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Surface Physical Interpenetrating Networks of Poly(ethylene terephthalate) and Poly(ethylene oxide) with Biomedical Applications

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ABSTRACT: Poly(ethylene terephthalate) (PET) films were modified by diffusing poly(ethylene oxide) (PEO) into the surface of the PET, which was swollen in a mutual solvent. Subsequent rapid deswelling in a nonsolvent for PET resulted in the stable entrapment of the PEO within the surface of the PET. The PET/PEO systems produced by this technique were phase-mixed nonequilibrium surface structures, kinetically stable below the T_g for PET. The surface-localized structure is referred to as a surface physical interpenetrating network (SPIN), due to the similarity of the forming technique to that for a sequential interpenetrating polymer network. Analyses of these materials by X-ray photoelectron spectroscopy (XPS) and NMR spectroscopy revealed PEO incoroporation as high as 23 mol % or 6.4 wt %, with a preferential localization of the PEO near the surface of the PET film. Differential scanning calorimetry (DSC) indicated a phase-mixed structure, despite the thermodynamic incompatibility of PEO and PET, which could be induced to phase separate upon heating above the PET T_g. These materials were stable at 37 °C for several months in an aqueous environment, but PEO leaching occurred upon incubation in water at temperatures near the PET T_g as well as upon swelling the PET with organic solvents at room temperature. These materials have been previously shown by us to be extraordinarily resistant to cellular adhesion.

Introduction

Poly(ethylene oxide) or poly(ethylene glycol) (PEO or PEG, used interchangeably) has been proposed by several investigators as a surface modifier for a variety of polymers where low levels of protein adsorption and cellular adhesion are required. The incorporation of PEO into these materials has been accomplished by covalent grafting,[1-8] block copolymerization,[9-11] adsorption of PEO-containing block copolymeric surfactants,[12,13] and synthesis of PEO-containing interpenetrating polymer networks.[14,15]

We have previously described a solution process whereby the PEO is entrapped into the surface of the polymer to be modified (base polymer) by a solvent processing technique.[16] The base polymer is placed in a solution of PEO in a solvent which slightly swells the base polymer; fine control can be obtained over solvent properties by diluting a good mutual solvent with a miscible solvent for only PEO. The PEO is allowed to diffuse into the swollen base polymer but remains localized near its surface due to kinetic diffusive limitations. After some period of time, the swollen base polymer impregnated with PEO is removed from the mutual solvent and is placed in a nonsolvent for the base polymer but a solvent for PEO which is also miscible with the solvent used for the swelling step. This results in a rapid deswelling or collapse of the base polymer, entangling the PEO near the surface. We demonstrated that PEO could be incorporated into poly(ethylene terephthalate) (PET), poly(methyl methacrylate), and a polyurethane.[16] The PEO, which was surface-incorporated by this procedure, was resistant to leaching from the surface when the material was placed in water, a solvent for PEO but not for any of the base polymers examined, for periods of at least 3 months at 37 °C.

It was observed that the molecular weight of PEO used in the surface incorporation plays an important role in successful entrapment at the base polymer surface. XPS and cell adhesion studies showed[16] that the amount of PEO incorporation into a PET surface displayed a maximum for a molecular weight of 18 500. Lower molecular weights of PEO were postulated to be ineffectively entrapped in the PET and thus subject to rapid leaching. Higher molecular weights were postulated to have diffusional limitations within the slightly swollen PET surface during the impregnation step; such limitations could also be thermodynamic, however, with higher molecular weight PEO being less soluble in the swollen polymer than lower molecular weight PEO. The PET/PEO surfaces modified to present PEO of MW 18 500 were shown to be protein repellant, cell nonadhesive, nonthrombogenic in vitro,[16] nonadhesive to bacteria,[17] and resistant to tissue encapsulation in vivo.[18]

The model proposed for the surface structure created by this solution processing technique was one of phase-mixed PEO entangled in the base polymer and present at higher concentrations near the polymer surface. This structure was given the name surface physical interpenetrating network (SPIN) to reflect the similarity between the synthesis of this structure and that of a semiinterpenetrating polymer network.[19] In the latter, monomer of component II (corresponding here to the PEO) is diffused into a cross-linked network of component I (corresponding to the base polymer) and is allowed to polymerize without cross-linking to itself or to the network of component I. By contrast, in the former SPIN, a polymer (rather than monomer) is diffused into a non-cross-linked (rather than cross-linked) base polymer; we have added the descriptor "physical" to emphasize the absence of chemical cross-links in the system. Additionally, the impregnating polymer is localized near the surface of the base polymer, hence the descriptor "surface". The structure is actually a polymer blend, but we use the name SPIN because the blend is not synthesized by normal blending procedures but is synthesized by procedures somewhat similar to those for semi-IPNs.

This report describes the physicochemical characterization of the SPIN structure for the PET/PEO system using a number of analytical techniques. PEO and PET are generally considered to be incompatible, and as such,

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a phase-mixed structure would be thermodynamically unstable and somewhat unexpected. It was our hypothesis that the rapid collapse of the swollen PET kinetically did not allow the diffusion of PEO relative to the PET to form PEO-rich and PEO-poor phases, resulting in a kinetically stable, but thermodynamically unstable, phase-mixed material near the surface. Single-phase but thermodynamically incompatible polymer blends have been synthesized and described by others. Single-phase blends of immiscible polymers have been prepared by freeze-drying of a homogeneous solution of the two components for PMMA with polystyrene,[20,21] and for PMMA with poly(vinyl acetate).[22] These systems displayed a single T_g and were kinetically stable below the T_g but were observed to rapidly phase separate when heated just above the T_g.[22] Other blend systems have been shown to phase separate very slowly, such as poly(acrylonitrile-*co*-styrene) with poly(maleic anhydride-*co*-styrene),[23] PMMA with poly(2-vinylnaphthalene),[24] poly(styrene-*co*-butadiene) with polybutadiene,[25,26] and PMMA with polycarbonate.[27] With these systems it is possible to obtain phase-mixed blends in spite of the immiscibility of the two polymer components. The lack of extraction in water of water-soluble components of miscible blends of water-soluble and water-insoluble polymers has also been described, although for systems which phase separate upon swelling in water.[28]

Experimental Section

Materials and Synthesis. Films of PET (1 mil; Mylar, Du Pont) were surface-modified with PEO of molecular weight 18 500 using the SPIN technique as described previously.[16] Briefly, PEO was dissolved in trifluoroacetic acid (TFAA; Morton Thiokol), which had been diluted to 80–82% with deionized water, at a concentration of 8% (w/v). TFAA was used because it is a mutual solvent for PET and PEO. Pure TFAA dissolved the PET films rapidly and was therefore diluted with water to 80–82%, at which concentration PET had borderline solubility. PET films were immersed in this solution for either 30 min (simply abbreviated as SPIN) or 48 h (abbreviated as 48-h SPIN). The 30-min treatment was standard, and the 48-h treatment was used to incorporate higher amounts of PEO to allow examination by bulk spectroscopic techniques, such as DSC and NMR. During this period, the PET surface swelled and allowed diffusion of PEO into its interstices. The swollen PET surface was then rapidly collapsed by the addition of excess water, entrapping chains of PEO at the surface. All solution processing was performed at room temperature. All newly formed SPIN films were incubated in water at 25 °C for 1 month prior to examination to allow the leaching of any unstably incorporated PEO.

It was observed that the amount of PEO present at the surface of PET as measured by XPS was quite sensitive to the preparation conditions. The strength of the solvent TFAA in the treatment mixture was critical, and a dilution range of 18–20% with water was essential for the formation of a SPIN. The concentration of PEO incorporated in the base polymer varied considerably with the concentration of TFAA even within this small range. Therefore, experiments that required direct comparison of PEO content between samples were performed using SPIN films generated in the same batch. Care was taken not to directly compare and make inferences about samples from one batch with another. In this report, two separate batches of SPIN films were used: one for the angle resolve studies and the second for the solvent leaching and water incubation studies. All batches of SPIN films, however, had sufficient concentrations of PEO18.5K present on their surfaces to make them protein repellant and hence cell nonadhesive.

Surface Analysis. The C 1s spectra of SPIN surfaces were examined by XPS (VG Instruments) for the presence of PEO. Angle-resolve studies were performed to probe the modified surface to various depths; take-off angles of 0°, 45°, and 75° were used for depths between approximately 100 and 10 Å. A pass energy of 20 eV was used to obtain good peak resolution.

NMR Spectroscopy. ^{1}H nuclear magnetic resonance spectroscopy (500 MHz, GN-500, General Electric) was used to obtain semiquantitative information on PEO present in the modified substrates. Deuterated trifluoroacetic acid (Aldrich) was used as the solvent for NMR analysis. NMR spectra of four different samples were collected in order to identify the peak contributions of the different moieties present. The samples analyzed were as follows: (i) PET alone; (ii) PET and PEO18.5K together but not as a SPIN, where 0.3 part (by mass) of PEO and 1 part of PET were dissolved in deuterated TFAA; (iii) PET-PEO18.5K as a 30-min SPIN; (iv) PET–PEO18.5K as a 48-h SPIN.

Differential Scanning Calorimetry. DSC analysis (Perkin-Elmer, 7 series thermal analysis system) was used to determine the nature of interactions between PET and PEO and the presence or absence of a phase-mixed or phase-separated structure on the SPIN substrates. Only the 48-h SPIN was examined to obtain measurements that related to the PEO modification; the PEO content of the 30-min SPIN was too small and too surface-localized to be observed by DSC. Scans were run from 0 to 300 °C or 0 to 150 °C for the different samples at a heating rate of 20 °C/min. A quench rate of 200 °C/min was used for cooling the sample to 0 °C following the heating cycles.

Solvent Swelling/Solubility Parameter Correlation. A number of solvents were examined for their ability to swell the base PET and allow PEO leaching, based on the proximity of their Hildebrand solubility parameter (δ) to the solubility parameter for PET. δ_{solvent} values close to δ_{PET} indicate a greater tendency for the solvent to swell the polymer. Values of δ were obtained as listed in ref 29 and are reported in the caption of Figure 6. PET films were incubated in these solvents for 2 h at room temperature, after which they were removed, rinsed in a fresh batch of the same solvent, and dried in vacuum. These polymers were then analyzed by XPS to test for the presence of PEO and also by tissue culture of human foreskin fibroblasts for cell adhesion, as described elsewhere[16] and briefly below. The adhesion of cells to these substrates would indicate the loss of PEO from their surfaces.

Cell Adhesion Bioassay. The attachment and spreading of human foreskin fibroblasts was measured as described in detail elsewhere.[16] Briefly, fibroblasts were suspended in Dulbecco's modification of Eagle's medium (DMEM), supplemented with 10% fetal calf serum and antibiotics. These cells were seeded at 10 000 cells/cm^2 on sterile substrates (sterilized by 5-s exposure to a 20% bleach solution in water, followed by extensive rinsing with sterile water) and were incubated at 37 °C in a 5% CO_2 humidified environment in a tissue culture incubator. Cell attachment and spreading was measured after the specified duration of culture using phase contrast microscopy on an inverted stage microscope (Leitz). The extent of confluency, or fraction of surface area occupied by adherent cells, was measured with the aid of a digital image processor (Imaging Technology Inc.).

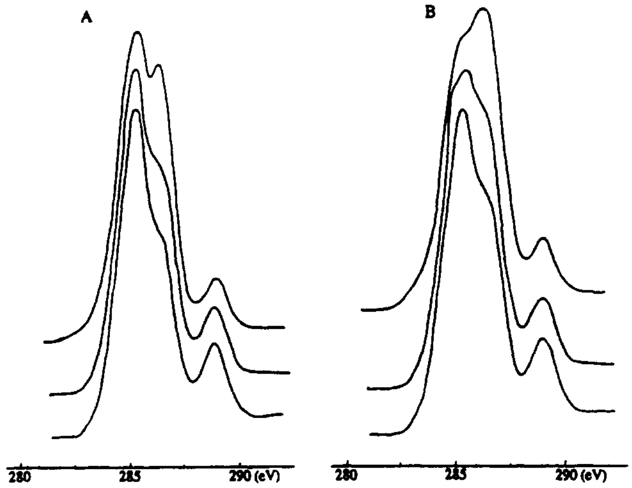

Figure 1. Angle-resolved high-resolution C 1s XPS spectra at takeoff angles of 0°, 45°, and 75° (from bottom to top) for PET–PEO18.5K SPIN surfaces: (A) SPIN with a treatment time of 30 min, the standard time; (B) SPIN with a treatment time of 48 h. The increase in intensity of the central ether peak with decreasing sampling depths from the polymer surface indicates that the PEO is localized near the film surface. At any given takeoff angle, the intensity of the ether peak was greater for the 48-h SPIN, indicating greater incorporation of PEO at the longer treatment times. The spectrum for native untreated PET is shown in Figure 5.

Leaching of PEO in Water near the T_g. The polymer films were incubated in water at 71 or 91 °C for different lengths of time. The glass transition temperature (T_g) of the base PET was determined to be 81 °C by differential scanning calorimetry. It was proposed that an incubation in water above the T_g for a sufficient length of time would allow a considerable relaxation of the polymer chains and permit the PEO to diffuse out of the PET into the surrounding water. This loss in PEO was then examined by XPS and cell adhesion assays.

Results and Discussion

Angle-Resolved XPS. Depth profiles of PET–PEO18.5K SPIN and 48-h SPIN films were recorded using XPS. High-resolution spectra were obtained for C 1s electrons at varying takeoff angles ranging from 0 to 75° from the surface normal to the sample. A takeoff angle (θ) of 0° (electron energy analyzer normal to the sample surface) detects electrons emanating from a maximum depth corresponding to about 3 times the mean free path (λ) of C 1s electrons in the polymer sample. As the takeoff angle is increased, the depth (D) from which the electrons are detected decreases according to $D = 3\lambda \cos \theta$. Parts A (SPIN) and B (48-h SPIN) of Figure 1 show angle-resolved spectra at takeoff angles of 0°, 45°, and 75°, which represent a sampling depth to 100%, 71‰, and 26%, respectively, of the maximum sampling depth.

Each spectrum has three component peaks (not shown, but apparent from the spectra): the C—C peak (left) at 285 eV, the C—O ether peak (middle) at 286.4 eV, and the C═O ester carbonyl peak (right) at 289 eV. All three components are present in the native PET at a theoretical normalized C—C:C—O:C═O ratio of 1.0:0.33:0.33. The presence of PEO (which contains essentially only C—O ether linkages) in the sample would result in the increase of the relative contribution of the C—O ether peak. In this analysis, a low pass energy of 20 eV was used to increase spectral resolution at the expense of a more quantitative result.

Both parts A and B of Figure 1 show the relative increase of the C—O peak with increase in takeoff angle or decrease in the sampling depth. The 48-h SPIN shows a greater amount of PEO present at all corresponding takeoff angles than the SPIN treated for 30 min, the standard treatment time. Inhomogeneity in composition as a function of depth is evident in both samples. One might expect that a long treatment time of 48 h would produce a polymer homogeneously incorporated with PEO, but apparently this was not the case and a drop in PEO concentration was observed with increasing depth from the sample surface. This could be due to insufficient time to reach equilibrium or to preferential swelling near the surface of the PET film.

NMR Analysis for PEO Detection. The spectra for samples i–iv as indicated earlier are shown in Figure 2. The spectrum for PET showed sharp peaks for the four aromatic protons at approximately 8.1 ppm while the four protons on the ethylene glycol unit were observed at 4.8 ppm. The peak at 11.6 ppm was from the acid. It was observed that the integrals for the peaks at 8.1 and 4.8 ppm were of equal height, indicating that the repeat unit for the polymer in the Mylar film was indeed of the chemical formula shown for PET in Figure 2. The peaks below 2.5 ppm were attributed to impurities. In the spectrum of PET + PEO18.5K, the four-proton ethylene glycol repeat units in PEO18.5K were identified as single peak, at 3.8 ppm. The four-proton ethylene glycol unit on PET, although structurally identical to the PEO repeat unit, appears downfield of the latter due to the deshielding by the aromatic ester group to which it is attached. The spectrum of the SPIN showed a small but repeatable and integrable peak for PEO in the region of 3.8 ppm. Upon ratioing the integral of the two ethylene glycol peaks (in PEO and PET), it was concluded that 10.0 ± 3.6 mol % of the ethylene glycol repeat units in the sample belonged to PEO in the case of the SPIN with 30-min treatment time. The spectrum of the 48-h SPIN showed a relatively larger PEO peak, which upon calculation was found to contribute 23.0 ± 4.5 mol % of the ethylene glycol repeat units in the sample. Thus, the 48-h SPIN showed greater than twice the incorporation of PEO as compared to the SPIN with a 30-min treatment time. These data corroborate the angular depth profile study by XPS on these substrates.

Differential Scanning Calorimetry. Our hypothesis regarding the structure of the SPIN is that PEO chains are homogeneously distributed (at a particular subsurface depth) and phase-mixed, present in the base polymer (PET) in a kinetically frozen state (entrapped), having local properties not unlike that of a polymer blend. If this were indeed the case, then a single glass transition temperature should be observed intermediate between the T_g's of the two homopolymers at a value determined by the weight fractions of the two polymers and approximated by the Fox equation.[30] If indeed this were the case and the SPIN was heated to a high enough temperature to permit reorganization of polymer chains, then the once nonequilibrium, phase-mixed structure should phase-separate to achieve the equilibrium state, producing distinct PET and PEO domains. Successive DSC runs on the same sample should then show a T_g for each homopolymer. Alternatively, since it has been observed in blends that PEO shows no T_g due to high crystallinity,[31] assuming there is a sufficient quantity of PEO present in the sample, DSC should show a melting point (T_m) for PEO if it is present in a separate phase domain. The T_g of PEO has been reported as −60 °C for a totally amorphous sample,[32] and a T_m of 66 °C has been reported.[31] The T_g of 81 °C has been reported for PET.[33]

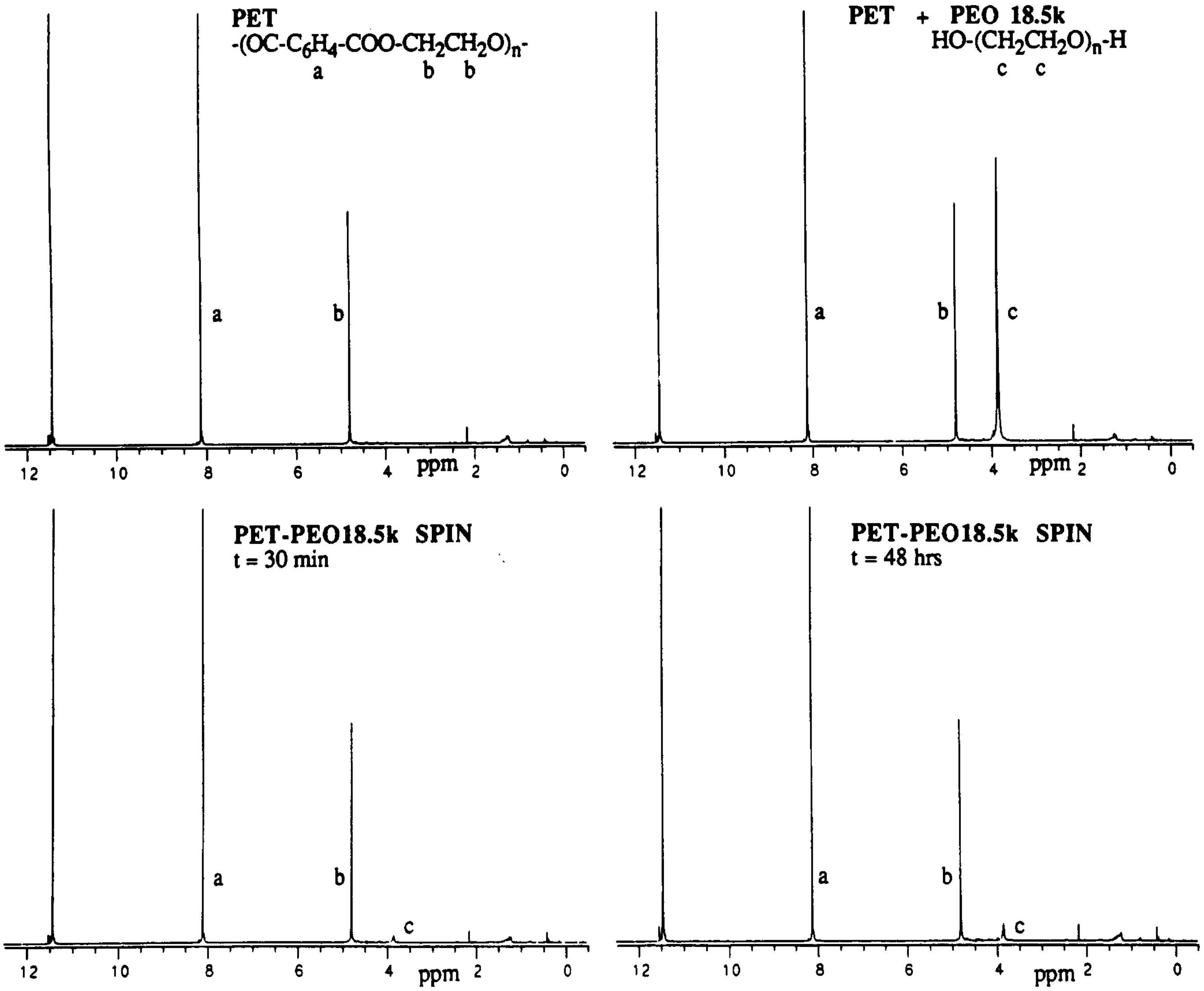

Figure 2. Proton NMR spectra of PET, PET and PEO18.5K (together, but not as a SPIN), PET–PEO18.5K SPIN with 30-min treatment time, and PET–PEO18.5K SPIN with 48-h treatment time. Approximately 23 mol % of the ethylene glycol units in the 48-h SPIN were attributed to PEO.

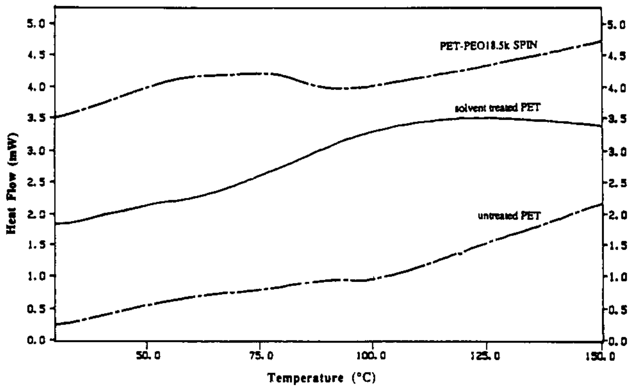

Figure 3. Differential scanning calorimetry traces for untreated PET, solvent-treated PET, and PET–PEO18.5K 48-h SPIN showing the first heating cycles. Heating ranges are from 0 to 300 °C at 20 °C/min.

Figure 3 shows DSC thermograms for untreated PET, the solvent-treated PET control, and the PET–PEO18.5K 48-h SPIN. The 48-h SPIN was examined rather than the standard 30-min SPIN to allow measurement of the minor PEO component (23 mol % of PEO mer by NMR); insufficient PEO was incorporated into the 30-min SPIN to allow measurement by DSC (10 mol % of PEO mer by NMR). The solvent control consisted of PET immersed in 80:20 TFAA/water solution, i.e., the SPIN treatment solution in absence of the modifying polymer PEO; this was done to separate the effects of the solvent on PET from the combined effect of solvent and PEO on the PET substrate. The first heating cycles for each of these substrates are shown in Figure 3. The PET curve shows a more or less even heat absorption through the heating cycle, indicating that the polymer is largely crystalline. The PET solvent control shows a small glass transition starting at 70–75 °C. This may be attributed to the partial dissolution in the treatment solution followed by precipitation of small amounts of amorphous PET during the water quenching step. Above approximately 120 °C, the curve changes slope, showing a mild exotherm which may be attributed to crystallization of the amorphous regions. Above 150 °C (not shown) the curve resumes its original slope until it reaches the melting point of approximately 250 °C. The curve for the 48-h SPIN substrate shows the combined effects of the solvent treatment and the presence of PEO in the sample. The solvent action provides a small degree of amorphous character (and therefore a glass transition), and the presence of PEO lowers the glass transition (compared to PET solvent control) which now occurs in the region of 50 °C. The T_g lowering is indicative of the phase-mixed structure as hypothesized above.

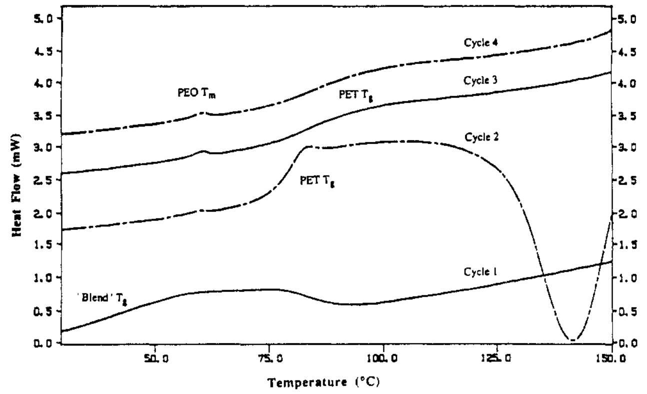

Figure 4. DSC thermograms for the PET-PEO18.5K 48-h SPIN showing successive heating cycles. Cycle 1 had a heating range of 0–300 °C, and cycles 2–4 had temperature ranges of 0–150 °C. At the end of each heating cycle, the sample was quenched to 0 °C at a rate 200 °C/min.

Figure 4 shows successive heating cycles 1–4 for the PET-PEO18.5K 48-h SPIN. The curve representing cycle 1 is identical to the one in Figure 3; it shows a lowering of the T_g due to the presence of phase-mixed or interpenetrating PET and PEO chains. In this cycle, the sample is heated to 300 °C during cycle 1 and is then rapidly cooled to 0 °C. The PET melting endotherm occurred at 252 °C. Due to the rapid cooling following cycle 1, one would expect that a significant fraction of the PET present should not crystallize and therefore should show a larger glass transition due to the larger amorphous fraction during heating cycle 2. This was indeed the case in cycle 2. In addition, the PET T_g occurred at a higher temperature (approximately 78 °C) compared to cycle 1. There is also the presence of a small but quite repeatable peak, at 61 °C in cycle 2, which can be attributed to PEO melting. Thus, it can be concluded that, during cycle 1, a reorganization of polymer chains occurred above the PET T_g, during which the PET and PEO phase-separated due to their thermodynamic immiscibility, resulting in at least the partial destruction of the SPIN phase-mixed structure. The phase separation is, however, not completed in cycle 1. In cycle 2 (and all subsequent cycles), the sample was heated from 0 to 150 °C. A crystallization peak occurred at 142 °C, during which most of the amorphous PET crystallized. Cycle 3 showed a more distinct PEO T_m at 61 °C compared with cycle 2, due to a more complete phase separation between PET and PEO. The PET showed a much smaller glass transition, because most of it crystallized in cycle 2. Cycle 4 showed thermal behavior identical with that in cycle 3, indicating that no further rearrangements of polymer chains occurred and that phase separation was complete. These observations support the hypothetical phase-mixed structure proposed for the SPIN modification and suggest that it is a kinetically determined nonequilibrium structure that can be induced to reach equilibrium and phase-separate at temperatures that allow sufficient mobility of polymer chains.

Effects of Organic Solvents on the SPIN. C 1s XPS spectra for the PEO18.5K SPINs after immersion in organic solvents for 2 h gave interesting correlations with the solvent Hildebrand solubility parameters. Solvents whose δ values were close to that of PET showed the largest removal of PEO. Figure 5 shows XPS C 1s spectra of PET, the PEO18.5K SPIN, and the SPINs treated with different organic solvents. The resolved peaks in each spectrum are, in the direction of increasing binding energy, the hydrocarbon C—C, the C—O ether, and the C═O carbonyl ester, having binding energies of 285, 286.4, and 289 eV, respectively. The intensities of the component peaks are expressed in the ratios C—C:C—O:C═O, measured relative to the intensity of the C—C component.

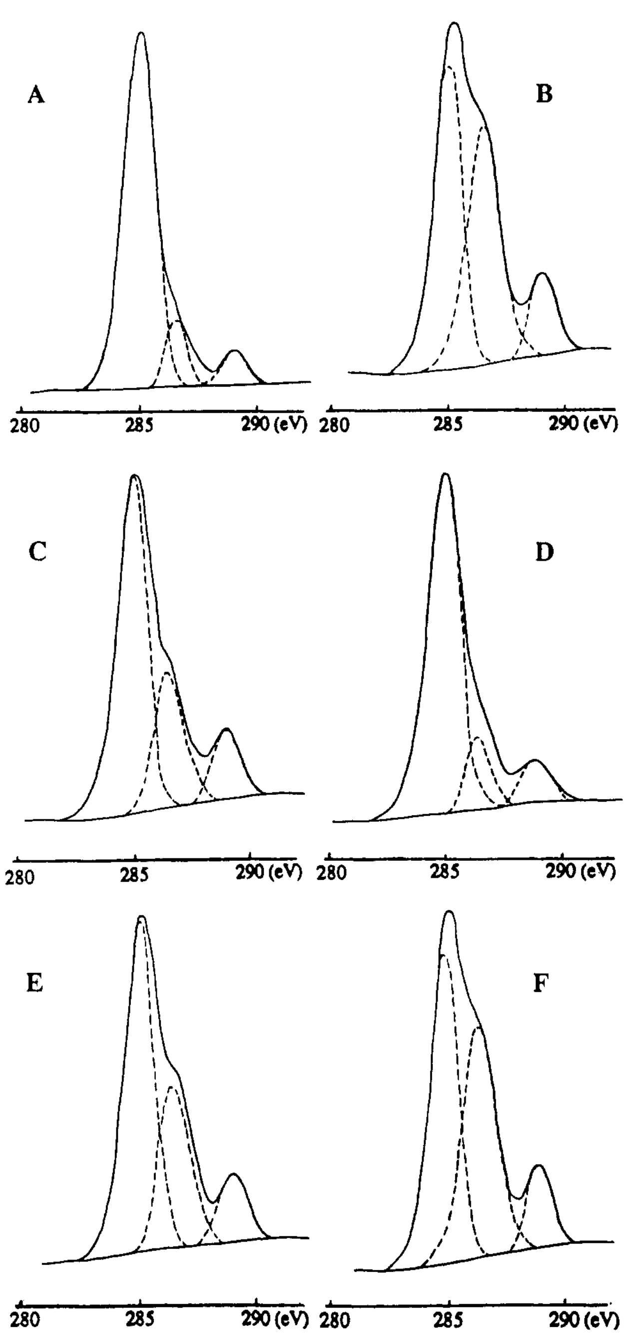

Figure 5. High resolution C 1s XPS spectra of solvent-treated PEO18.5K SPINs showing the effect of PEO leaching on C—C: C—O:C═O ratios: (A) native PET, 1.0:0.11:0.07; (B) PET-PEO18.5K SPIN, 1.0:0.94:0.21; (C) dioxane-treated SPIN, 1.0: 0.35:0.21; (D) benzene-treated SPIN, 1.0:0.16:0.11; (E) toluene-treated SPIN, 1.0:0.49:0.19; (F) carbon tetrachloride treated SPIN, 1.0:0.92:0.24. An error of ±5% is associated with the ratios as obtained from two separate sets of data. A pass energy of 20 eV and a takeoff angle of 45° were used for these measurements.

The intensity of the central peak in each spectrum is proportional to the amount of PEO present in the vicinity of the sample surface. A decrease in the relative contribution of the C═O ether peak compared to the untreated SPIN is evident in the case of some of the solvent-treated SPINs. Although the solubility parameters in order of decreasing proximity to the PET value are dioxane, benzene, toluene, and carbon tetrachloride, the benzene-treated SPIN showed the maximum removal of PEO (δ and $(\delta_{\text{solvent}} - \delta_{\text{PET}})^2$ values as shown in the Figure 6 caption).

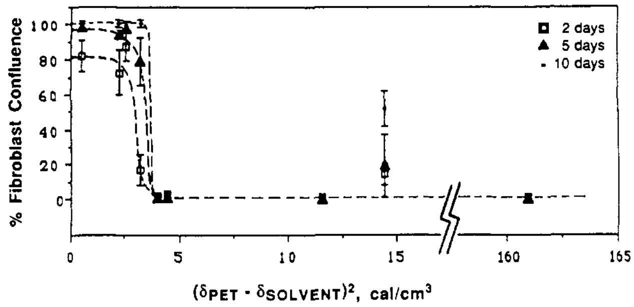

Figure 6. Percent confluence at 2, 5, and 10 days after initial seeding plotted versus differences in solubility parameter values (squared) showing a sharp cutoff for solvent leaching of PEO above values of 4.0 cal/cm^3. $\delta_{PET} = 10.7$ [cal/cm^3]$^{1/2}$, and the data points from left to right are, in order of increasing squared difference values, dioxane (solubility parameter $\delta = 10.0$ [cal/cm^3]$^{1/2}$, $[\delta_{PET} - \delta_{solvent}]^2 = 0.491$ cal/cm^3), benzene (9.2, 2.25), tetrahydrofuran (9.1, 2.56), toluene (8.9, 3.24), ethanol (12.7, 4.00), carbon tetrachloride (8.6, 4.41), *n*-hexane (7.3, 11.56), methanol (14.5, 14.44), and water (23.4, 161.00). Solubility parameter values were obtained from ref 29.

This effect may be attributed to the poor solubility of PEO in dioxane at room temperature. The amount of PEO removal as function of the solvent was in the order benzene > dioxane > toluene > carbon tetrachloride. A comparison of the carbon tetrachloride treated SPIN with the untreated SPIN showed a similar amount of PEO present, implying that the solvent did not cause significant swelling of PET and therefore leaching of PEO.

In the cell adhesion studies on the solvent-treated polymers, when $(\delta_{PET} - \delta_{solvent})^2$ approached the value of 4.0 cal/cm^3 (ethanol), it was observed that cell adhesion and spreading dropped sharply to zero, indicating no or very little removal of PEO and a low degree of swelling. A measurement of the percent confluence (or percent coverage of the sample surface by spread fibroblasts) versus $(\delta_{PET} - \delta_{solvent})^2$ at 2 days after cell seeding (Figure 6) showed a strongly adhesive response for dioxane, benzene, and tetrahydrofuran; a mildly adhesive response to toluene; and zero adhesion on ethanol, carbon tetrachloride, hexane, and water. This behavior is listed in order of increasing $(\delta_{PET} - \delta_{solvent})^2$ values. The only exception to the trend was methanol (14.44 cal/cm^3), which showed a mild adhesive response. Similar behavior was observed at 5 and 10 days postseeding. The correlation with solubility parameter is striking and indicates, along with the thermographic results, that polymer relaxation, here achieved by swelling, allows phase separation in the SPIN structure, with subsequent PEO leaching. The discrepancy in the case of methanol may be explained by its highly polar nature, which is not well described by Scatchard–Hildebrand solubility parameters.

High-Temperature Leaching of PEO in Water. XPS measurements following incubation of the PET–PEO18.5K SPIN in water at different temperatures (37, 71, and 91 °C) showed a large loss of PEO from the substrates incubated at 91 °C for 48 h. The ratios C—C: C—O:C=O as obtained by XPS measurements following the leaching were 1.0:0.94:0.24, 1.0:0.68:0.18, and 1.0:0.44: 0.14 for SPINs incubated at 37, 71 (T_g − 10), and 91 °C (T_g + 10), respectively (spectra not shown). Compared to the SPIN incubated at 37 °C (which has the same peak intensity ratio as the untreated SPIN, indicating no leaching of PEO at 37 °C), the material incubated above the T_g of PET showed a decrease in PEO content of 53% while the SPIN incubated below the T_g showed a decrease of PEO content of 28%.

Fibroblast adhesion and spreading measurements on these substrates corroborated the results obtained by XPS. Cell adhesion and spreading were monitored on the SPIN substrates which had been incubated for 1, 4, 20, and 48 h in water at 71 and 91 °C. No cell adhesion was observed on the substrates which had been incubated at 71 °C for the first three time points, but a small degree of adhesion and spreading was observed on the substrate after 48 h of incubation in water, indicating that sufficient amounts of PEO had leached at longer times for some cell adhesion to occur. On the SPIN substrates incubated at 91 °C, adhesion was observed as early as 1 h after incubation in water, but the cells were relatively unspread, indicating that the surface was still not sufficiently adhesive for normal cell growth. After 20 h of water incubation, the cells showed a completely spread morphology on these substrates.

Fibroblast culture of the 48-h water-incubated substrates showed considererable differences in the percent confluency after 2 days of following the cell seeding. The SPIN substrates incubated at 91 °C showed a 30 ± 9.6% (mean ± SD) coverage of the surface with fibroblasts, while the ones incubated at 71 °C showed a much lower surface coverage of 3.3 ± 3.8%. These results support the hypothesis that PEO chains are indeed entrapped in the base PET polymer and a relaxation of PET chains near the glass transition temperature of 81 °C allows the PEO to leach out into the aqueous environment.

Conclusions

We have previously described a solution process by which to impregnate the surface of a variety of polymers with PEO.[16] We have previously demonstrated that these materials are extraordinarily resistant to mammalian cell,[16,34] bacterial,[17] and tissue attachment. In the present study, we sought to characterize the surface structures so produced, which are referred to as a surface physical interpenetrating network and to examine the hypothesis that the PEO exists in a phase-mixed state within the base polymer. The PET–PEO18.5K system was chosen for examination. PET and PEO are an immiscible polymer system; as such, a phase-mixed structure would be somewhat unexpected. It was hypothesized, however, that the rapid nonsolvent quench from the swollen state would result in a kinetically stable, although thermodynamically unstable, phase-mixed structure. Moreover, it was hypothesized that the diffusive nature of the synthetic scheme would result in the preferential localization of the PEO near the surface of the PET films treated.

The experiments reported herein support the hypothesized SPIN structure. DSC indicated a phase-mixed structure by showing a T_g that was intermediate to those of PET and PEO on the first thermal cycle. Upon the second and subsequent cycles, the T_g approached that of PET and a second small but repeatable PEO melting peak appeared. This suggests that the PEO was initially homogeneously dispersed (at a given subsurface depth), but phase-separated upon heating above the T_g. This was corroborated by heating and leaching in water near the PET T_g and by increasing polymer chain mobility through mildly swelling solvents, using surface spectroscopic and biological assays. Angle-resolved XPS demonstrated that the PEO was present in the SPIN at a higher concentration near the surface of the PET film.

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