

Effect of Different Experimental Conditions on Biodegradable Polylactide Membranes Prepared with Supercritical CO₂ as Nonsolvent

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ABSTRACT: There is increasing interest in the application of supercritical CO₂ (SCCO₂) in the preparation of polymer membranes. Membrane formation with SCCO₂ as a nonsolvent is analogous to the conventional immersion precipitation process using an organic nonsolvent. Polylactide membranes were prepared with SCCO₂ as the nonsolvent under different experimental conditions such as different polymer concentrations, different depressurization rates, and different nonsolvent compositions. The effects of these conditions on the cross-sectional structure were investigated through

scanning electron microscopy. In addition, solvent-induced crystallization and CO₂-induced crystallization were studied. The crystallinity of PLA membranes prepared with different solvents or at different pressures was characterized by wide-angle X-ray diffraction and differential scanning calorimetry. © 2005 Wiley Periodicals, Inc. *J Appl Polym Sci* 98: 831–837, 2005

Key words: supercritical CO₂; polylactide; membrane

INTRODUCTION

It is well known that supercritical fluids (SCFs) have some distinctive properties, which include gaslike viscosity and diffusivity, and liquidlike density and dissolvability. Small changes in temperature and pressure can cause dramatic changes in the diffusivity, dissolvability, and dielectric properties of the fluid, which makes it a tunable solvent.^{1–3} Therefore, SCFs are being increasingly applied as solvents for polymer processing based on their ability to achieve desirable morphologies. SCF technology, referred to as “green chemistry technology,” has been developed to form polymeric materials such as microspheres, porous fibers, porous foams, and porous membranes. Typical processes are rapid expansion of supercritical solutions (RESS),^{4–6} a microcellular foaming process,^{7–9} and precipitation with compressed fluid antisolvent (PCA).^{10–13} In the RESS process, supercritical solution is expanded through

a nozzle to form microspheres or microfibers. In the microcellular foaming process, a polymer pellet is saturated with SCCO₂ and nucleation is induced by supersaturation caused by a sudden depressurization. In the PCA process, a polymer solution is sprayed through a capillary into a vessel containing compressed CO₂ or SCCO₂.

Most polymer membranes are prepared by the immersion precipitation process. The application of SCCO₂ has been attracting more and more attention, especially in the preparation of polymer membranes.^{14–16} The general advantages of membrane formation with SCCO₂ as the nonsolvent are as follows.^{14–18} CO₂ is inexpensive, environmentally benign, and nonflammable and its mild critical conditions ($P_c = 73.8$ bar, $T_c = 31.1^\circ\text{C}$) allow it to be used with safe laboratory and commercial operation conditions. Another advantage is that CO₂ can be easily and completely removed from products and a dry polymer membrane is obtained without a collapsed structure. In addition, the solvent can be easily recycled from gaseous CO₂ after the pressure is diminished. Furthermore, it is convenient to control the morphology of products by altering the pressure and temperature.

Polylactide (PLA) is a kind of green material because of its biodegradability. Medicine and biology have been the focus of uses of PLA recently, such as PLA hollow fibers, PLA nanoparticles and porous PLA membranes used in the controlled delivery of drugs,^{19–21} PLA foams used as scaffolds,^{22–24} and porous PLA films used to culture some cells.²⁵

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We previously²⁶ studied the compatibility between solvents [tetrahydrofuran (THF) and chloroform] and SCCO₂, and the effects of the solvents and preconditioning on the morphology of PLA membranes were investigated. In this study, the effects of other experimental conditions on the cross-sectional structure of the membranes are discussed, such as the polymer concentration, depressurization rate, and composition of the nonsolvent. Because the use of polymer membranes may be limited by their mechanical properties, it is necessary to study the effect of solvents and CO₂ pressure on the crystallinity of membranes. It is also found that the crystallinity of PLA membranes is increased after being posttreated with SCCO₂.

EXPERIMENTAL

Materials

PLA (mp 120°C) was supplied by CSIRO CMIT in the form of semitransparent pellets. After being dried *in vacuo* at 80°C for 48 h, PLA pellets were placed in a desiccator prior to use. Analytical grade solvents (chloroform and THF) were purchased from Tianjin Chemical Co., and analytical grade methanol was obtained from Luoyang Chemical Plant. CO₂ (99.9% purity) was supplied by Zhengzhou Shuangyang Gas Co. All reagents were used without any further purification.

Procedures

Membrane formation was conducted in a high-pressure stainless steel vessel (21.4 mL). A high-pressure syringe pump (DB-80, Beijing Satellite Manufacturing Factory, Beijing) used to charge CO₂ into the vessel was attached to the vessel via a coupling and high-pressure tubing. A pressure gauge consisting of a transducer (model 93, IC Sensors Co.) and an indicator (XS/A-1, Beijing Tianchen Automatic Instrument Factory, Beijing) with an accuracy of ± 0.01 MPa was also connected to the vessel to observe the *in situ* pressure change of the system. During the experiments, the vessel was placed in an isothermal water bath, which included a temperature control module (model C10, Thermo Haake) and a bath vessel (model P5, Thermo Haake). The temperature fluctuation of the bath was less than $\pm 0.1^\circ\text{C}$.

Casting solution

An appropriate amount of PLA pellets was dissolved in THF or chloroform to prepare a casting solution with a certain concentration. The components were capped and magnetically stirred at 308 K for 48 h.

Membrane formation

A thin membrane from the casting solution was cast onto a clean glass slide using a blade. The initial

membrane thickness was 182 μm . Then, the glass slide with the membrane was immediately transferred into the pressure vessel and CO₂ was introduced into it. The vessel was placed in the isothermal bath (308 K). When the desired pressure was reached, it was held for 1 h. Then the pressure was diminished and a dry PLA membrane was obtained.

We changed the solvent, CO₂ pressure, polymer concentration, depressurization rate, or the composition of the nonsolvent to obtain PLA membranes with different morphologies.

Posttreatment with SCCO₂ on PLA membrane prepared with chloroform/methanol as solvent/nonsolvent

A membrane was prepared by casting the PLA/chloroform solution (15 wt %) on a glass slide with a blade and immersing the solution into methanol. The temperature of the bath was kept at 20°C. The membrane was kept in methanol for 72 h, dried (24-h air-drying, 24-h vacuum drying), and transferred into the pressure vessel with CO₂ charged into it. The temperature of the system was 308 K. After keeping the system at 13 MPa for 1 h, CO₂ was vented for 1 h.

Membrane characterization

The PLA membranes were prepared for scanning electron microscopy (SEM) analysis by first fracturing them in liquid nitrogen. Then, the fractured samples were stabilized vertically on aluminum stubs using adhesive and sputter coated with an approximate 100 Å layer of gold. An SEM microscope (AMRAY-1000B) at an accelerating voltage of 20 kV was used to observe the structure of PLA membranes.

Wide-angle X-ray diffraction (WAXD) measurements were conducted to examine the crystallinity of the membranes. The apparatus was made up of an XRD unit (D/MAX-3B, Rigaku Co.) with a Ni-filtered Cu K α beam and a step length of 0.02°.

Membranes were scanned with a Netzsch 204 differential scanning calorimeter under an atmosphere of N₂ at a heating rate of 10°C/min from 25 to 200°C.

RESULTS AND DISCUSSION

Effects of experimental conditions on cross-sectional structure of PLA membranes

Effect of polymer concentration

When SCCO₂ was used as the nonsolvent, PLA membranes were prepared with different concentrations of casting solution. The SEM photographs of the cross-sectional structure of these membranes are shown in Figure 1. The figure shows that, with the increase of the polymer concentration, the average pore size de-

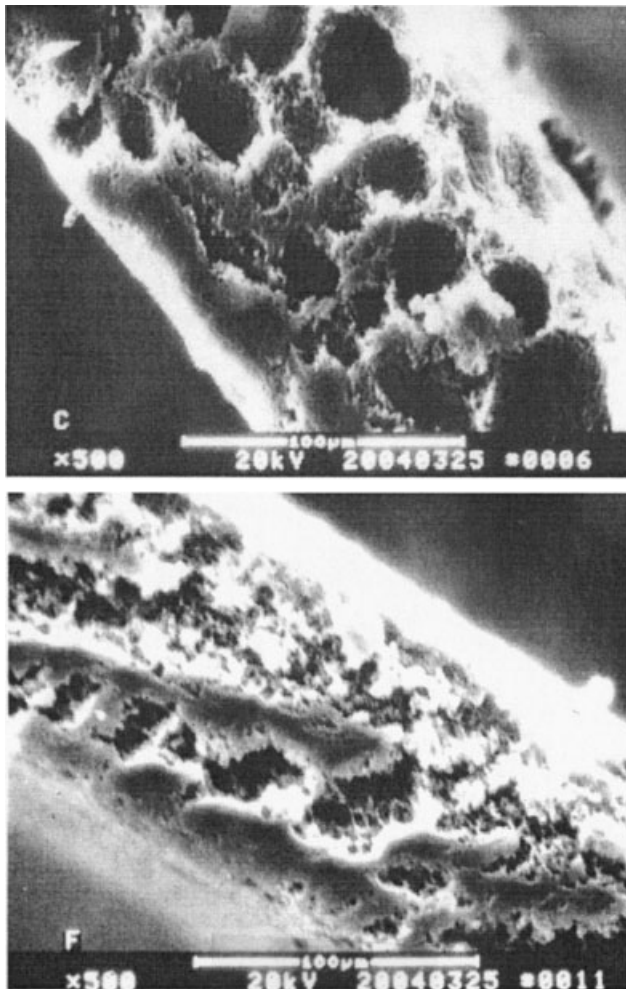


Figure 1 SEM photographs of the cross-section structure of PLA membranes prepared with different polymer concentrations: C = 20 wt %, F = 25 wt % solvent, THF; CO₂ pressure = 13 MPa; pressure = 1-h; depressurization = 1-h; temperature = 308 K.

creased and the uniformity of the pores became lower. In addition, if the polymer concentration was too high, dense and nonporous areas formed in the cross section of the membrane (Fig. 1, bottom). The lower viscosity brought about by the lower polymer concentration led to the easy coarsening of the droplets, which resulted in larger pores.

Effect of depressurization rate

Figure 2 shows the SEM photographs of the cross-sectional structure of PLA membranes prepared with different depressurization rates. The average pore size increased and the pore density decreased with the prolonged depressurization time, as shown in Figure 2. This was consistent with polystyrene foams prepared with SCCO₂ that were studied by Arora et al.²⁷ It was apparent that a porous structure formed prior to depressurization, and SCCO₂ had some foaming

action on the membrane because of the absorption of CO₂. CO₂ gaseous nuclei formed after depressurization and, when the depressurization time was longer, the gaseous nuclei had more time to grow, so larger pores were obtained.

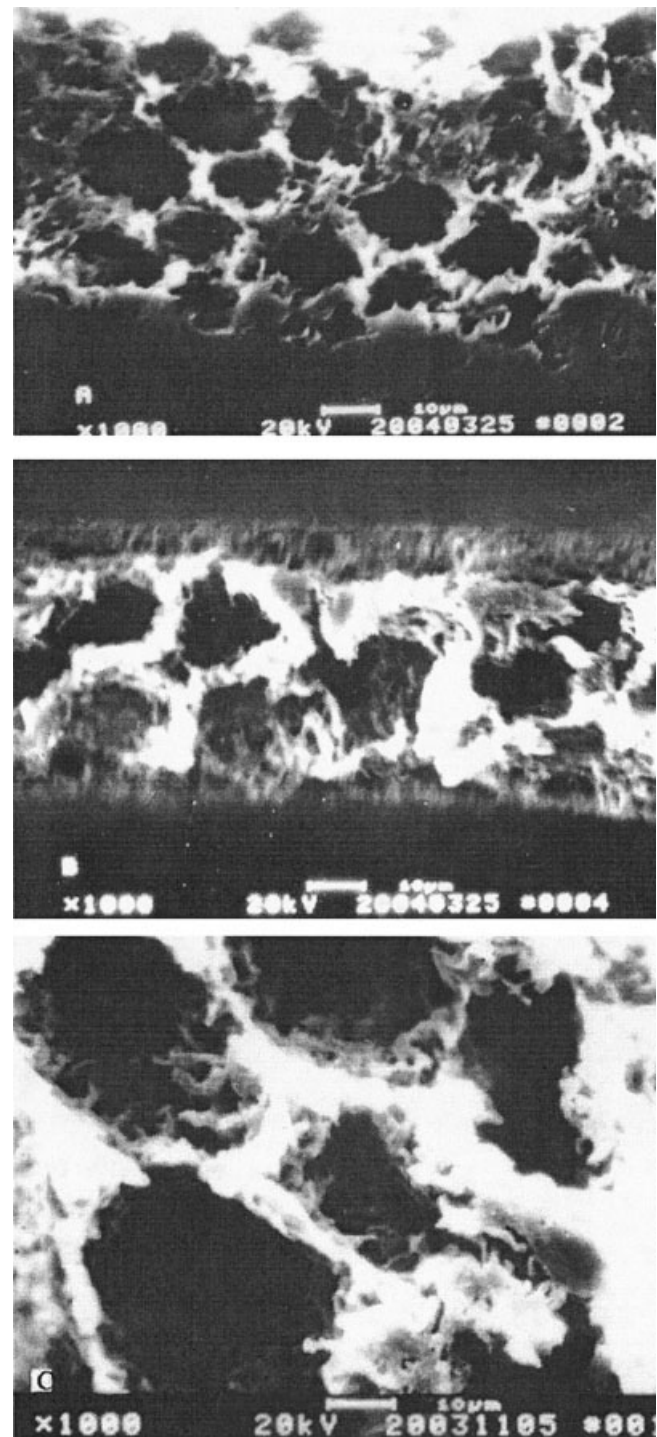


Figure 2 SEM photographs of the cross-section structure of PLA membranes prepared with depressurization times of (A) 2, (B) 15 and (C) 30 min; solvent, THF; polymer concentration = 15 wt %; CO₂ pressure = 13 MPa; pressure = 1 h; temperature = 308 K.

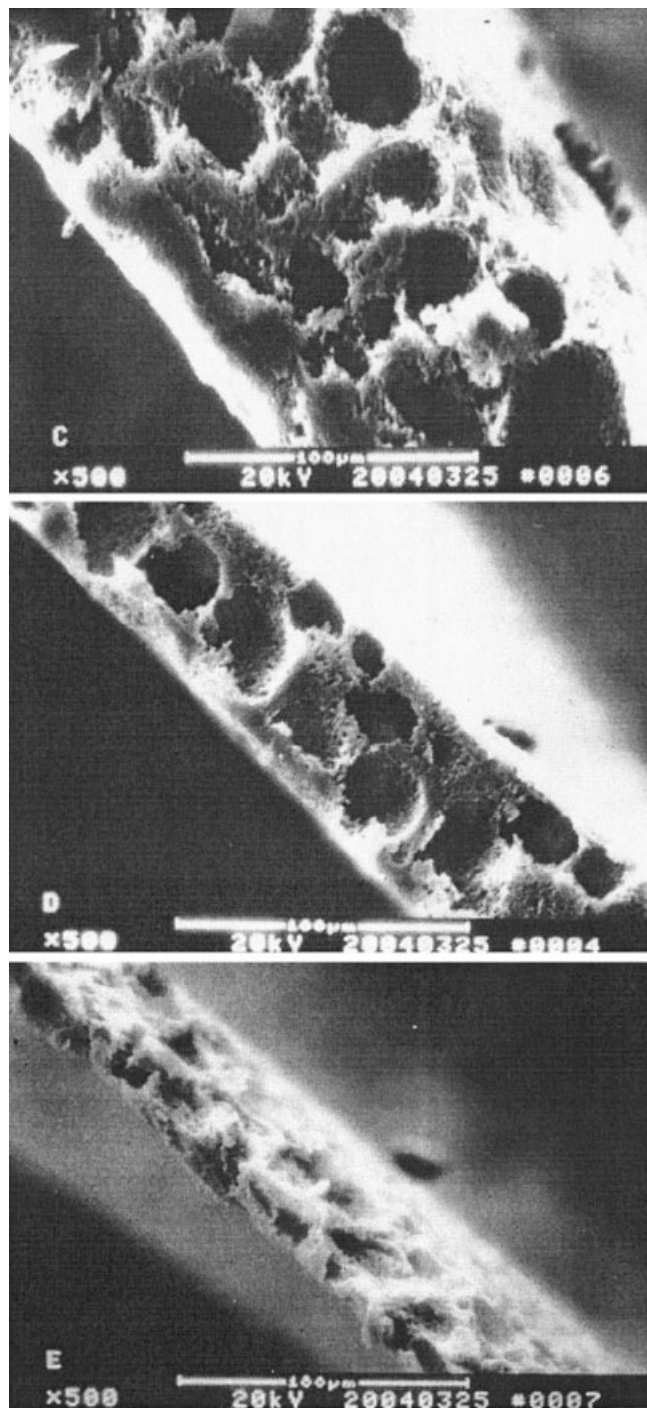


Figure 3 SEM photographs of the cross-section structure of PLA membranes prepared with different compositions of nonsolvent: (C) THF/SCCO₂ = 0 : 100 (vol/vol); (D) THF/SCCO₂ = 1 : 99; (E) THF/SCCO₂ = 2 : 98; solvent, THF; polymer concentration = 20 wt %; CO₂ pressure = 13 MPa; pressure = 1 h; depressurization = 1 h; temperature = 308 K.

Effect of composition of nonsolvent

For the conventional immersion precipitation process, the strength of the nonsolvent coagulation bath was decreased by introducing solvent into it. This was the

concept of a soft coagulation bath that allowed for the relatively slow exchange of solvent and nonsolvent. Then, delayed liquid–liquid demixing occurred and a dense top layer formed.

Similarly, in an attempt to alter the strength of the nonsolvent SCCO₂, solvent was introduced into the bottom of the vessel to alter the composition of the nonsolvent. In addition, the additional solvent and the casting membrane did not touch each other prior to the charging of CO₂. The procedures were the same with those discussed above.

The ratio of the introduced excess solvent THF to SCCO₂ by volume were 1 : 99 (0.21 mL), 2 : 98 (0.43 mL), and 3 : 97 (0.64 mL). A series of PLA membranes were prepared with different compositions of nonsolvents, the SEM results of which are presented in Figure 3. Apparently, with the increase of the amount of excess solvent, the membrane thickness decreased and the morphology became worse. No membrane was

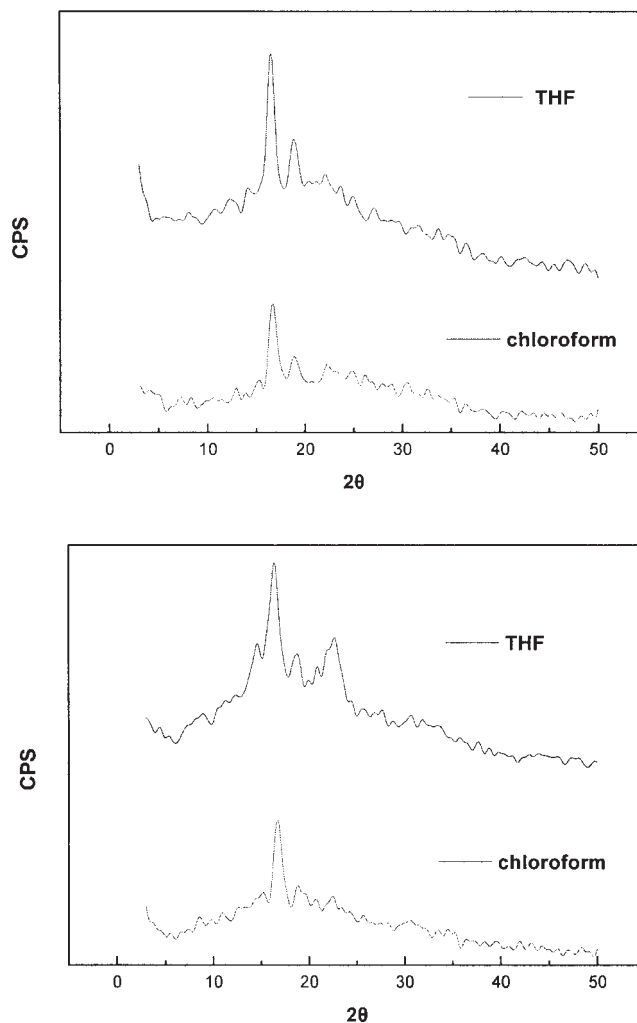


Figure 4 The results of WAXD measurements of PLA membranes prepared with different solvents at 13 (top) and 7 MPa (bottom); polymer concentration = 15 wt %; pressure = 1 h; depressurizing = 1 h; temperature = 308 K.

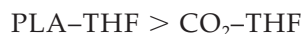
TABLE I
Heat of Fusion of PLA Membranes Prepared with Different Solvents and Calculated from DSC Patterns

CO ₂ pressure (MPa)	Solvent	Heat of fusion (J/g)
13	THF	42.78
	Chloroform	21.74
7	THF	38.02
	Chloroform	27.77

Polymer concentration = 15 wt %; pressure = 1 h; depressurization = 1 h; temperature = 308 K.

obtained when 0.64 mL (3 : 97) or more THF was introduced.

According to the study of the compatibility between the solvent and SCCO₂, when the pressure was lower than 6 MPa, the interaction of molecules in the PLA/THF/SCCO₂ ternary system was as follows:



that is, the affinity of PLA and THF was stronger than that of CO₂ and THF while the pressure was relatively low. During the pressurization, the additional solvent diffused into the casting membrane because of the carryover of CO₂. This led to the dilution of the casting solution, which caused the decrease of the membrane thickness. When the viscosity of the casting solution was too low because of dilution of the excess solvent, it led to worse morphology and even the failure of membrane formation.

Study of crystallinity of PLA membranes

Effect of solvent

It is well known that the crystallization of some amorphous and semicrystalline polymers can be induced

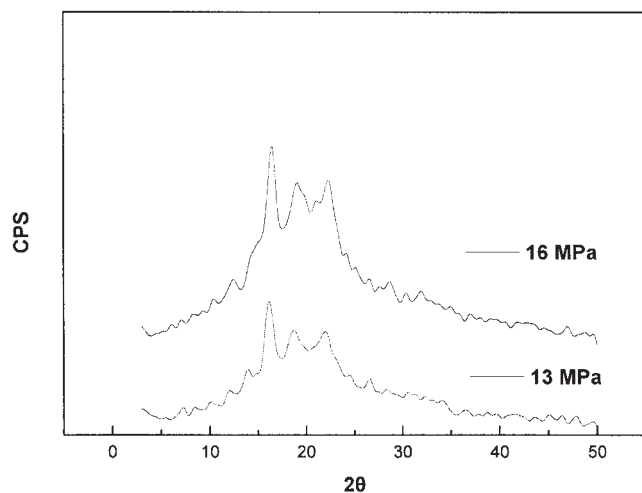


Figure 5 The results of WAXD measurements of PLA membranes prepared at different pressures; solvent, THF; polymer concentration = 20 wt %; pressure = 1 h; depressurizing = 1 h; temperature = 308 K.

TABLE II
Heat of Fusion and T_g of PLA Membranes Prepared at Different Pressures and Calculated from DSC Patterns

CO ₂ pressure (MPa)	Heat of fusion (J/g)	T_g (°C)
13	36.44	53.3
16	38.51	52.3

Solvent, THF; Polymer concentration = 20 wt %; pressure = 1 h; depressurization = 1 h; temperature = 308 K.

by solvents as well as heat and strain. The interaction between the polymer and solvent can reduce the glass-transition temperature (T_g) effectively. If the reduction of the T_g is large enough to put the system in the crystallization temperature region, the polymer chains can rearrange themselves into a lower free energy state.^{28,29} Solvent-induced crystallization occurs and higher crystallinity is obtained.

In our previous work,²⁶ we discussed the effects of the solvent on the crystalline morphology of the membrane. Different crystallinities were obtained in PLA membranes with different solvents, which were characterized by WAXD and differential scanning calorimetry (DSC).

The results of WAXD measurements are shown in Figure 4. It is well known that narrower and stronger diffraction peaks imply higher crystallinity in a WAXD pattern. As shown in Figure 4 (top), the diffraction pattern of the PLA membrane with THF as the solvent exhibited a strong diffraction peak at a 2θ value of 16.56°, but a weaker crystallization peak appeared at 16.60° for the membrane prepared with chloroform. It can be concluded that, at 13 MPa, the membrane prepared with THF had higher crystallinity. The same result was obtained at 7 MPa.

DSC measurements were conducted to obtain further evidence. The area of the fusion peak was calcu-

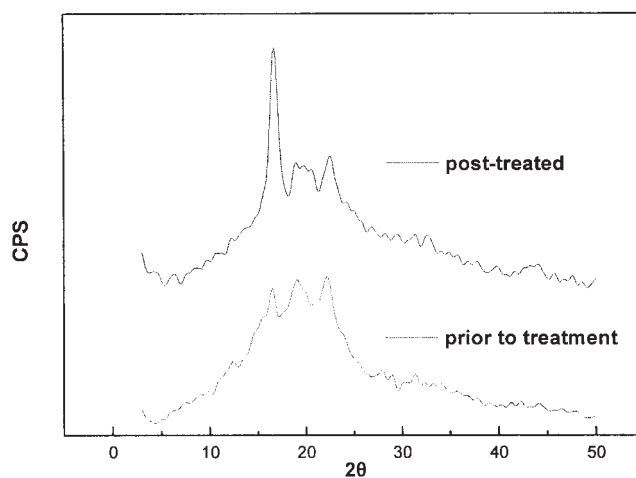


Figure 6 The results of WAXD measurements of untreated and posttreated PLA membranes with SCCO₂.

TABLE III
Heat of Fusion and T_g of Untreated and Posttreated PLA Membranes with SCCO₂

PLA membrane	Heat of fusion (J/g)	T_g (°C)
Untreated	27.82	62.7
Posttreated with SCCO ₂	28.67	54.1

lated, and the results are provided in Table I. It is well known that the heat of fusion is proportional to the crystallinity of polymers. Therefore, the larger the area of the fusion peak is, the higher the crystallinity of the polymer. The results in Table I make it obvious that the PLA membrane prepared with THF had a larger melting heat at both 7 and 13 MPa.

Effect of CO₂ pressure

Chiou et al.,³⁰ Condo et al.,^{31,32} and Mizoguchi et al.³³ reported that SCCO₂ induced crystallization of polymers. This induced-crystallization effect was brought about by the plasticization of CO₂ just as the sorption of CO₂.

Figure 5 provides the WAXD results of PLA membranes prepared at 13 and 16 MPa. Obviously, the PLA membrane had higher crystallinity at 16 MPa. For further verification, DSC measurements were performed and the results are shown in Table II. Note that the membrane prepared at 16 MPa had a higher heat of fusion. Furthermore, it was also found that the T_g of the membrane prepared at 16 MPa was lower than

that obtained at 13 MPa. This indicated that the plasticization effect due to the absorption of CO₂ was enhanced with pressure, which contributed to the reduction of the T_g .

Posttreatment with SCCO₂ on PLA membrane prepared with chloroform/methanol as solvent/nonsolvent

To study the effect of posttreatment on the crystallinity of membrane, a series of characterization measurements were carried out. The results of WAXD measurements are presented in Figure 6. After posttreatment, three bulged and weak peaks were replaced by a narrow and strong crystallization peak at 16.76°. It was obvious that the crystallinity increased after the posttreatment with SCCO₂.

In an attempt to verify the WAXD results, the heat of fusion of untreated and treated PLA membranes are listed in Table III. This indicates that the crystallinity increased because of the induced crystallization of CO₂, which led to the increase of the heat of fusion. In addition, the decrease of the T_g was caused by the plasticization of CO₂.

Figure 7 shows that there was an apparent exothermic peak at 94.3°C in the DSC pattern of the membrane without treatment, which might have been caused by stress history stored in the membrane. However, the exothermic peak disappeared for the posttreated membrane. This suggested that the stress effect stored in the membrane could be eliminated by the treatment with SCCO₂ and the mechanical and

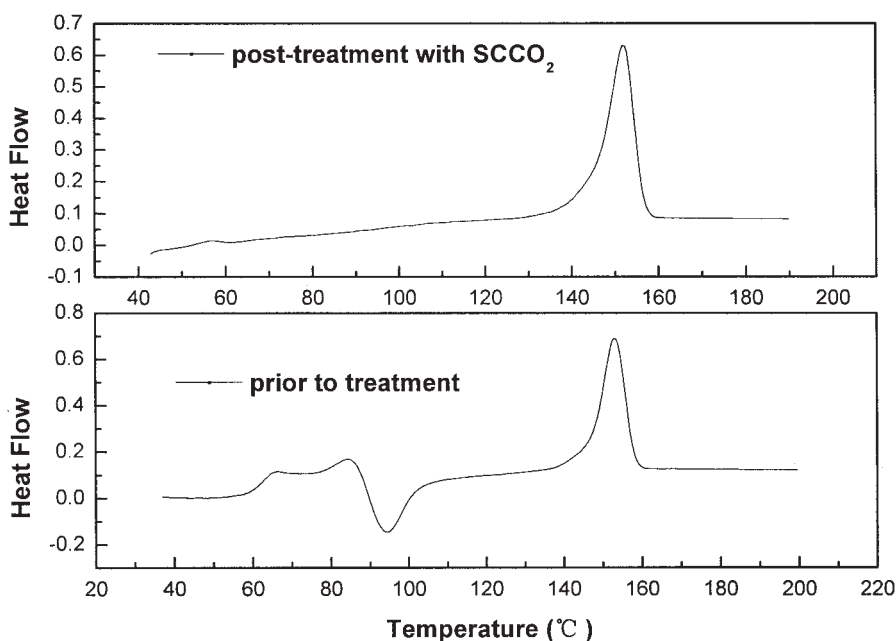


Figure 7 The DSC patterns of untreated and posttreated PLA membranes with SCCO₂.

thermal properties of the membrane could be improved.

CONCLUSION

With SCCO₂ used as a nonsolvent, PLA membranes were prepared under different experimental conditions such as different solvents, pressures, polymer concentrations, depressurization rates, and nonsolvent compositions. A series of measurements, which included SEM, WAXD, and DSC, were performed to characterize the membranes. We found that the pore size and uniformity of pores decreased with the increase of the polymer concentration. When the depressurization time was prolonged, the pore size increased and the pore density decreased. As the amount of the introduced solvent was increased, the membrane thickness decreased. Moreover, the crystallinity of the membranes was varied with different solvents and different pressures. When THF was used as the solvent, the membrane had higher crystallinity. For the membrane treated with SCCO₂, the crystallinity increased and the mechanical and thermal properties of membranes were simultaneously improved.

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References

1. Wells, S. L.; DeSimone, J. *Angew Chem Int Ed* 2001, 40, 518.
2. Berens, A. R.; Huvarad, G. S. In *Supercritical Fluid Science and Technology*; Johnston, K. P.; Penniger, J. M. L., Eds.; ACS Symposium Series 406; American Chemical Society: Washington, DC, 1989.
3. McHugh, M.; Krukoni, V. *Supercritical Fluid Extraction—Principles and Practice*; Butterworths: Boston, 1986.
4. Matson, D. W.; Fulton, J. L.; Petersen, R. C.; Smith, R. D. *Ind Eng Chem Res* 1987, 26, 2298.
5. Tom, J. W.; Debenedetti, P. G. *Biotechnol Prog* 1991, 7, 403.
6. Tom, J. W.; Debenedetti, P. G.; Jerome, R. J. *J Supercrit Fluids* 1994, 7, 9.
7. Colton, J. S.; Suh, N. P. *Polym Eng Sci* 1987, 27, 493.
8. Goel, S. K.; Beckman, E. J. *Polym Eng Sci* 1994, 34, 1137.
9. Goel, S. K.; Beckman, E. J. *Polym Eng Sci* 1994, 34, 1148.
10. Dixon, D. J.; Johnston, K. P.; Bodmeier, R. *AIChE J* 1993, 39, 127.
11. Dixon, D. J.; Johnston, K. P. *J Appl Polym Sci* 1993, 50, 929.
12. Luna-Barcenas, G.; Kanakia, S. K.; Sanchez, I. C.; Johnston, K. P. *Polymer* 1995, 36, 3173.
13. Randolph, T. W.; Randolph, A. D.; Mebes, M.; Yeung, S. *Biotechnol Prog* 1993, 9, 429.
14. Matsuyama, H.; Yano, H. *J Membr Sci* 2001, 194, 157.
15. Matsuyama, H.; Yamamoto, A. *J Membr Sci* 2002, 204, 81.
16. Kho, Y. W.; Kalika, D. S.; Knutson, B. L. *Polymer* 2001, 42, 6119.
17. Chang, Y.; Xu, Q. *J Appl Polym Sci* 2003, 90, 2040.
18. Xu, Q.; Chang, Y. *Polymer* 2003, 44, 5449.
19. Eenink, M. J. D.; Feijen, J. *J Controlled Release* 1987, 6, 225.
20. Romero-Cano, M. S.; Vincent, B. *J Controlled Release* 2002, 82, 127.
21. Park, Y. J.; Ku, Y. *J Controlled Release* 1998, 51, 201.
22. Veronique, M.; Didier, M.; Brigitte, M. *J Biomed Mater Res* 2000, 52, 639.
23. Gough, J. E.; Arumugam, M. *Materialwissenschaft Werkstofftech* 2003, 34, 654.
24. Chifeng, T.; Qing, C.; Jian, Y. *Polym Adv Technol* 2003, 14, 565.
25. Zoppi, R. A.; Contant, S. *Polymer* 1999, 40, 3275.
26. Xu, Q.; Pang, M. Z.; Peng, Q.; Li, J. B.; Jiang, Y. *J Appl Polym Sci* 2004, 94, 2158.
27. Arora, K. A.; Lesser, A. J.; McCarthy, T. J. *Macromolecules* 1998, 31, 4164.
28. Makarewicz, P. J.; Wilkes, G. L. *J Polym Sci Polym Phys Ed* 1978, 16, 1559.
29. Jameel, H.; Waldman, J.; Renbenfeld, L. *J Appl Polym Sci* 1981, 26, 1795.
30. Chiou, J. S.; Barlow, J. W.; Paul, D. R. *J Appl Polym Sci* 1985, 30, 3911.
31. Condo, P. D.; Paul, D. P.; Johnston, K. P. *Macromolecules* 1994, 27, 365.
32. Condo, P. D.; Johnston, K. P. *J Polym Sci Part B: Polym Phys* 1994, 32, 523.
33. Mizoguchi, K.; Hirose, T.; Naito, Y.; Kamiya, Y. *Polymer* 1987, 28, 1298.