

Surface characteristics of PLA and PLGA films

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Abstract

Surface segregation and restructuring in polylactides (poly(D,L-lactide) and poly(L-lactide)) and poly(D,L-lactide-co-glycolide) (PLGA) films of various thicknesses were investigated using both attenuated total reflection FTIR (ATR-FTIR) and contact angle relaxation measurements. In case of poly(D,L-lactide) (DLPLA), it was observed that the surface segregation and the surface restructuring of methyl side groups are influenced by the polymer film thickness. This result has been confirmed by X-ray photoelectron spectroscopy (XPS). In the same way, PLGA thick films were also characterized by an extensive surface segregation of methyl side groups. Finally, surface restructuring was investigated by dynamic contact angle measurements and it was observed when film surface comes into contact with water.

In parallel, we also found that poly(L-lactide) (PLLA) thin and clear films with thickness $\sim 15 \mu\text{m}$ undergo conformational changes on the surface upon solvent treatment with certain solvents. The solvent treated surface of PLLA becomes hazy and milky white and its hydrophobicity increases compared to untreated surface. FTIR spectroscopic analysis indicated that polymer chains at the surface undergo certain conformational changes upon solvent treatment. These changes are identified as the restricted motions of C–O–C segments and more intense and specific vibrations of methyl side groups. During solvent treatment, the change in water contact angle and FTIR spectrum of PLLA is well correlated.

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1. Introduction

Poly(D,L-lactide) (DLPLA), poly(D,L-lactide-co-glycolide) (PLGA) and poly(L-lactide) (PLLA) are biodegradable and bioresorbable polymers used in various biomedical applications [1] like absorbable sutures, wound healing materials, artificial skin grafts, orthopaedic and reconstructive implants and controlled drug delivery systems.

For all the biomedical applications, the rate of hydrolytic degradation and the mechanism of erosion of the polymeric devices are considered to be one of the important criteria for the selection of the biomaterial. In other respects, it was observed that the thickness of DLPLA and PLGA films has significant influence onto the rate of water sorption and consequently onto the hydrolytic degradation of the device [2]. Moreover, it was reported that the rate of hydrolytic degradation in thick films

was higher than that observed in case of thin ones. The accelerated degradation in thick films was explained by the formation of acid by-products during the hydrolysis, which act as catalysts during the hydrolytic degradation. On other hand, such acid by-products could easily diffuse out from the thin films and do not cause the auto-acceleration of the hydrolytic degradation. However, the influence of the film thickness onto the water diffusion kinetics remains unexplained.

Therefore, in order to contribute to the study of thickness dependent surface characteristics, in the first part of this paper, we have made an attempt to get more understanding about the influence of the film thickness onto surface morphology of DLPLA and PLGA, which has not been studied. Two different techniques have been described to investigate surface segregation and surface restructuring. Since a few years, attenuated total reflection FTIR (ATR-FTIR) spectroscopy has gained significant importance to analyze the surface composition of blend films and also to investigate the surface segregation in polymer [3,4]. In the present study, we have used ATR-FTIR spectroscopy to qualitatively study the surface segregation of methyl side groups in DLPLA and PLGA films with different thickness. Surface segregation of such a

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hydrophobic side branches at polymer/air interface is also often reported using sum frequency generation (SFG) spectroscopies [5–10]. XPS has been performed to confirm this segregation of methyl side groups in case of DLPLA films. Moreover, since the first report by Holly and Refojo [11], surface reorganization in the presence of water has been investigated several times by contact angle measurements. Thus, contact angle relaxation is a well-adopted technique to study the surface dynamics of polymer surface [11–15]. In this way, surface restructuring in DLPLA and PLGA films was also investigated in this paper with contact angle relaxation measurements.

Poly(L-lactide) is also used in various biomedical applications. In order to obtain the various biomedical devices, poly(L-lactide) is generally processed from its solution in chloroform or dichloromethane. However, the effect of different solvents onto the conformational changes of poly(L-lactide) chains is not reported. Therefore, we demonstrate, in the last part of this paper, the solvent induced conformational changes in poly(L-lactide). As an important advancement, we have observed that the hydrophobicity of poly(L-lactide) surface was significantly increased upon treating the polymer surface with certain solvents.

2. Materials and methods

2.1. Materials

Samples of poly(D,L-lactide) (DLPLA—average Mw: 75,000–120,000) and poly(D,L-lactide-co-glycolide) (PLGA—Mw: 40,000–75,000), which was composed by a 50:50 ratio of D,L-lactide and glycolide units, were purchased from Aldrich–Sigma and used as received. Poly(L-lactide) (average Mw: 100,000–150,000) was procured from Fluka.

2.2. Film sample preparation

DLPLA, PLGA and PLLA were dissolved in chloroform and film samples of various thicknesses were prepared by solution casting of polymer solution onto cleaned glass slides. Solvent was allowed to evaporate slowly at room temperature for 48 h and then the samples were dried under vacuum at 50 °C. The films were glossy and having smooth surface giving reproducible contact angle values. In case of PLLA films (thickness about 15 μm), conformational changes were induced by dipping these films (always coated onto glass slides) into four different solvents: toluene, acetone, tetrahydrofuran (THF) and ethyl acetate and drying in at room temperature for 12 h and in vacuum at 40 °C for 24 h. The initially clear films were found to become totally white and opaque after solvent treatment. In each case, films were then taken out from the glass substrate and air-facing or treated sides were analyzed by FTIR spectroscopy.

2.3. Fourier transform infrared measurements

The infrared spectra were recorded with a Bruker IFS 25 spectrometer at room temperature. A zinc selenide (ZnSe)

internal reflection element (IRE) with a fixed angle of incidence of 45° was used for attenuated total reflection (ATR) measurements. Air-facing sides of DLPLA, PLGA and treated slides of PLLA were analyzed for all the films. 64 and 128 scans for the transmission FTIR and ATR-FTIR measurements were respectively used.

2.4. Contact angle relaxation measurements

Contact angle relaxation of water droplet on films was measured by sessile drop method using contact angle goniometer called TRACKER from IT concept, France. Contact angle at $t = 0$ was measured after less than 1 s and estimated from the first automatic image of droplet.

2.5. X-ray photoelectron spectroscopy

XPS measurements have been performed at a residual pressure of 10^{-9} mbar, using a KRATOS Axis Ultra electron energy analyzer operating with an Al K α monochromatic source.

3. Results and discussion

3.1. Surface segregation in DLPLA and PLGA films

Surface segregation of apolar side groups at polymer/air interface was observed for many polymers and was well characterized using various analytical techniques [5–12]. For example, in case of poly(methacrylate)s, it was reported that the non-polar methyl groups tend to be exposed at the air-facing surface [7,12]. In this paper we choose to study the surface segregation in DLPLA and PLGA films with the ATR-FTIR spectroscopy.

FT-IR analysis was performed on DLPLA and PLGA films with different thickness. As it is well known, ATR-FTIR is used for the surface characterization but the intensity of the observed bands depends on the wavelength onto the ATR-FTIR spectrum. For that reason, comparison between ATR-FTIR and FTIR-transmission spectra is not allowed in general. However, there are some exceptions [4] where such comparison is made feasible by making different intensity correction in ATR-FTIR spectrum according to the wavelength.

In our case, it is clear from the Figs. 1 and 2 that ATR-FTIR and FTIR-transmission spectra of DLPLA and PLGA are very similar with some changes in the intensity of some peaks. Therefore, we have made such comparison only for the peaks whose intensities have significant difference. For example, it was observed that the carbonyl and C–O–C stretching peaks, respectively about 1750 and 1080 cm^{-1} , were shifted towards lower wavenumber in the ATR spectrum for both the polymers (Figs. 1 and 2). Another peak about 1450 cm^{-1} is due to C–H stretching in methyl groups and was observed in both the ATR-FTIR and FTIR-transmission spectra. We chose to normalize spectra to the intensity of this peak. It is clear from Figs. 1 and 2 that the intensity of a peak about 1043 cm^{-1} is different in both ATR-FTIR and FTIR-transmission spectra. This particular peak

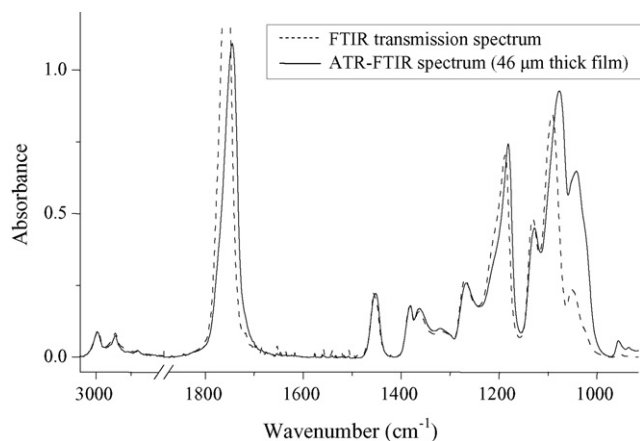


Fig. 1. FTIR transmission and ATR-FTIR spectra of poly(D,L-lactide).

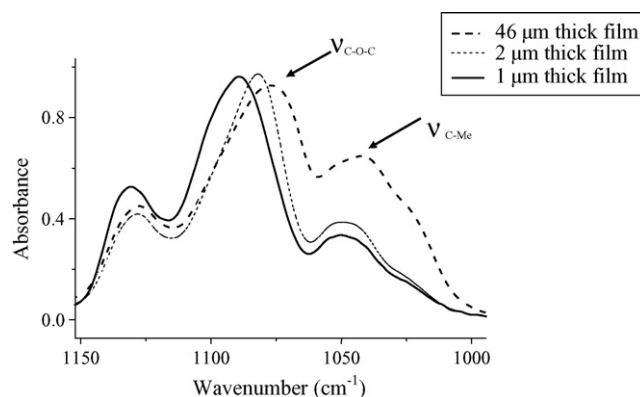


Fig. 3. Evolution of ATR-FTIR spectra of poly(D,L-lactide) with varying the film thickness.

is assigned to the C–CH₃ stretching vibrations [16]. In the ATR-FTIR spectrum the intensity of the peak at 1043 cm⁻¹ is clearly increased as compared to FTIR-transmission spectrum. Increase in this intensity is an indication for the relatively higher population of methyl groups on the surface of poly(D,L-lactide) and poly(D,L-lactide-co-glycolide) films. Therefore, it is clear that poly(D,L-lactide) and poly(D,L-lactide-co-glycolide) films comprise the surfaces which are segregated in such a manner that the methyl groups preferentially oriented at polymer/air interface and are more free to vibrate. X-ray photoelectron spectroscopy (XPS) analysis on poly(D,L-lactide) and blends confirm this observation [17].

Another study was carried out to investigate the effect of film thickness onto the segregation of methyl side groups on these film surfaces. For example, Fig. 3 shows the change in ATR-FTIR spectrum with the increase of the DLPLA film thickness. All the spectra are normalized with the peak at 1450 cm⁻¹ and it was observed that the intensity of the peak at 1043 cm⁻¹ decreases with decreasing the film thickness. As shown in Fig. 3, absorbances at 1043 cm⁻¹ in ATR spectra for the 1, 2 and 46 μm thick films are 0.31, 0.37 and 0.65, respectively. Consequently, films with 1 μm thickness show the lowest

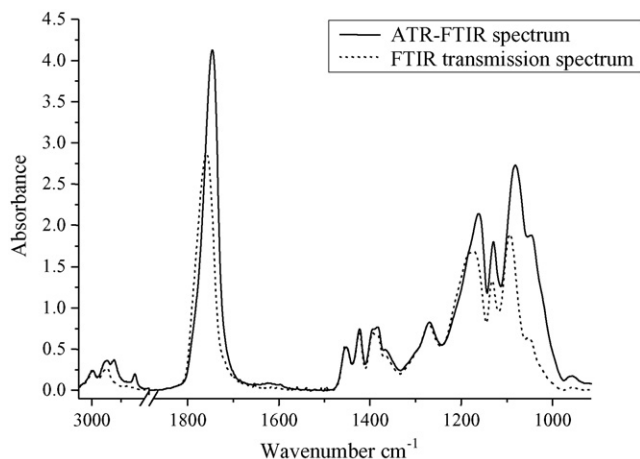


Fig. 2. FTIR transmission and ATR-FTIR spectra of poly(D,L-lactide-co-glycolide).

intensity of the peak at 1043 cm⁻¹ and the population of methyl side groups on the film surface decreases with decreasing the film thickness. This influence of the film thickness on the segregation of methyl side groups indicates that the segmental motions in DLPLA and PLGA are dependent on the film thickness. Actually, as the thickness decreases, the surface/bulk ratio increases. Therefore, surface enrichment could be higher in thick films in comparison to thin films. In such a way, thick films have higher segmental motion than thin ones and preferentially orient the hydrophobic methyl side groups towards polymer/air interface. On the other hand, surface to bulk ratio is very high in very thin films (1 μm thickness) and consequently the thin films do not exhibit a surface segregation as there is only surface and very less bulk that can provide hydrophobic methyl groups to surface.

The peak at 1043 cm⁻¹ shift marginally to lower frequency with increasing film thickness (Fig. 3). Therefore, the energy requires for C–CH₃ stretching vibration is less when film thickness is higher. This indicates that the methyl groups on the surface of thick films are more “free” to vibrate as compared to methyl groups on the surface of thin films. Surface segregation of methyl groups in thick films could be responsible for the unrestricted vibrations of C–CH₃ groups in comparison to the same groups in thin films.

In order to confirm this surface segregation, XPS measurements have been performed of DLPLA films with different thickness. XPS allows the determination of the elemental and average chemical composition of the film at its surface in 5–10 nm depth by measuring the binding energy of electrons associated with atoms. Concerning the chemical structure of DLPLA, we could assign signals at 288.7, 286.6 and 284.6 eV to the carboxylic carbon (–CO–O), to the neighbouring carbon in chain (C–O) and to the alkyl carbon (C–H), respectively [18a]. According to the XPS spectra, the atomic ratio of C/O on the surface of DLPLA films were calculated and shown in Fig. 4. This figure shows that this C/O ratio for surface was higher than the C/O ratio in bulk (C/O in bulk is equal to 1.5 [18b]) Moreover, this ratio increased with the thickness of the DLPLA film, in such a way that the surface segregation of the methyl side groups is confirmed.

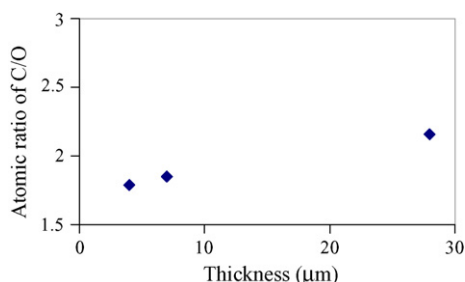


Fig. 4. Evolution of the atomic ratio of C/O at the surface of poly(D,L-lactide) with varying the film thickness.

3.2. Surface restructuring in DLPLA and PLGA films. Influence of time

As we proved that the surface segregation exhibited for both DLPLA and PLGA films was in relationship with their thickness, we chose to investigate the surface restructuring of methyl side groups with time in case of films with two different thicknesses (1 and 15 μm). In this paper, existence of such a segmental motion in the methyl side groups segregated at the air-facing surfaces of the thick films (15 μm thickness) was emphasized by the contact angle relaxation measurements. Change in the contact angle of water droplet with time was monitored for DLPLA and PLGA films and was reported in Fig. 5. As observed, water contact angle decreases continuously with time for DLPLA and PLGA thick films. The water contact angle for poly(D,L-lactide-co-glycolide) thick films decreases continuously from 98° to 75° within 60 s. In case of poly(D,L-lactide) films, initial value of contact angle is as high as 96° and it decreases continuously to 81° within 50 s. These values are in agreement with the higher hydrophobicity of DLPLA in comparison to PLGA [19]. PLGA is less hydrophobic because of the presence of glycolide units, which are considered more hydrophilic than lactide units. Reported values of water contact angle for poly(D,L-lactide) without surface modification ranges from 87° to 69° [20]. Therefore, this observed contact angle relaxation would be one of the reasons for such variations in the reported values [20]. This decrease of the contact angle value is

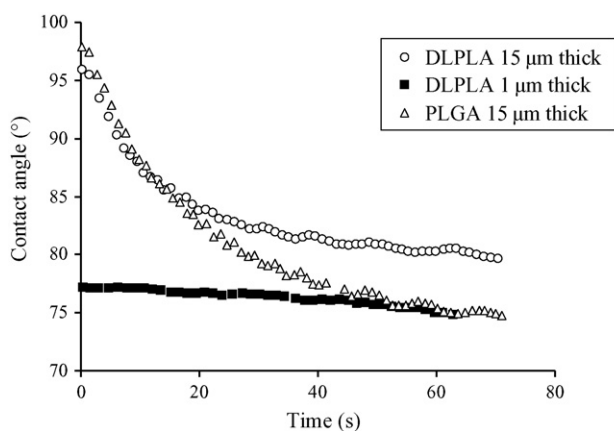


Fig. 5. Change in water droplet contact angle with time for poly(D,L-lactide) and poly(D,L-lactide-co-glycolide) films.

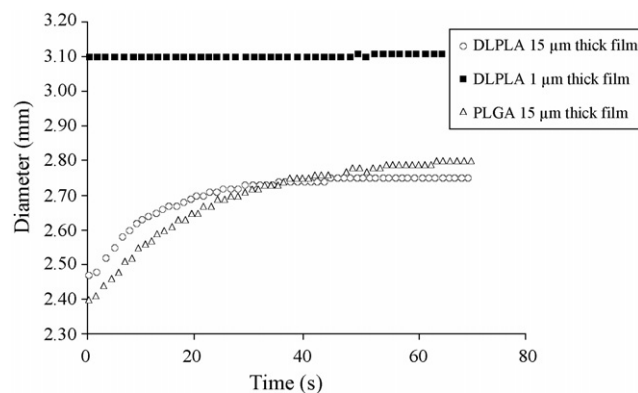


Fig. 6. Evolution of drop diameter with time for poly(D,L-lactide) and poly(D,L-lactide-co-glycolide) films.

closely connected to the drop diameter increase (Fig. 6), which demonstrates that the wetting is increased for the thick film surfaces with time.

Higher values of initial contact angles for both DLPLA and PLGA thick films in comparison to thin ones indicate the higher hydrophobicity of these thick film polymer surfaces. Therefore, these results are in agreement with ATR-FTIR results, which indicated the higher extent of hydrophobic methyl groups on the thick film surface for DLPLA and PLGA (Figs. 1 and 2). But as the surface coming into contact with water, its hydrophobicity decreases with time and reaches to a plateau value.

At the beginning, poly(D,L-lactide-co-glycolide) thick films have the value of contact angle almost slightly above than the value of contact angle for thick poly(D,L-lactide) films. This shows that initially PLGA surface has slightly higher hydrophobicity as poly(D,L-lactide). This observation is a clear indication of the somewhat higher extent of segregation of methyl side groups at the air-facing PLGA surface in comparison with DLPLA one. In order to explain this phenomenon, we can take the example of ethylene-propylene copolymers. In case of polypropylene (PP) and poly(ethylene-propylene) copolymers, it was reported that the segregation of methyl side groups increase with increasing ethylene contents in the copolymers [5]. This effect was explained with the fact that the segmental motion of propylene segments is less hindered in ethylene propylene copolymers than in PP. The similar phenomenon may explain the slight difference between the initial extent of hydrophobicity in PLGA and DLPLA. But within 20 s after coming into contact with water, the surface of DLPLA thick films exhibit higher hydrophobicity than PLGA ones because DLPLA is basically more hydrophobic than PLGA [19].

Relaxation in water contact angle with time, in case of thick films, is closely connected to a segmental motion of polymer chains at the surface of the films. Thick films with relatively higher extent of hydrophobic groups on the surface undergo restructuring as their surface comes in contact with water. Reorientation of methyl side groups at the surface is considered as the major segmental motion responsible for surface restructuring in thick films of poly(D,L-lactide) and poly(D,L-lactide-co-glycolide).

As shown in Figs. 5 and 6, thin DLPLA films with 1 μm thickness do not exhibit any relaxation of contact angle value. Moreover, the initial value of contact angle for these films (77°) is quite less than the initial value of contact angle for thick poly(D,L-lactide) films (96°). Therefore, the surface of thin films is neither segregated with hydrophobic methyl side groups nor undergoes restructuring when it comes into contact with water. Thus, the contact angle results are in agreement with ATR-FTIR analysis results, which indicated low extent of hydrophobic methyl groups at the surface of thin poly(D,L-lactide) films (Fig. 3).

3.3. Solvent induced conformational changes in PLLA films

Solvent induced conformational and morphological changes in polymeric materials have gained significant importance these days [21]. We observed that treating the poly(L-lactide) film surface with certain solvents makes it hazy and milky white. These solvents (toluene, acetone, THF and ethyl acetate) are not ‘very’ good solvents for poly(L-lactide) and therefore, do not dissolve the polymer. However, they swell it [22] and evaporate by causing certain conformational changes onto the PLLA film surface. The water contact angles on the poly(L-lactide) surface before and after toluene treatment have been measured. It was observed that the contact angle increases after this treatment. The initial contact angle value for 15 μm clear poly(L-lactide) film was $77 \pm 2^\circ$ and, for example, it increased to $116 \pm 4^\circ$ after toluene treatment (Fig. 7). The reported [23] value of water contact angle on to poly(L-lactide) surface is $77 \pm 1^\circ$. Therefore, the solvent treatment had tremendous effect on to the surface characteristics of the polymer. Increasing the water contact angle by nearly 40° was a significant development. Moreover, the existence of two different contact angles for the same polymer was an amazing thing and that led us to further investigation. This increase in water contact angle after solvent treatment has been already reported in case of some polymers [24] and is usually attributed to a rougher surface [24,25]. We found that the increase in the water contact angle is also in relationship with the segregation of the methyl hydrophobic groups at the polymer surface.

Fig. 7 shows that there is no relaxation in contact angle as it was observed for poly(D,L-lactide) and poly(D,L-lactide-co-

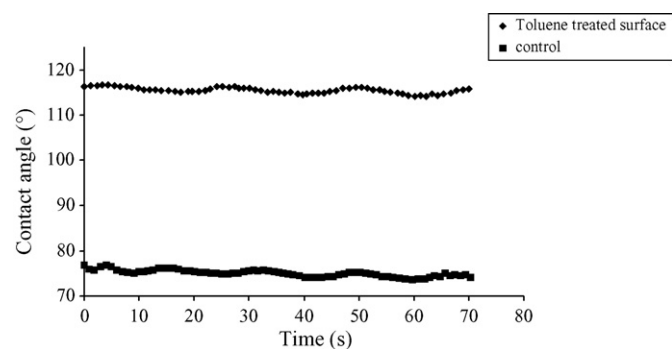


Fig. 7. Change in water contact angle with time for the poly(L-lactide) before and after toluene treatment.

glycolide). It is reported that the glass transition temperature (T_g) has a great influence onto the surface segregation of methyl groups [7]. Thus, poly(*n*-octyl methacrylate), which has a low T_g value (-70°C), showed higher surface restructuring extent in comparison with poly(methyl methacrylate) with higher T_g value (105°C). Then, we propose that the T_g value (65°C) of poly(L-lactide), as compared to the T_g of DLPLA (56°C) [26] and PLGA (40°C) [27] does not allow the surface restructuring upon coming into contact with water and this in turn prevents the contact angle relaxation in poly(L-lactide) [28].

In order to investigate the conformational changes induced by the solvent treatment, we analyzed the toluene treated slide of poly(L-lactide) films with FTIR spectroscopy. Fig. 8 shows the FTIR spectra of poly(L-lactide) film treated with different solvents. It is clear from this figure that the peaks between 1000 and 1200 cm^{-1} have become sharper after the solvent treatment. It was reported that the semi-crystalline poly(L-lactide) samples showed sharp peaks in FTIR spectrum as compared to amorphous samples [16]. We consider the sharpening of the peaks could be due to the oriented polymer segments that vibrate at a more specific frequency. Fig. 8 also indicates that the intensity of the peak at 1090 cm^{-1} is decreased after solvent treatment. As this particular peak is assigned for C–O–C asymmetric stretching, the reduction of this band intensity is a sign of restriction of C–O–C asymmetric vibrations [16a]. This is an indication for the more closely packed polymer segments, which have restricted vibrations. Moreover, the intensity of the peak at 1184 cm^{-1} is decreased, while the intensity of a peak at 1212 cm^{-1} is increased after the solvent treatment. Peak at 1184 cm^{-1} is assigned for A type C–O–C symmetric stretching mode and the peak at 1212 cm^{-1} is assigned for E_1 type symmetric stretching modes [16b]. Change in the intensity of these peaks is another evidence for the change in the chain conformation after the solvent treatment. This change can be termed as the shifting of the peak at 1184 – 1212 cm^{-1} upon the solvent treatment and such shift in C–O–C stretching mode from lower to higher frequency can be interpreted as the transition of stretching mode from lower energy to the higher one. Requirement of higher energy for a specific vibrations is indicative of stiffened segmental motions. Therefore, the solvent treatment causes the stronger interactions between the C–O–C segments which restricts their motion.

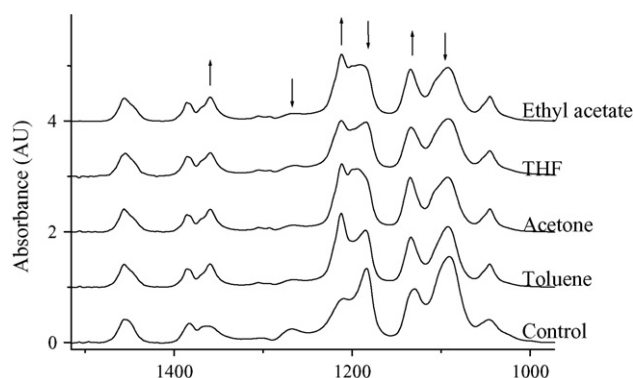


Fig. 8. FTIR spectra of poly(L-lactide) treated with various solvents.

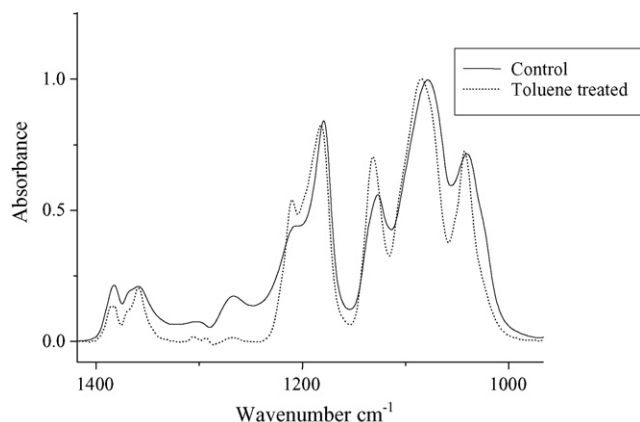


Fig. 9. Change in ATR-FTIR spectrum of poly(L-lactide) after toluene treatment.

Increase in the peak intensity at 1134 cm^{-1} , which is assigned for CH_3 rocking vibrations [16a] and the sharpening of this peak was observed after solvent treatment. Sharpening of this peak and increase in the intensity suggest that the methyl groups in the PLLA chains are oriented in such a way that they are more labile to vibrate. This could be explained by the fact that the intermolecular association of C–O–C segments leads to exclusion of hindering methyl groups outward and point them more specifically at the surface, yielding to increase the surface hydrophobicity. This could explain why the water contact angle is high for treated surface (Fig. 7). To confirm this observation, Fig. 9 shows the comparison between the ATR-FTIR spectra of the poly(L-lactide) films before and after toluene treatment. Increase in the peak intensity due to the CH_3 rocking (1134 cm^{-1}) in these spectra of treated film is a clear indication for the higher population of CH_3 groups on the treated surface. Thus, the solvent treatment could lead to more hydrophobic polymer surface and consequently increase the water contact angle (Fig. 7).

4. Conclusions

ATR-FTIR spectroscopy was used for investigating the presence of specific methyl groups vibrations at the surface of poly(D,L-lactide) and poly(D,L-lactide-co-glycolide) films. It was demonstrated that thick films of these two polyesters bear the surface segregated with the orientation of hydrophobic methyl side branches. Contact angle relaxation with time indicated that these surfaces undergo restructuring when exposed to water. Reorientation of methyl side groups was thus considered as the main motive for the surface restructuring.

We have also observed that the segregation of methyl side groups at the surface is well influenced by the thickness of the films and it is significantly reduced in case of thin films. Thus, poly(D,L-lactide) films with thickness of $1\text{ }\mu\text{m}$ do not exhibit surface segregation of methyl side groups. Furthermore, these thin films do not exhibit surface restructuring when come into contact with water. These results on segmental motion differences between thick and thin films could be a great aid to understand the thickness dependent water sorption and degradation kinetics in poly(D,L-lactide).

Poly(L-lactide) thin and clear films with thickness $\sim 15\text{ }\mu\text{m}$ undergo conformational changes upon solvent treatment. The increased hydrophobicity in solvent treated poly(L-lactide) surface was correlated with change in FTIR spectrum. The decrease in the intensities of the peaks characteristic of C–O–C vibrations were interpreted as the hindered motion of these segments upon solvent treatment. Increase in the peak intensity of CH_3 vibrations at the surface of the poly(L-lactide) were identified responsible for the increased hydrophobicity of the polymer after solvent treatment.

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