) as well as the PCL block (e.g., $-C(=O)-CH_2-$ peak b at ~2.3 ppm). The molecular characteristics of PCL-*b*-

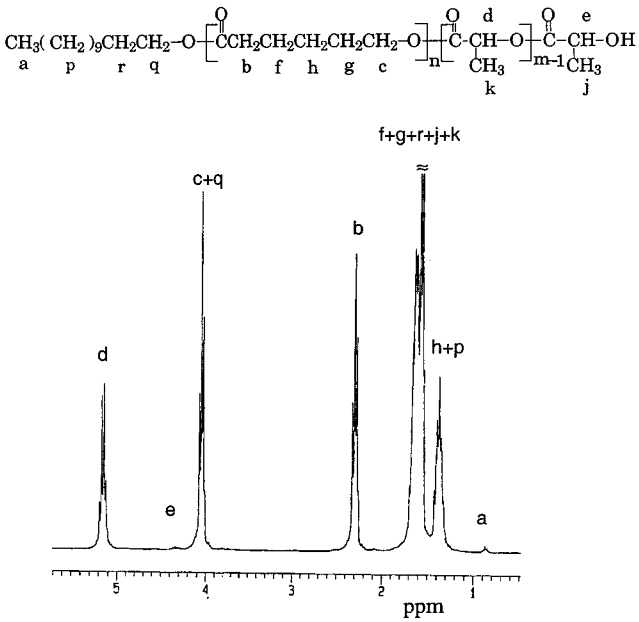


Figure 1. ^{1}H NMR spectrum of as-synthesized diblock copolymer of PCL and PLLA in CDCl$_3$.

Table 1. Molecular Characteristics of PCL-*b*-PLLA Diblock Copolymer

copolymer	DP$_{PCL}$^{a} (n^c)	DP$_{PLLA}$^{a} (m^c)	M_n^{a} × 10^{-3}	M_n^{b} × 10^{-3}	M_w/M_n^{b}
PCL-*b*-PLLA	94	82	16.8	17.2	1.37

[a] Calculated from the integration of characteristic signals in ^{1}H NMR spectra. [b] Determined by GPC measurements. [c] See Scheme 1.

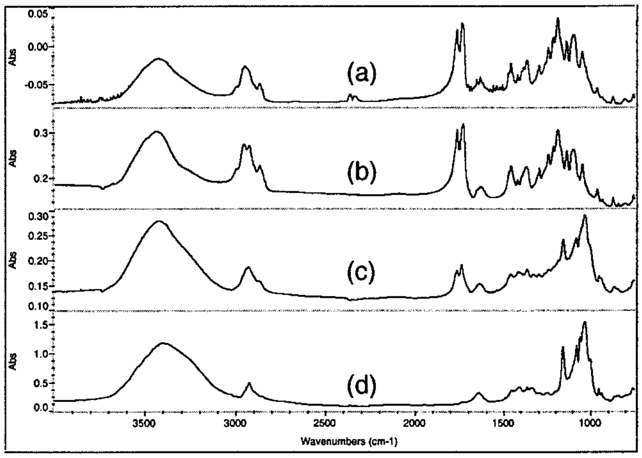


Figure 2. FTIR spectra of coalesced sample (a), as-synthesized PCL-*b*-PLLA (b), α-CD–copolymer IC (c), and α-CD (d).

PLLA obtained from GPC and ^{1}H NMR measurements are summarized in Table 1.

FTIR Analysis. Figure 2 shows the FTIR spectra of the coalesced copolymer sample, as-synthesized copolymer, the copolymer inclusion complex, and α-CD. The copolymer is characterized by strong and distinct peaks at ~1726 cm^{-1} (s, $V_{C=O}$ of PCL block) and ~1759 cm^{-1} (s, $V_{C=O}$ of PLLA block). α-CD is characterized by the three most intense bands at 1158 cm^{-1} (antisymmetric ν_s of the C–O–C glycosidic bridge) and 1079 and 1026 cm^{-1} (coupled $\nu_{s(C-C/C-O)}$).[18,19] Note also that the FTIR spectra of the coalesced and as-synthesized block copolymers are virtually identical, which is a strong indication that coalescence from its α-CD IC crystals has not degraded the block copolymer. The spectrum of the block copolymer α-CD IC shows signals from copolymer and α-CD, indicating that both α-CD and copolymer exist in the inclusion complex, although we cannot be sure if copolymer has been included by α-CD based on this information alone. On the other hand, it is clear that α-CD molecules were successfully removed during the coalescence process, because the spectrum of the coalesced sample does not show any recognizable signal from α-CD.

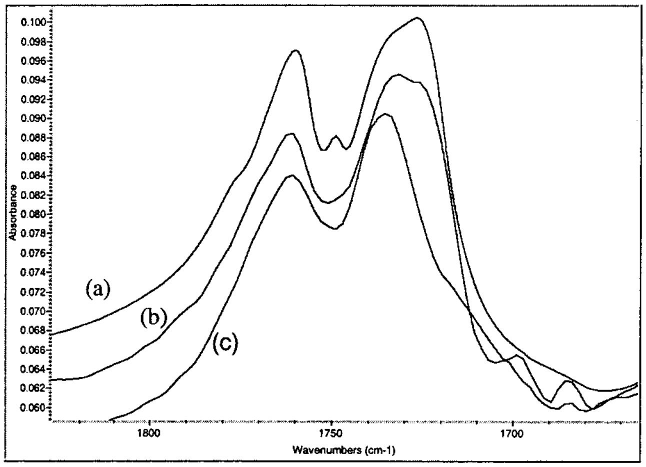


Figure 3. FTIR in the carbonyl region (s, $\nu_{C=O}$) for as-synthesized PCL-*b*-PLLA (a), coalesced sample (b), and α-CD–block copolymer IC (c).

Expansion of the carbonyl region of the spectra, as shown in Figure 3, gives us very helpful information concerning the formation of IC and the phase structures of the coalesced and as-synthesized copolymer samples. In Figure 3, the carbonyl absorption of the PLLA block is not well resolved into amorphous and crystalline bands for all samples. Therefore, we are not able to study the changes in phase structure of PLLA domains from the FTIR measurements. However, the PCL carbonyl absorption band of the as-synthesized copolymer are well resolved into a peak at 1726 cm^{-1} and a prominent shoulder at 1736 cm^{-1}, corresponding to the carbonyl absorption of the crystalline PCL phase and that of the amorphous PCL regions, respectively, according to previous research on semicrystalline PCL.[20] As shown in Figure 3, the C=O absorption of crystalline PCL regions completely disappears, and only the C=O absorption of noncrystalline PCL blocks is detected in the spectrum of the IC. This result indicates that no crystalline PCL phase exists in the inclusion complex, and all polymer chains have been involved in the inclusion process. Very interestingly, the absorption of crystalline PCL regions at 1726 cm^{-1} becomes weak and appears as a shoulder, while the absorption of the amorphous PCL regions at 1736 cm^{-1} is much stronger and becomes the main peak in the spectrum of the coalesced sample. This result at least demonstrates that the crystallization of PCL blocks has been significantly suppressed in the coalesced sample.

X-ray Diffraction. The wide-angle X-ray diffraction patterns of α-CD, as-synthesized copolymer, α-CD-copolymer IC, and the coalesced copolymer sample are presented in Figure 4. The diffraction pattern of as-synthesized copolymer clearly indicates the microphase-separated character in the crystalline regions. The characteristic peaks for PLLA crystalline phase[21] are observed at 16.5° and 18.7°, and the characteristic peaks

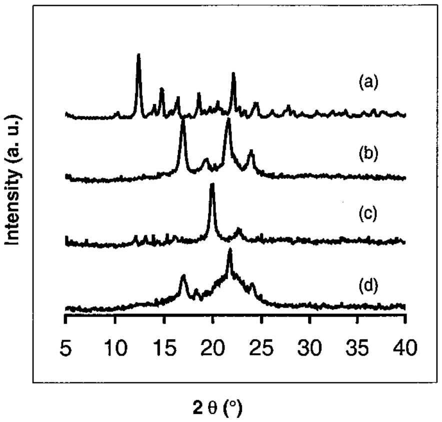


Figure 4. X-ray diffraction patterns of α-CD (a), as-synthesized PCL-*b*-PLLA (b), α-CD−block copolymer IC (c), and coalesced block copolymer sample (d).

for PCL crystalline phase[9] are observed at 22° and 23.8°. Major peaks at 9.6°, 12.03°, 19.5°, and 21.8° are observed for pure α-CD. The diffraction pattern of α-CD−copolymer IC is not a simple superimposition of the copolymer pattern onto that of α-CD. For the IC, no peaks corresponding to either the crystalline phases of PCL or PLLA are detected, and two prominent peaks are observed at 20° and 22.6° (2θ), which are well-known to be characteristic of α-CD-based IC crystals adopting a channel structure.[3,6,9] This indicates that copolymer and α-CD have formed an inclusion complex with a channel structure in which both the PCL and PLLA blocks of all copolymer chains are fully included inside the α-CD channel. Each copolymer chain is isolated from others by the surrounding α-CD molecules, and neither PCL block nor PLLA block may aggregate to form a crystalline phase other than the new generated IC crystals.

This result is consistent with the FTIR result that no carbonyl absorption attributed to the PCL crystalline phase can be detected in the IC spectrum. As shown in Figure 4d, the X-ray diffraction pattern of the coalesced sample is different from that of both as-synthesized block copolymer and the block copolymer α-CD IC. No diffraction peaks are observed at 12.03°, 20°, and 22.6° for the coalesced sample. This demonstrates that the IC crystals were disrupted and the α-CD molecules were completely removed, when washing the IC crystals with hot water and coalescing the copolymer chains together. This result agrees with the FTIR observation that no signal is detected from α-CD for the coalesced sample.

Diffraction peaks corresponding to PCL and PLLA crystalline phases are present in the diffraction pattern of the coalesced sample, but it is noteworthy that the diffraction intensity of both PCL and PLLA crystalline phases is much weakened in comparison with that of as-synthesized copolymer. On the other hand, the scattering from amorphous regions clearly becomes stronger than that observed for the as-synthesized copolymer. From these results, we are able to draw the conclusion that the crystallization of both PCL and PLLA blocks has been substantially suppressed in the coalesced sample. Very similar results have been obtained not only from the previous FTIR observations but also from TGA and DSC measurements, which will be discussed now.

Thermal Analysis. The thermal decomposition behaviors of α-CD, as-synthesized copolymer, copolymer IC, and the coalesced block copolymer sample revealed by TGA measurements are shown in Figure 5. Two significant changes in the slopes of the degradation curves can be observed for the as-synthesized copolymer corresponding to the decompositions of phase-separated PLLA and PCL blocks, respectively. The two transitions almost disappear in both the IC and the coalesced samples. The fact that the IC shows unimodal decomposition behavior different from that of the as-synthesized copolymer implies that no free copolymer exists in the IC, and both PCL and PLLA blocks of each copolymer chain have been fully included inside the IC channel. In our previous research, when we coalesced PC/PMMA from their common IC crystals, the resulting intimate blend also showed unimodal decomposition behavior, while two distinct weight-loss transitions were observed in the TGA scans of the PC/PMMA physical blends.[15] We have concluded on the basis of those results that the two intimately mixed polymers have some effect on each other's decomposition, and the two polymers codegrade at a molecular level in the intimate blends. The similar results obtained in the present research on the coalesced block copolymer sample also indicate that microphase separation has been much suppressed in comparison with the as-synthesized copolymer.

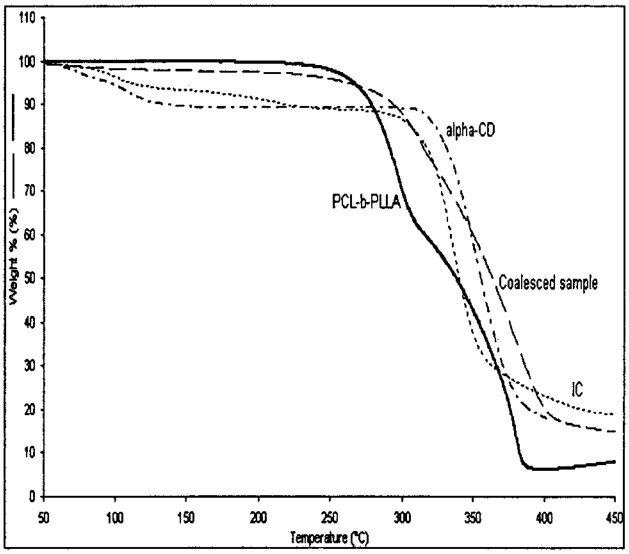


Figure 5. Comparison of thermal degradation behaviors observed in TGA scans.

Although the coalesced sample still contains some PCL and PLLA crystals as revealed by FTIR, WAXD, and also, as we shall see, DSC, it appears reasonable to claim that the proportion of isolated PCL or PLLA phases is relatively low, and the size of crystalline domains is quite small. DSC measurements also show convincing evidence, indicating that the crystallization of both PCL and PLLA blocks has been significantly suppressed in the coalesced sample.

The first heating run DSC thermograms of α-CD, IC, and the as-synthesized and coalesced copolymer samples are shown in Figure 6. The copolymer−α-CD IC does not show any thermal transitions, indicating again that in the IC both PCL and PLLA blocks of all copolymer chains have been included inside the cylindrical channels of α-CD. Since the composition of the copolymer has been ascertained by us, as shown in Table 1, we are able to calculate the crystallinity of PCL and PLLA blocks based on their enthalpies of fusion determined by DSC measurements, with the following equation:

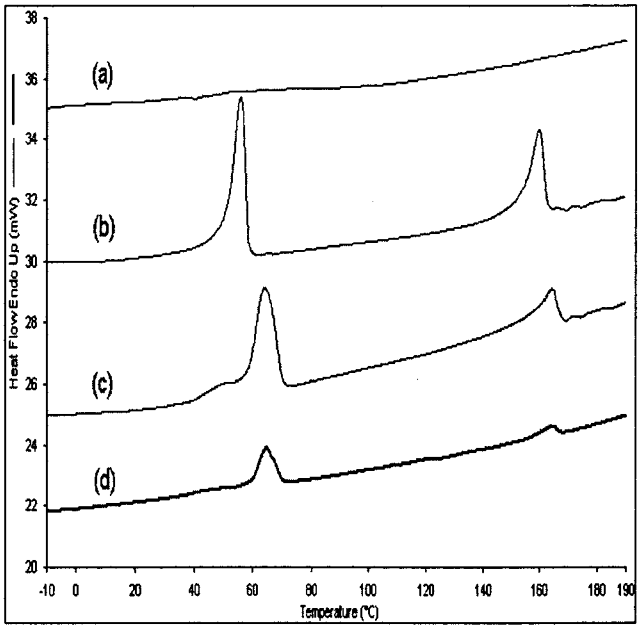


Figure 6. First heating run DSC thermograms of α-CD−block copolymer IC (a), as-synthesized PCL-*b*-PLLA (b), coalesced sample (c), and coalesced sample after annealing for 30 min at 190 °C (d).

$$X_c = \Delta H/(\Delta H°W)$$

where ΔH is the apparent enthalpy of each block indicated in DSC thermograms as melting enthalpy per gram of sample, ΔH° is the melting enthalpy of the corresponding block in its completely crystalline state (93 J/g for PLLA[22] and 139 J/g for PCL[23]), and *w* is the weight fraction of corresponding block calculated from the copolymer composition.

The thermal properties of as-synthesized and coalesced copolymers revealed in the first heating or cooling run DSC measurements are summarized in Table 2. The crystallinity of PCL blocks in the coalesced sample has decreased to 25.2% from 48.1% of the as-synthesized copolymer, nearly a 50% decrease. In contrast, the crystallinity of the PLLA blocks in the coalesced sample shows a more significant decrease from 66% in the as-synthesized copolymer to just 13.4%, a decrease of 79%.

Interestingly, as shown in Table 2, the melting temperatures of both PCL and PLLA blocks exhibit an obvious increase in the coalesced block copolymer sample, pointing to an enhanced thermal stability of the crystals of both blocks. Similar results were observed in our earlier research on PLLA/PCL blends.[9] This may imply that more extended crystals with less chain folding were also produced during the coalescence of our block copolymer.

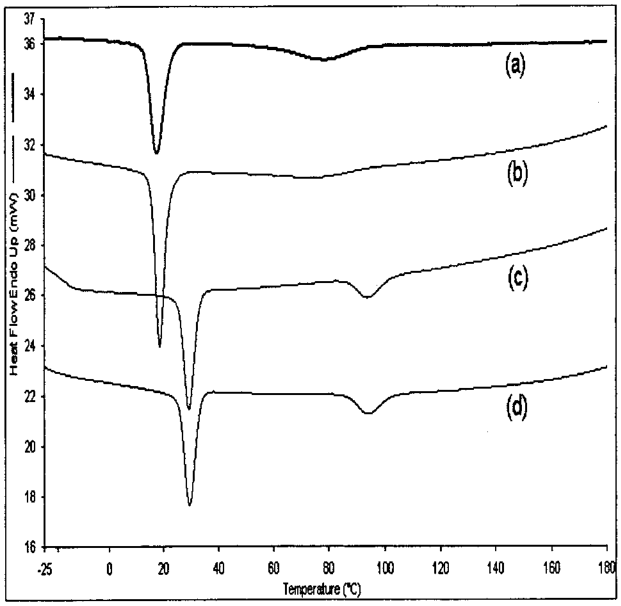


Figure 7. Cooling run DSC thermograms of as-synthesized PCL-*b*-PLLA, first cooling (a) and second cooling (b); coalesced sample, first cooling (c) and second cooling (d). Annealing time for both samples is 10 min.

The crystallization behavior of the coalesced sample is very different from that of as-synthesized copolymer, as shown in Figure 7 and Table 2. The cold crystallization temperature (T_{cc}) of PCL blocks in the coalesced sample is 12 °C higher than that of PCL blocks in the as-synthesized copolymer, and T_{cc} of PLLA blocks in the coalesced sample is 16 °C higher than that of PLLA blocks in the as-synthesized copolymer. Considering that we detected a slight decrease in the T_{cc} of PLLA when coalescing it from the PLLA−α-CD IC,[9] we believe that the increase in T_{cc}'s of PCL and PLLA blocks is not due to the chain extension of crystals revealed by the increased T_m's. Chemical and/or physical interactions between polymer blend components may lead to changes in their cold crystallization temperatures (T_{cc}'s). Therefore, attention is often paid to T_{cc} shifts during the study of component compatibility in polymer blends.[21,24,25] The significant increase in the T_{cc}'s of PCL and PLLA blocks indicates that it is difficult for both of them to crystallize in the coalesced sample. Further, it is reasonable to conclude that PCL and PLLA blocks have been reasonably intimately mixed in the coalesced sample; therefore, each block is not allowed to crystallize as easily as in the phase-separated, as-synthesized copolymer.

To sum up, the results of FTIR, WAXD, and DSC measurements clearly show two features indicating the effect of the coalescence process on the phase structure of the copolymer. The two blocks have been more intimately mixed and therefore the crystallization of both PCL and PLLA blocks has been greatly suppressed, and second a small proportion of PCL and PLLA blocks are still able to aggregate to form independently small crystals. These features are theoretically reasonable, because in the process of IC formation, both identically oriented chains and oppositely oriented chains have the opportunity to reside in neighboring IC channels. Therefore, the phase transitions during IC formation and

Table 2. Thermal Properties of As-Synthesized and Coalesced Block Copolymer Samples[a]

identity	T_{m-PCL} (°C)	T_{cc-PCL} (°C)	ΔH_{PCL} (J/g)	X_{c-PCL} (%)	T_{m-PLLA} (°C)	$T_{cc-PLLA}$ (°C)	ΔH_{PLLA} (J/g)	X_{c-PLLA} (%)
as-synthesized block copolymer	56.1	17.6	66.89	48.1	159.7	77.9	61.42	66
coalesced sample	63.7	29.3	35.01	25.2	164.3	93.9	12.49	13.4

[a] Results of first heating and cooling run DSC measurements. ΔH's are calculated on the basis of the copolymer composition (64% PCL fraction, in wt %).

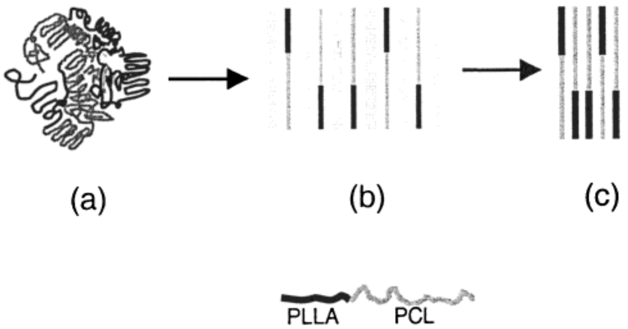


Figure 8. Proposed phase transition of as-synthesized copolymer (a) to IC (b), and to coalesced copolymer sample (c), during the processes of IC formation and copolymer coalescence.

copolymer coalescence may be roughly illustrated as in Figure 8. To gain deeper insight into the whole process, we are beginning to study the coalesced sample by means of various solid-state NMR techniques.

We have mentioned that, in the coalesced sample, the crystallinity of PCL and PLLA blocks has been greatly lowered by 50% and 79%, respectively. Still, it is noteworthy that the decrease in the degree of crystallinity for the PLLA block is much higher than that for the PCL block. To account for this phenomenon, the block lengths of the copolymer were calculated from its composition as revealed by the ^{1}H NMR measurements. Although the molar ratio of repeat units for the two blocks is close to 1:1, as shown in Table 1, PCL blocks are much longer than PLLA blocks. The PCL blocks contain an average of 658 bonds, while the PLLA blocks contain 246 bonds on average, in the main chain. This means that the segments of two PCL blocks are still able to aggregate even in the case that two copolymer chains with completely opposite orientations are coalesced, according to Figure 8. Therefore, the crystallization of PCL blocks would not be expected to be suppressed as much as that of PLLA blocks.

Annealing the sample at 190 °C for 30 min does not lead to a significant increase of crystallinity for both blocks, and the T_m's of the PCL and PLLA blocks of the coalesced sample do not show obvious shifts upon annealing, as shown in Figure 6. These results demonstrate that the intimacy of the two blocks in the coalesced sample did not change much even after heating at 190 °C.

Conclusions

A block copolymer of PCL and PLLA (ca. 1:1 molar ratio) was synthesized by ring-opening polymerization of ϵ-caprolactone and L-lactide. Furthermore, PCL and PLLA blocks were found to be able to be included simultaneously by α-CD to form an inclusion complex with a channel-type crystalline structure. By washing the IC crystals with hot water, α-CD molecules were removed and copolymer chains were coalesced. TGA, FTIR, WAXD, and DSC measurements demonstrate that phase separation of the PCl and PLLA blocks in the coalesced sample has been substantially suppressed, in comparison with the as-synthesized copolymer. DSC measurements show that the crystallinity of PCL and PLLA blocks has decreased by ca. 50% and up to 79%, respectively, in the coalesced sample. In addition, WAXD and DSC results show evidence indicating more amorphous regions exist in the coalesced sample.

Nevertheless, some small and possibly more extended PCL and PLLA crystals, with less chain folding, are observed to still be present in the coalesced sample, based on the results of FTIR, WAXD, and DSC measurements. From the copolymer composition revealed by ^{1}H NMR measurement, the PCL blocks are much longer than the PLLA blocks. Consequently, the segments of two PCL blocks are still able to aggregate even in the case that two copolymer chains with completely opposite orientations are coalesced together. Therefore, the suppression of PCL block crystallinity is much less than that of the PLLA blocks in the coalesced sample. These results allow us to surmise that, during IC formation and coalescence of copolymer from the IC crystals, copolymer chains of both identical and opposite orientations are isolated and distributed randomly into the IC channels constructed by α-CD molecules. Therefore, the chance for both PCL and PLLA blocks to self-aggregate during the coalescence process is much reduced compared to the solidification of the block copolymer from solution. We believe that the novel method reported here for modifying the phase structures of block copolymers may also be applicable to other microphase-separated copolymer systems if both blocks of the copolymer are able to form inclusion complexes with CD molecules.

Ongoing research in our group is being conducted to improve our understanding of the effects of block copolymer structures (e.g., di-, tri-, or multiblocks), relative length of blocks, and the CD types on the morphology of both IC and coalesced block copolymer samples.

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