Properties and Morphology of Poly(L-lactide). III. Effects of Initial Crystallinity on Long-Term *In Vitro* Hydrolysis of High Molecular Weight Poly(L-lactide) Film in Phosphate-Buffered Solution

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ABSTRACT: The effects of crystallinity (x_c) on the hydrolysis of high molecular weight poly(L-lactide) (PLLA) films in a phosphate-buffered solution at 37°C was investigated by gel permeation chromatography, tensile testing, differential scanning calorimetry, scanning electron microscopy, and polarizing optical microscopy. The change in molecular weight distribution and surface morphology of the PLLA films after hydrolysis revealed that the hydrolysis of PLLA film in a phosphate-buffered solution proceeded homogeneously along the film cross section, mainly via the bulk-erosion mechanism. The induction period until the start of the decrease in mass remaining and the tensile strength became longer with a decrease in the initial x_c of the PLLA films. The rate of molecular weight reduction was higher as the initial x_c of the PLLA films increased when hydrolysis was carried out up to 24 months. Melting and glass transition temperatures of the PLLA films increased in the first 12 months of hydrolysis, while they decreased in another 24 months, irrespective of the initial x_c. The x_c value of the PLLA films increased monotonously by hydrolysis. The lamella disorientation in PLLA spherulites after hydrolysis implied that the hydrolysis of PLLA chains occurred predominantly in the amorphous region between the crystalline regions in the spherulites. The area of a specific molecular weight in GPC spectra at 36 months increased with increase in the initial x_c of the PLLA film, suggesting that the specific peak should be due to the component of one fold in the crystalline region. The reason for enhanced hydrolysis of PLLA films having higher initial crystallinities was discussed in terms of tie chains and terminal groups of PLLA. J Appl Polym Sci 77: 1452–1464, 2000

Key words: polylactide; poly(lactic acid); hydrolysis; degradation; crystallinity

INTRODUCTION

The family of lactide (or lactic acid) and glycolide (or glycolic acid) polymers has been intensively studied because of their hydrolyzability in the human body as well as in natural circumstances.[1–7] In a previous study of this series, we investigated nonenzymatic hydrolysis of poly(L-lactide) (PLLA) films having different crystallinities, crystalline thicknesses, and spherulite sizes in a dilute alkaline solution of pH 12.[8] This work disclosed the following:

1. Hydrolysis of PLLA film in a dilute alkaline solution proceeded mainly via a surface-erosion mechanism.

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2. Hydrolysis of PLLA chains occurred predominantly in the amorphous region between the crystalline regions inside and outside the spherulites.
3. The radius of spherulites had practically no significant effect on the hydrolysis of PLLA film.
4. The specific low molecular weight of PLLA chains produced by hydrolysis was due to the component of one fold in the crystalline region.

However, the hydrolysis mechanism of PLLA film in a phosphate-buffered solution with pH around 7 seems to differ from that in a dilute alkaline solution.[8] Li et al.[9] and Migliaresi et al.[10] studied *in vitro* hydrolysis of amorphous and crystallized PLLA specimens in phosphate-buffered and Ringer solutions up to 21 and 26 months utilizing PLLAs having initial weight-average molecular weights of 1.3×10^5 and 1.8×10^5, respectively. Since Li et al. reported that hydrolysis was accelerated at the core of the PLLA specimens having a thickness of 2 mm due to the catalytic effect of oligomers trapped in their core,[9] similar acceleration must have occurred in PLLA specimens having a similar thickness of 1.5 mm studied by Migliaresi et al.[10]

The purpose of this work was to study the effects of the initial crystallinity of high molecular weight PLLA films on their long-term *in vitro* hydrolysis in a phosphate-buffered solution. For this purpose, we prepared PLLA films having different crystallinities starting from a single PLLA source having a high weight-average molecular weight (1.3×10^6) by annealing or crystallization of solution-cast films at a fixed temperature for different durations from the melt.[11] As will be shown below, each of annealed PLLA films having different crystallinities has approximately the same molecular weight after annealing. Therefore, only the crystallinity effect on hydrolysis will be observed. To exclude the acceleration effect of trapped oligomers at the core of the PLLA specimen, the thickness of the PLLA films was kept as thin as 50 and 25 μm.[12] This study employed a phosphate-buffered solution as a hydrolysis medium because of an insignificant difference in PLLA hydrolysis between the phosphate-buffered solution and *in vivo*.[13,14] Hydrolysis of PLLA film was performed up to 36 months and the hydrolyzed films were studied using gel permeation chromatography (GPC), tensile testing, differential scanning calorimetry (DSC), gravimetry, scanning electron microscopy (SEM), and optical polarizing microscopy.

EXPERIMENTAL

Materials

The synthesis and characterization of PLLA used in this work were described in detail in previous articles.[8,11,15,16] PLLA films for hydrolysis were prepared from purified PLLA ($M_v = 3.9 \times 10^5$, $M_w = 1.3 \times 10^6$, and $M_w/M_n = 2.1$) with the method described in previous articles.[8,11] Briefly, PLLA films of 25 ± 5 and 50 ± 10 μm thickness were placed between two microcover glasses and sealed in a glass tube under reduced pressure. The sealed PLLA films were melted at 200°C for 3 min and annealed at 140°C for predetermined times (t_a) or the PLLA films were melted at 200°C for 3 min and quenched at 0°C. All the annealed films were quenched at 0°C to avoid further crystallization. PLLA films annealed for 0, 15, 30, 45, and 60 min are abbreviated PLLA0, PLLA15, PLLA30, PLLA45, and PLLA60 films, respectively. The thickness of the starting PLLA films was either 50 or 25 μm.

Hydrolysis

Hydrolysis of the PLLA films (18 × 30 mm) was performed in 10 mL of 0.15*M* of the phosphate-buffered solution (pH 7.4 ± 0.1) at 37°C for predetermined periods of time, exchanging the buffered solution once a month. After hydrolysis, the PLLA films were washed intensively with double-distilled water at room temperature, followed by drying under reduced pressure for at least 2 weeks.

Measurements

The crystallization and melting temperatures (T_c and T_m, respectively) and the enthalpy of crystallization and melting (ΔH_c and ΔH_m, respectively) of the PLLA films were determined with a Shimadzu DT-50 differential scanning calorimeter. The PLLA films were heated under a nitrogen gas flow at a rate of 10°C/min for the DSC measurements. T_c, T_m, ΔH_c, and ΔH_m were calibrated using tin, indium, and benzophenone as standards. The crystallinity (x_c) of the PLLA films was evaluated according to the following equation[8,11]:

Table I Characteristics of 50-μm-Thick PLLA Films Before and After Hydrolysis in Phosphate-buffered Solution for 3 Years

Sample Code	x_c (%)		$M_w/10^5$ (g/mol)		M_w/M_n		T_m (°C)		SR_m[a] (μm)	
	Before	After	Before	After	Before	After	Before	After	Before	After
PLLA0	0	29	10.8	0.69	2.0	4.6	177	171	0	
PLLA15	2	34	10.9	0.64	2.0	6.5	177	172	20	
PLLA30	30	63	10.8	0.25	2.1	6.4	181	174	50	
PLLA45	45	76	10.5	0.15	2.1	4.8	182	175	80	
PLLA60	54	78	11.1	0.19	1.9	4.2	182	176	110	

Sample Code	Tensile Strength (kg/mm^2)		Young's Modulus (kg/mm^2)		Elongation at Break (%)	
	Before	After	Before	After	Before	After
PLLA0	5.0	0.4	174	90	27	0.6
PLLA15	4.4	0.3	171	65	26	0.5
PLLA30	5.0	0.0	181	0	21	0.0
PLLA45	5.3	0.0	199	0	13	0.0
PLLA60	5.6	0.0	184	0	12	0.0

[a] Maximum radius of spherulite estimated for 25-μm-thick film.

$$x_c\ (\%) = 100(\Delta H_m + \Delta H_c)/93 \qquad (1)$$

where 93 (J/g of the polymer) is the enthalpy of melting of the PLLA crystal having the infinite crystal thickness reported by Fischer et al.[17]

Molecular weights and their distribution were evaluated in chloroform at 40°C by a Tosoh GPC system with TSK gel columns ($GMH_{XL} \times 2$) using polystyrene as a standard. The tensile properties of the PLLA films were measured at 25°C and 50% relative humidity using a tensile tester at a crosshead speed of 100%/min. The initial length of specimens was always kept at 20 mm.

Microscopy

The morphology of the PLLA films was studied with an SEM (Hitachi S-2300) and a Zeiss polarizing microscope. The thickness of the PLLA films utilized for microscopic observation was 25 μm. The PLLA films for SEM observation were coated with carbon to a thickness of about 20 nm.

RESULTS

Table I tabulates the observed values of x_c, M_w, M_w/M_n, T_m, tensile strength, Young's modulus, and elongation at break of PLLA films with a thickness of 50 μm and the maximum spherulite radius (SR_m) of the films with a thickness of 25 μm before and after hydrolysis in the phosphate-buffered solution for 36 months at 37°C. As seen, the PLLA films have different x_c, but approximately the same initial M_w. This indicates that no significant chain scission of PLLA occurred during annealing at 140°C under a very small decrease in M_w from 1.3×10^6 to 1.1×10^6 during melting at 200°C. T_m decreased upon hydrolysis for all the films, while their x_c significantly increased. M_w/M_n increased for all PLLA films after hydrolysis, irrespective of the t_a. The SR_m value was given only for the films before hydrolysis in Table I, since no significant change was observed for SR_m after hydrolysis, in agreement with the result for the PLLA films hydrolyzed in an alkaline solution.[8] PLLA0 and PLLA15 films have nonzero tensile strength, Young's modulus, and elongation at break 36 months after hydrolysis, although these values are practically zero for the PLLA30, PLLA45, and PLLA60 films. Figure 1 shows polarizing optical photomicrographs of PLLA15, PLLA30, PLLA45, and PLLA60 films before hydrolysis. It is seen that the radius of the PLLA spherulites and the area covered with the spherulites increased with the t_a.

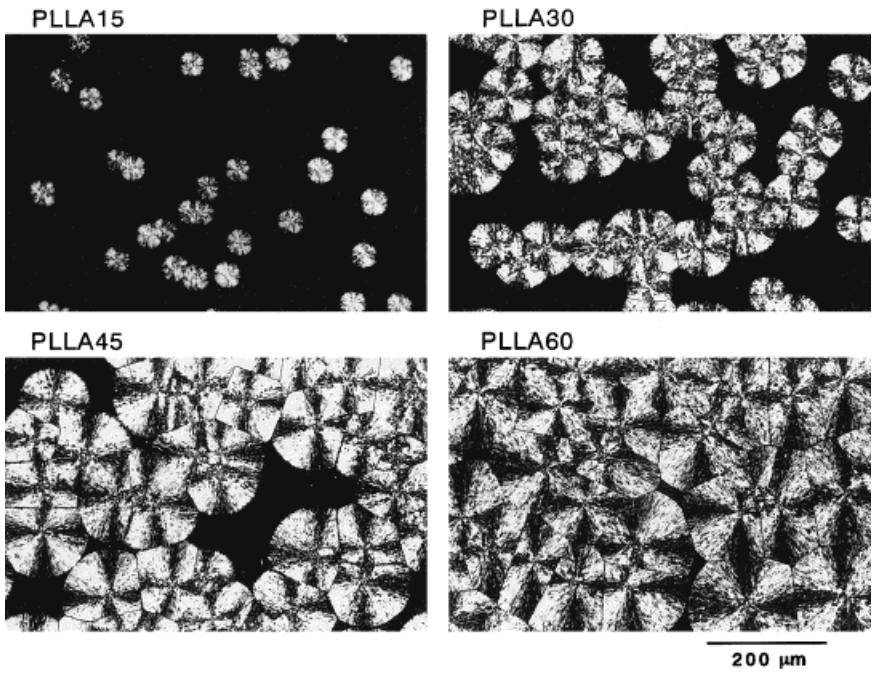

Figure 1 Polarizing photomicrographs of PLLA15, PLLA30, PLLA45, and PLLA60 films before hydrolysis.

Mass Remaining

Figure 2 shows the mass remaining for PLLA0, PLLA15, PLLA30, PLLA45, and PLLA60 films as a function of hydrolysis time. The mass loss is an index for the content of water-soluble oligomers formed by hydrolysis and then released from the mother PLLA films into the surrounding medium. Film mass remained unchanged, although hydrolysis was allowed to preceed up to 18 months for all the samples and the mass loss started 24 months after hydrolysis. The mass decrease rate became higher with an increase in t_a or the initial x_c before hydrolysis. No mass change for the PLLA0 film up to 36 months suggests that water-soluble oligomers were formed to an insignificant extent. This film was prepared by melt-quenching to have zero x_c before hydrolysis. The induction period until the apparent mass decrease was shorter for crystallized PLLA films than for the initially amorphous PLLA0 film. This result is in good agreement with that reported by Li et al. (in a phosphate-buffered solution),[9] Nakamura et al. (*in vivo*),[18] and Pistner et al. (*in vivo*).[19] Our previous study on blend films prepared from an amorphous poly(DL-lactide) and a crystallizable poly(D-lactide) or PLLA at different blending ratios and contents of the crystalline region[20] was also in agreement with this finding. The period required until the start of mass decrease was longer in this study for both the crystallized and

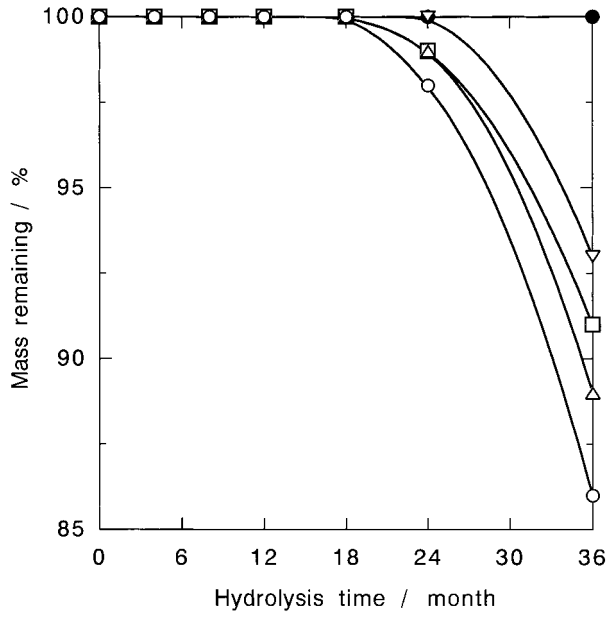

Figure 2 Mass remaining of PLLA films as a function of hydrolysis time: (●) PLLA0; (▽) PLLA15; (□) PLLA30; (△) PLLA45; (○) PLLA60.

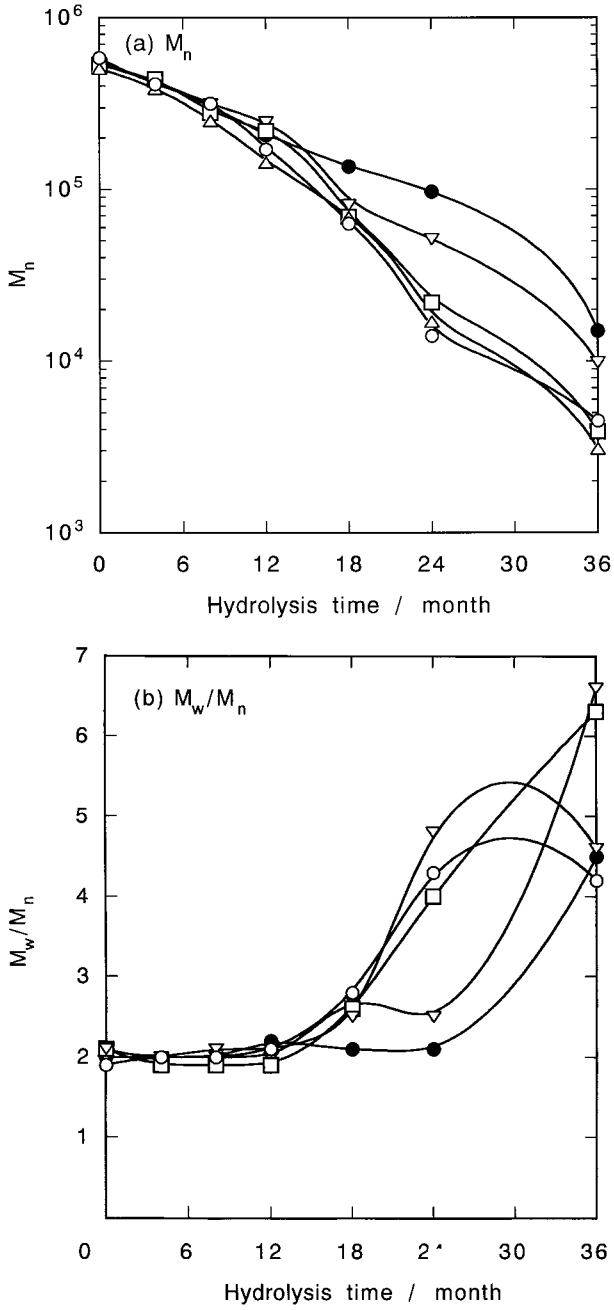

Figure 3 (a) M_n and (b) M_w/M_n of PLLA films as a function of hydrolysis time: (●) PLLA0; (▽) PLLA15; (□) PLLA30; (△) PLLA45; (○) PLLA60.

amorphous PLLA specimens than that reported before.[9,10,18,20]

Molecular Weight

Figure 3 shows M_n and M_w/M_n values of PLLA0, PLLA15, PLLA30, PLLA45, and PLLA60 films as a function of hydrolysis time. There was no significant difference in M_n between these PLLA films up to 12 months of hydrolysis, while the M_n of PLLA films hydrolyzed for longer than 12 months was lower for PLLA films having a higher initial x_c. The initial rapid decrease in the M_n of PLLA with the initial high x_c is comparable with the result reported by Migliaresi et al. (in Ringer solution)[10] and Nakamura et al. (*in vivo*).[18] M_w/M_n remained around 2 for all the PLLA films hydrolyzed up to 12 months, but became larger than 2 when hydrolysis was continued for longer than 12 months. The induction period required for an increase in M_w/M_n was longer for the PLLA0 film having a zero initial x_c than for the others having nonzero x_c.

Figure 4 shows GPC spectra of PLLA0 and

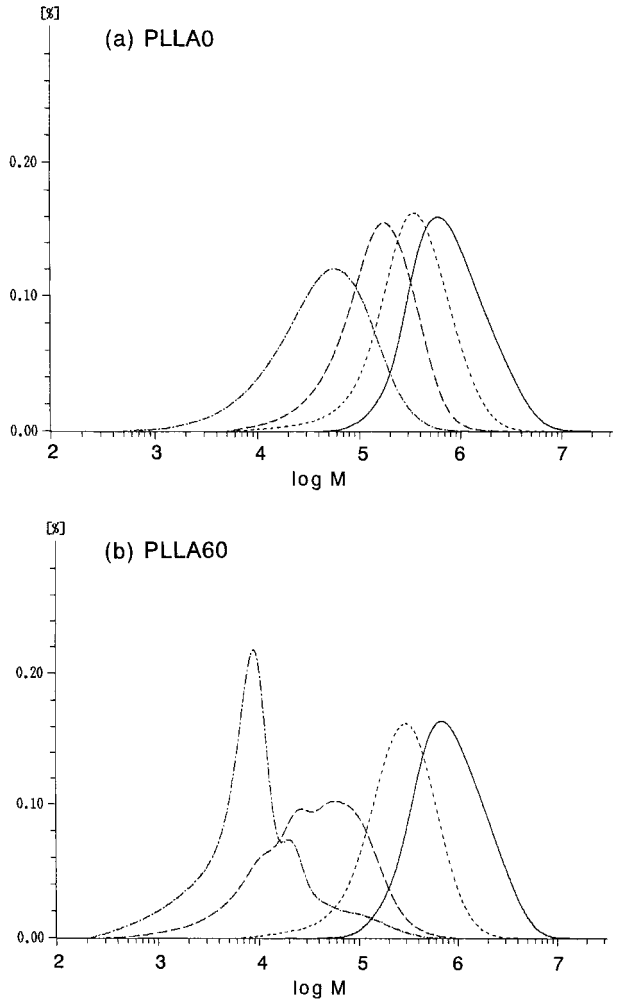

Figure 4 GPC spectra of (a) PLLA0 and (b) PLLA60 films after hydrolysis for different times: (—) 0 month; (·····) 12 months; (-----) 24 months; (-•-•-) 36 months.

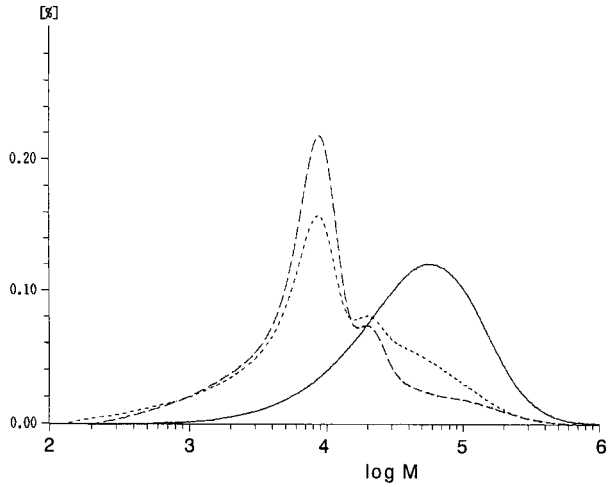

Figure 5 GPC spectra of (—) PLLA0, (· · · · ·) PLLA30, and (-----) PLLA60 films after hydrolysis for 36 months.

PLLA60 films hydrolyzed for different periods of time. The PLLA0 and PLLA60 films have initial x_c of 0 and 54%, respectively, before hydrolysis. The molecular weight of the PLLA0 film shifted to lower values on the whole without formation of any specific peak originating from crystalline regions during hydrolysis up to 36 months. This suggests that the crystalline regions formed during hydrolysis insignificantly influenced the molecular weight distribution of the PLLA0 film. This is in marked contrast with the reported results, which demonstrated specific peak formation for PLLA specimens with the zero initial crystallinity during hydrolysis.[9,10,19]

On the other hand, the molecular weight of the PLLA60 film shifted to lower values accompanying peak formation around the molecular weight of 9×10^3 when hydrolysis was carried out for longer than 24 months. The molecular weight of the specific peak position was higher for PLLA films hydrolyzed in the phosphate-buffered solution (8.8×10^3) than for those hydrolyzed in alkaline solution (5.7×10^3) (ref. 8) when both specimens were prepared by annealing at 140°C, suggesting strong hydrolyzability of the PLLA crystalline region in the alkaline solution. The time required for the specific peak formation of crystallized PLLA in this study (24 months) was longer than that reported for PLLA hydrolysis in the phosphate-buffered solution (12 months)[9] and *in vivo* (2 months).[19]

Figure 5 shows GPC spectra of PLLA0, PLLA30, and PLLA60 films 36 months after hydrolysis. The PLLA30 film (initial x_c = 30%) showed the spectrum intermediate between that of the PLLA0 and PLLA60 films.

To study in more detail the effect of initial x_c on PLLA hydrolysis, the hydrolysis rate constant (k) at different periods of hydrolysis time was calculated according to the following procedure. The kinetic equation expressing the scission of molecular chains during hydrolysis can be derived under the assumption that scission is autocatalyzed by terminal carboxyl groups of PLLA chains, occurring proportionally to the water and ester concentrations[21]:

$$d[\mathrm{COOH}]/dt = k'[\mathrm{COOH}][\mathrm{H_2O}][\mathrm{ester}] \quad (2)$$

where [COOH] is the concentration of the terminal carboxyl group. If $[H_2O]$[ester] is assumed to be constant, integration of eq. (2), coupled with the relationship [COOH] $\propto M_n^{-1}$, gives eq. (3):

$$M_{n,t} = M_{n,0} \exp(-kt) \quad (3)$$

where $M_{n,t}$ and $M_{n,0}$ are the number-average molecular weight at hydrolysis time = t and 0, respectively, and k is equal to $k'[H_2O]$[ester]. Equation (3) can be converted to eq. (4):

$$\ln M_{n,t} = \ln M_{n,0} - kt \quad (4)$$

The k values evaluated according to eq. (4) are plotted in Figure 6 for a hydrolysis of 0–12 months, 12–24 months, and 24–36 months. The k value of $2 - 7 \times 10^{-3}$ day^{-1} was comparable with that for compression-molded PLLA found by Cha and Pitt[21] (6.72×10^{-3} day^{-1} for 0–42 days) and that for our solution-cast PLLA (5.20×10^{-3} day^{-1} for 0–20 months).[22] The k values for 0–12 months and 12–24 months increased with an increase in the initial x_c, while the PLLA60 film had the lowest k value for 24–36 months. The k value for PLLA 30, PLLA45, and PLLA60 films increased and exhibited a maximum at hydrolysis times of 12–24 months, followed by a decrease. This is in agreement with the degradation rate dependence of initially crystallized PLLA specimens on hydrolysis time, estimated by the method of Migliaresi et al.[10]

Mechanical Properties

Figure 7(a–c) demonstrates the change of residual tensile strength, Young's modulus, and elongation at break, respectively, for the PLLA0,

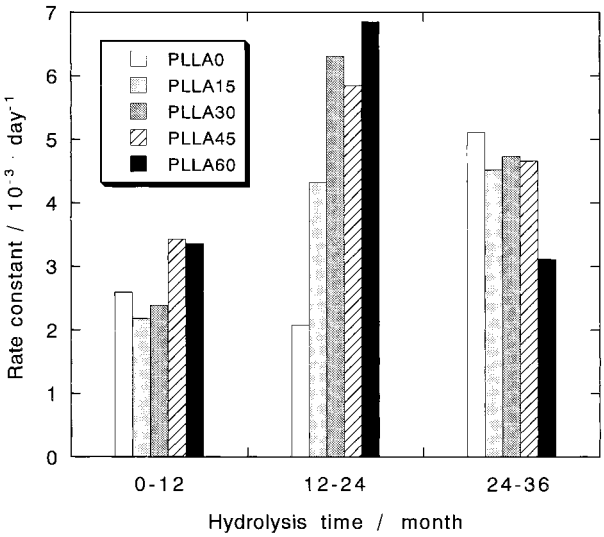

Figure 6 Hydrolysis rate constant (k) of PLLA0, PLLA15, PLLA30, PLLA45, and PLLA60 films hydrolyzed for 0–12 months, 12–24 months, and 24–36 months.

PLLA15, PLLA30, PLLA45, and PLLA60 films. As evident from Figure 7(a), the induction period, until a noticeable decrease in tensile strength, became shorter with the initial x_c. The x_c effect on the tensile strength change of PLLA films during hydrolysis is in agreement with that reported on the bending[18,23] and flexural strength[10] of PLLA specimens.

The Young's modulus of all PLLA specimens decreased rapidly in the first 8 months without any induction period. The Young's modulus of the PLLA0 film remained unchanged for hydrolysis times between 8 and 36 months, while the secondary decrease occurred for PLLA films having nonzero x_c at hydrolysis for longer than 18 months. The decrease of the Young's modulus after hydrolysis for longer than 18 months became more prominent with the increasing initial x_c. The Young's modulus of PLLA45 and PLLA60 films approached zero 24 months after hydrolysis.

The elongation at break of all PLLA films decreased dramatically in the first 4 months and then remained unchanged during hydrolysis from 4 to 12 months. The elongation at break of PLLA0, PLLA15, and PLLA30 films and of PLLA45 and PLLA60 films decreased again when hydrolysis was carried out for longer than 24 and 18 months, respectively, and approached zero 36 months after hydrolysis.

Change in the Crystalline Region

Figure 8 shows DSC thermographs of the PLLA films before and after hydrolysis of 36 months. The melting peak appearing around 180°C before hydrolysis shifted to lower temperature after hydrolysis of 36 months for all the PLLA films accompanying an area increase, irrespective of the initial x_c of the films before hydrolysis, in agreement with reported results.[9,10,19] Similar to the melting peak, the cold crystallization peak around 110°C shifted to lower temperature for the PLLA0, PLLA15, and PLLA30 films.

The T_m, T_g, and x_c of the PLLA films are plotted as a function of hydrolysis time in Figures 9(a–c), respectively. As seen, the T_m and T_g of all the films increased after hydrolysis of 12 months, but decreased after hydrolysis for longer than 24 months. The T_m and T_g of the PLLA films increased and decreased, respectively, with the increasing initial x_c when compared at the same hydrolysis time. On the other hand, the x_c of all the PLLA films increased monotonously upon hydrolysis, although the x_c of the PLLA45 and PLLA60 films showed a plateau for a hydrolysis time longer than 24 months. The increase in x_c observed during a relatively short hydrolysis time is in agreement with reported results.[9,10,19] The final x_c of PLLA0 film at 36 months (29%) is lower than that reported for initially amorphous PLLA specimens by Li et al. (49% at 21 months),[9] Migliaresi et al. (60% at 26 months),[10] and Pistner et al. (82% at 12 months),[19] indicating that crystallization of the PLLA0 film was delayed during hydrolysis.

Morphological Change

Polarizing optical photomicrographs of PLLA60 films with a thickness of 25 μm before and after hydrolysis for 36 months are shown in Figure 10. Apparently, the PLLA60 film prior to hydrolysis involves three regions: (1) the crystalline region in the spherulites, (2) the amorphous region between lamellae in the spherulites, and (3) the free amorphous region outside the spherulites, which is similar to that in the completely amorphous PLLA0 film. The decreased photographic contrast between the bright and the dark regions in the spherulites caused by hydrolysis in spite of increased x_c suggests that the crystallized PLLA film was hydrolyzed preferentially at the chains in the amorphous region connecting the crystalline lamellae in the spherulites, resulting in re-

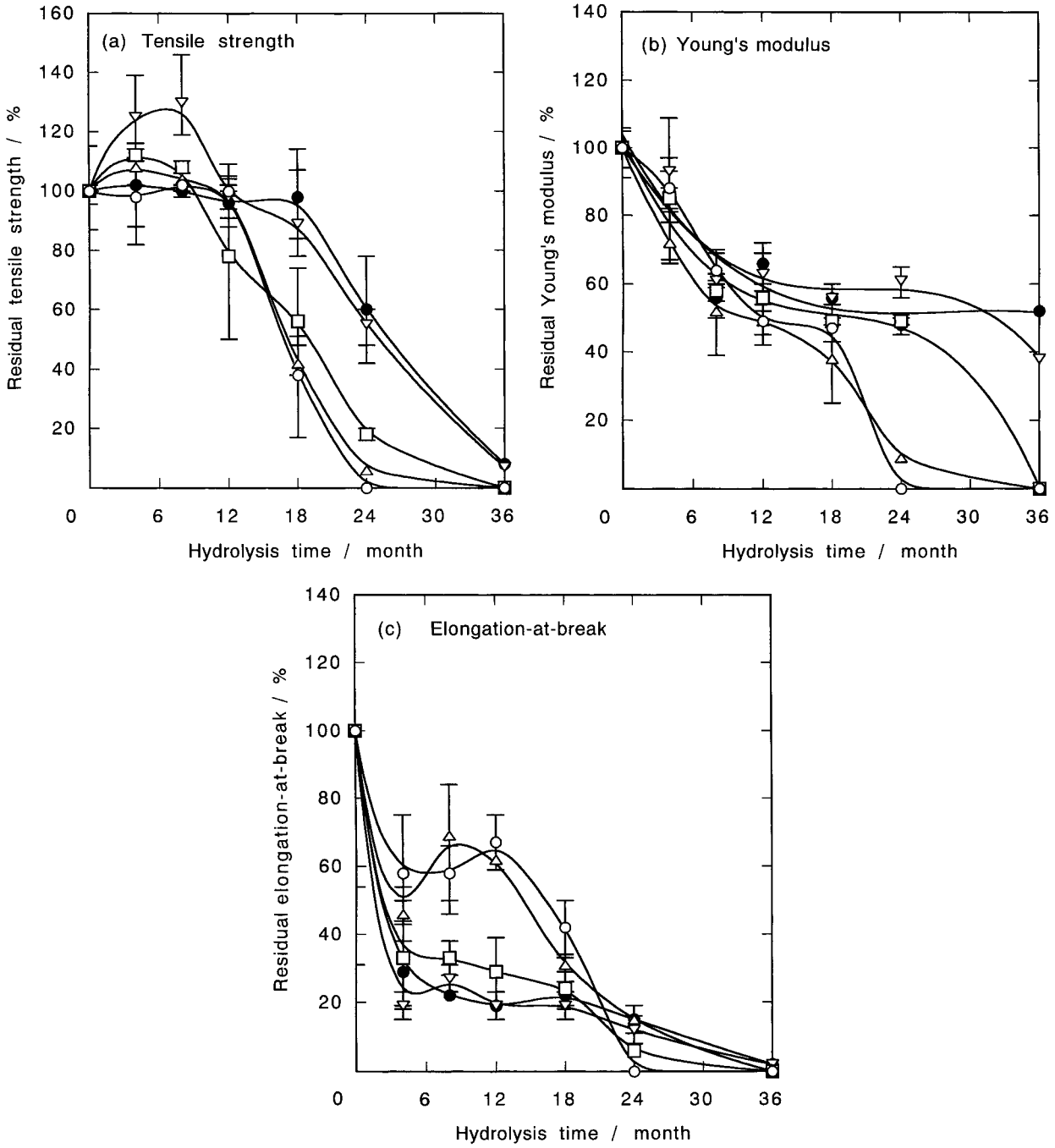

Figure 7 (a) Residual tensile strength, (b) Young's modulus, and (c) elongation at break of PLLA films as a function of hydrolysis time: (●) PLLA0; (▽) PLLA15; (□) PLLA30; (△) PLLA45; (○) PLLA60.

duced orientation of the lamellae. However, the spherulitic structure was preserved 36 months after hydrolysis, in contrast to the PLLA films subjected to hydrolysis in the alkaline solution for 150 days, where the spherulitic structure completely disappeared.[8]

SEM photomicrographs of PLLA30 film 36 months after hydrolysis are shown in Figure 11. The surface outside the spherulite is brighter than that inside the spherulite, suggesting that hydrolysis produced a highly porous structure in the amorphous region outside the spherulite.

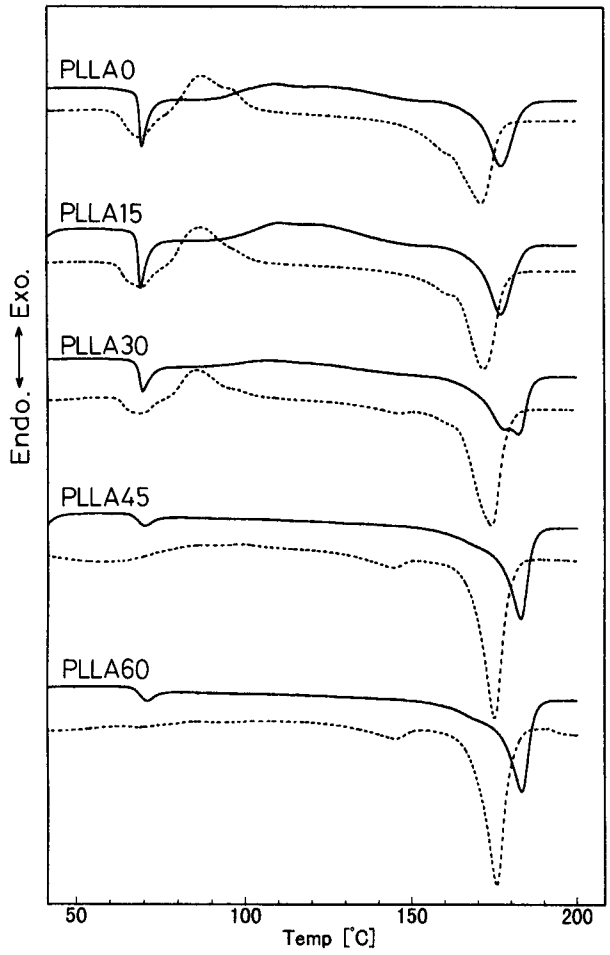

Figure 8 DSC thermograms of PLLA0, PLLA15, PLLA30, PLLA45, and PLLA60 films (—) before and (-----) after hydrolysis for 36 months.

Pores could be observed at both the inside and outside of the spherulite in the magnified SEM photograph. The estimated pore size was in the order of 0.1 μm. No height difference was observed between the inside and the outside of the spherulite and also between the amorphous and the crystalline regions in the spherulite. Such a height difference was clearly observed when the PLLA film was hydrolyzed in the alkaline solution.[8]

DISCUSSION

Hydrolysis Mechanism

The initial shift of the whole molecular weight distribution of PLLA0 and PLLA60 films to lower molecular weight (Fig. 4) and the SEM photographs of a hydrolyzed PLLA30 film demonstrate that the bulk-erosion mechanism was dominant for hydrolysis of PLLA films in the phosphate-buffered solution at pH 7.4, in contrast to hydrolysis in dilute alkaline solution at pH 12, where the surface-erosion mechanism prevailed.[8] The unvaried monodisperse GPC spectra of the initially amorphous PLLA0 film during hydrolysis indicate that PLLA films with thickness below 50 μm underwent homogeneous hydrolysis along the film cross section, in contrast to those having thickness higher than 2 mm, where hydrolysis was accelerated at the core.[9,12,24]

An increase in M_w/M_n for PLLA30, PLLA45, and PLLA60 films hydrolyzed for longer than 12 months, the peak formation in GPC spectra of PLLA60 films around the molecular weight of 9×10^3 for hydrolysis of longer than 24 months, and the decreased degree of lamella orientation in spherulites due to a reduced number of tie chains (Fig. 10) suggest that hydrolysis occurred selectively in the amorphous region between lamellae, leaving the crystalline lamellae, in good agreement with reported results.[8–10,19] In other words, crystallization of PLLA films before hydrolysis appeared to enclose the middle of the chains into the crystalline region, protecting them from hydrolysis. The protected PLLA chains were detected as the specific molecular weight peak at the later stage of hydrolysis. The increase in peak area at the specific molecular weight around 9×10^3 with the increase in the initial x_c of the PLLA films at 36 months (Fig. 5) suggests that the specific peak can be ascribed to the component of one fold in the crystalline region. The higher molecular weight of the specific peak position of PLLA films hydrolyzed in the phosphate-buffered solution than that hydrolyzed in the alkaline solution suggests weak hydrolyzability of the crystalline region in the phosphate-buffered solution. On the other hand, the increase in M_w/M_n observed for the PLLA0 film hydrolyzed for longer than 24 months may be ascribed to random scission of PLLA chains by hydrolysis, not to further crystallization and removal of the chains in the amorphous region between lamellae, since no significant weight loss due to removal of water-soluble chains was observed for the PLLA0 film after hydrolysis for 36 months.

The molecular weight distribution of the PLLA30 film shown in Figure 5 also implies that hydrolysis of PLLA chains in the spherulites and the free amorphous region outside the spherulites in the PLLA30 film was not affected by the neigh-

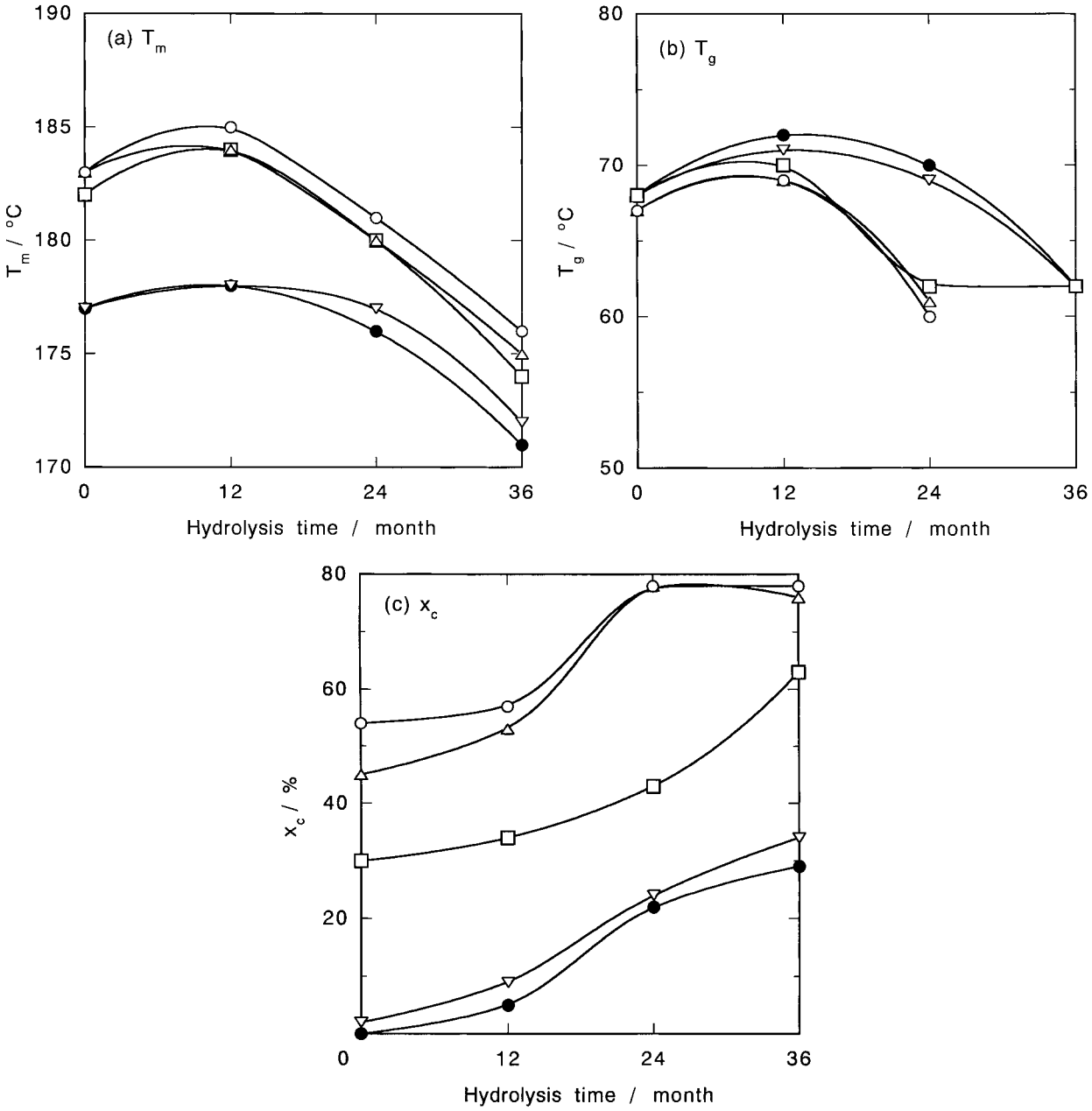

Figure 9 (a) T_m, (b) T_g, and (c) x_c of PLLA films as a function of hydrolysis time: (●) PLLA0; (▽) PLLA15; (□) PLLA30; (△) PLLA45; (○) PLLA60.

boring free amorphous region and spherulites, respectively. It follows that the chains in spherulites and in the free amorphous region in PLLA30 film were hydrolyzed as if they were buried in the spherulites surrounded by spherulites alone as in the PLLA60 film and were in the completely free amorphous region as in the PLLA0 film, respectively.

The shift of the cold crystallization peak of PLLA0, PLLA15, and PLLA30 films to lower temperature after hydrolysis of 36 months (Fig. 8) can be ascribed to an increase in PLLA chain mobility due to the decreased molecular weight and crystallite nuclei formation during hydrolysis. The crystallization peak of PLLA0, PLLA15, and PLLA30 films still existing after hydrolysis of 36 months indicates that free crystallizable amorphous regions remain in these films. The increase in T_m at the first 12 months may be explained in terms of the thickening of PLLA crystallites by

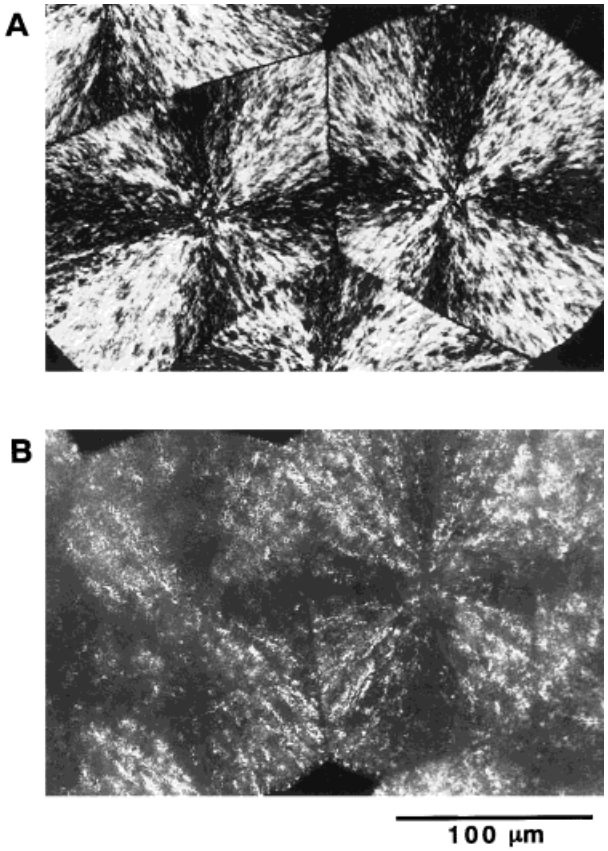

Figure 10 Polarizing optical photomicrographs of PLLA60 film (A) before and (B) after hydrolysis for 36 months.

the enhanced chain mobility induced by scission of chains in the amorphous region and the plasticizing effect of water molecules. The increase of T_g at the first 12 months may be due to stabilized chain packing in the amorphous region by low-temperature annealing in the presence of water molecules which are acting as a plasticizer. On the other hand, the decrease in T_m and T_g by hydrolysis for longer than 24 months may be simply due to reduced thickness of the crystallites and molecular weight of the hydrolyzed PLLA films, respectively.

Effects of Crystallization Before Hydrolysis

The rapid decrease in tensile strength of PLLA films having higher initial x_c is probably due to the same reason as for the difference in the induction period for blends from an amorphous poly(DL-lactide) and a crystallizable poly(D-lactide) or PLLA with different blending ratios and crystallinities.[20,25] A detectable reduction in tensile strength of the crystalline polymeric materials begins when a certain fraction of tie molecules connecting microcrystallites, and, therefore, responsible for the tensile strength, undergoes main-chain scission by hydrolysis. On the other hand, each chain in amorphous polymeric materials having no crystalline region is bound to the neighbors by the van der Waals force at temperatures below the T_g. As a result, a considerably large number of chain scissions are required for the amorphous polymeric materials to exhibit a noticeable reduction in the tensile strength. When compared at the hydrolysis time of longer than 18 months, PLLA films with a lower initial x_c showed higher residual strength. Seemingly, the rapid decrease in the elongation at break of the PLLA0, PLLA15, and PLLA30 films, compared to that of the PLLA45 and PLLA60 films, may be explained by the relatively larger initial elongation at break of PLLA0 (27%), PLLA15 (26%), and PLLA30 (21%) films than those of PLLA45 (13%) and PLLA60 (12%) films.

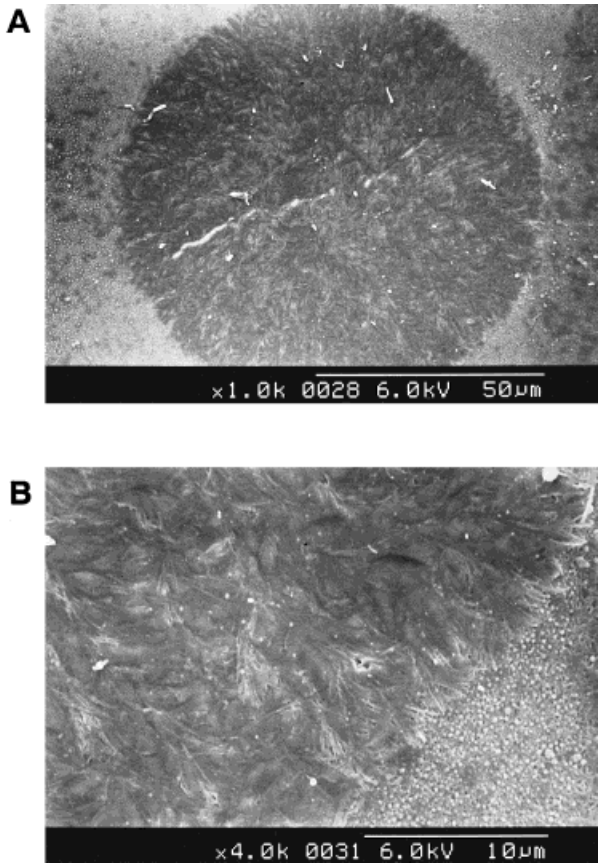

Figure 11 SEM photomicrographs of PLLA30 film after hydrolysis for 36 months. (B) is a 5× magnified photograph of (A).

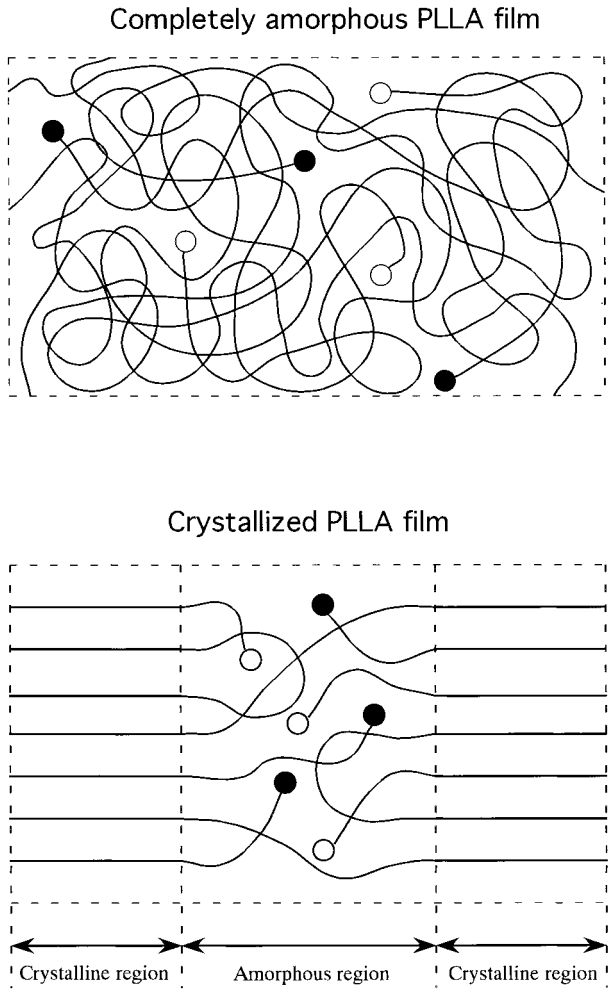

Figure 12 Schematic representation of structure of the completely amorphous PLLA film and the crystallized PLLA film: (○) carboxyl group; (●) hydroxyl group.

Enhanced hydrolysis of PLLA films with a higher initial x_c can be evidenced by the quicker decrease of mass remaining and M_n upon hydrolysis. The short induction period of crystallized PLLA films until a detectable decrease in mass remaining and tensile strength can be ascribed to the increased density of terminal carboxyl and hydroxyl groups in the amorphous region between the lamellae in comparison with that in the completely free amorphous PLLA film, because of their exclusion from the crystalline region during crystallization. The structures of completely amorphous PLLA film and crystallized PLLA film are schematically shown in Figure 12. The increased density of hydrophilic terminal groups will cause loose chain packing in the amorphous region between the lamellae, and the loose chain packing as well as an increased density of hydrophilic terminal groups will increase the diffusion rate of water. This loose chain packing in the amorphous region was evidenced by the lower T_g of crystallized PLLA films compared with that of initially completely amorphous PLLA0 film in Figure 9(b). A higher diffusion rate of water and density of catalytic carboxyl groups enhanced hydrolysis in the amorphous region between the lamellae compared to those in the completely amorphous PLLA film, resulting in a rapid decrease of mass of the crystallized PLLA films. However, prolonged hydrolysis will show that the mass remaining of crystallized PLLA film becomes higher than that of initially completely amorphous PLLA film due to a larger amount of crystalline residue of the former. The accelerated scission of tie chains in the amorphous region between the lamellae will result in a rapid decrease of tensile strength and the Young's modulus of crystallized PLLA films in addition to the reason mentioned above.

The higher k values observed for initially crystallized PLLA films which underwent 12–24 months hydrolysis than those of 0–12 months may be ascribed to the highly microporous structure or increased surface area per unit weight of PLLA films having a higher initial x_c, formed by removal of water-soluble oligomers. This is obvious from the mass remaining in the PLLA films hydrolyzed for 24 months (Fig. 2). The highly porous structure of crystallized PLLA films will promote a water supply which is essential for hydrolysis, resulting in accelerated scission of chains. The smaller k values for 24–36 months of hydrolysis than those for 12–24 months may be due to the hydrolytically resistant chains remaining in the crystalline region resulting from selective hydrolysis.

Effects of Other Parameters

The difference between our results and those reported may be explained by the difference in the initial molecular weight of PLLA, specimen thickness, and condition of sample preparation.[8–11,18–20,23] The initial higher molecular weight of PLLA films than that of the others must have prolonged the induction period until the start of the decrease in weight remaining and formation of specific peaks in the GPC spectra.[8–11,18,19] The low density of catalytic and hydrophilic terminal groups caused by high molecular weight PLLA will have a lower catalytic

ability and rate of water supply. The increased chain length will retard formation of water-soluble oligomers by chain scission. In addition, a concentration of catalytic water-soluble oligomers will be reduced by its ready elution from thin films, resulting in suppressed hydrolysis. The crystallization of the PLLA0 film during hydrolysis was probably delayed by the reduced mobility of PLLA chains originating from long chain length and a small amount of absorbed water molecules. The decrease in formation of water-soluble oligomers and the delay in crystallization of the PLLA0 film seems to have delayed the specific peak formation in the GPC spectra by preferred hydrolysis and removal of the chains in the amorphous region between lamellae.

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