Water-Assisted Formation of Honeycomb Films of Poly(L-lactic-*co*-glycolic acid)

Ye Tian,[1] Huaiyu Ding,[2] Yanqiao Shi,[1] Qingze Jiao,[2] Xiaolin Wang[3]

[1]School of Chemical Engineering and Environment Science, Beijing Institute of Technology, Beijing 100081, People's Republic of China
[2]Institute of Chemistry, Chinese Academy of Sciences, Beijing 100080, People's Republic of China
[3]Department of Chemical Engineering, Tsinghua University, Beijing 100084, People's Republic of China

ABSTRACT: The ordered honeycomb structures of poly(L-lactic-*co*-glycolic acid) and poly(D,L-lactic-*co*-glycolic acid) fabricated in a humid atmosphere were reported in this paper. It was found that surfactants were important in the formation of honeycomb films of hydrophobic polymer. The affecting factors, such as the environment temperature, the atmosphere humidity, and the concentration of the polymer solution of the honeycomb porous structure, were also tested. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 100: 1013–1018, 2006

Key words: poly(L-lactic-*co*-glycolic acid); sodium lauryl sulfate; high humidity; honeycomb structure

INTRODUCTION

The formation of the regular honeycomb porous structure in high humidity is one of the great developments in the field of molecular self-assembly.[1,2] It may be applied in biology,[3,4] tissue engineering,[5] micrographics,[6] separation science, and pharmacy. The ordered porous films can be obtained by evaporating the solvent (such as chloroform) of the polymer solution in a high humid atmosphere.[7,8] Since first fabrication of honeycomb films by François et al.,[9–11] with poly (styrene-*b*-polyparaphenylene), many polymer materials have been studied to form honeycomb-like films, which include rod-coil block copolymer,[12–14] star polymer,[15,16] comb polymer,[16] linear polymer,[17,18] polymer-crown ether block copolymer,[19] amphiphilic copolymer,[20,21] organic/inorganic hybrid materials,[22] polyion complexes,[23,24] etc. The character of such materials is that they all have hydrophilic structures in their molecules, and their molecules have the property of hydrophile–lyophile balance. Because of this balance, these materials can stabilize the water droplets that condensate at the surface of the polymer solution.

Polylactic acid (PLA) has good prospects due to its advantages:[25] nontoxicity, degradability, good chemical inertia, good biocompatibility, etc. However, PLA cannot form honeycomb films via the water-assisted method because of its low hydrophilicity. If the hydrophilic property of PLA is improved by copolymerizing the hydrophilic units, the honeycomb films may be obtained. Zhao et al.[20] prepared the honeycomb films using poly(D,L-lactic-*co*-glycolic acid) (PLGA, mole ratio, 50 : 50), but the PLGA (90 : 10) and the PLGA (70 : 30) could not form a honeycomb structure. They concluded that this phenomenon was caused by the low hydrophilicity of the PLGA (90 : 10) and the PLGA (70 : 30).

A surfactant is surface active because of its special molecular structure. Adding a surfactant to hydrophobic polymer solution will improve the hydrophilicity of the polymer solution, and honeycomb films are probably formed.

In this paper, the possibility of fabricating honeycomb structure by poly(L-lactic-*co*-glycolic acid) (PLLGA) has been researched. We prepared a series of PLLGA (Fig. 1) with different additions of sodium lauryl sulfate, which caused the solutions to have different hydropilicity values. We also compared the hydropilicity of PLLGA with that of PLGA. We successfully obtained regular porous films by PLLGA, with several additions of surfactant. Furthermore, the factors affecting the formation of honeycomb structure, such as the environment temperature, the atmosphere humidity and the concentration of the polymer solution, were investigated.
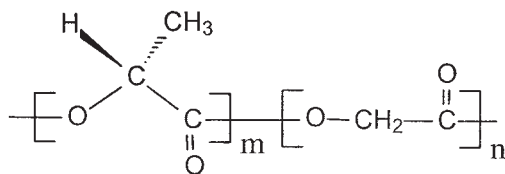
EXPERIMENTAL

Materials

The copolymers of poly(L-lactic-*co*-glycolic) (PLLGA, molar ratio, 80 : 20) and poly(D,L-lactic-*co*-glycolic

Figure 1 Chemical formula of the used copolymers.

TABLE II
Hydrophilicity of PLGA with Different LA/GA Ratios

Polymer films	Contact Angle (°)
PLGA (90 : 10)	67
PLGA (80 : 20)	62
PLGA (50 : 50)	59

acid) (PLGA, molar ratios, 90 : 10, 70 : 30, 50 : 50) were prepared by copolymerizing polylactic acid (PLA) and polyglycolic acid (PGA), supplied by Changchun Institute of Applied Chemistry. The molecular mass of PLLGA (80 : 20) is $M_n = 5 \times 10^4$. The molecular weight of PLGA (all kinds of ratios) varies from 9×10^4 to 1.1×10^5. Water was purified by a Millipore system (Milli-Q, Millipore). Chloroform was of spectroscopy grade. Sodium lauryl sulfate and sodium dodecyl benzene sulfonte (SDBS) were supplied by Xinglongda (Xiamen, China).

The hydrophilicity of copolymers, some of which have been added with different additions of surfactant, were characterized by the contact angle on a contact angle meter (FACE CA-D, Kyowa kaimenkagaku). The results of these series of copolymers are shown in Tables I and II.

Film preparation and characterization

The honeycomb films were prepared directly by casting the PLLGA and PLGA–chloroform solution (80 μm) on glass substrates in an atmosphere with controlled humidity and temperature. The surface morphology of the casting films were characterized by optical microscopy (BH2, Olympus, Japan) and scanning electron microscopy (S-4300, Hitachi, Tokyo, Japan).

RESULTS AND DISCUSSION

The process of formation of the honeycomb films is described as follows[26,27]: (1) Water droplets are condensed at the surface of the solution because of the cooling by solvent evaporation. (2) Because of the

TABLE I
Hydrophilicity of PLLGA with Different Additions of Surfactant

| Polymer films	Contact angle (°)
PLLGA (80 : 20)	65.8
PLLGA (80 : 20) + 0.001 g/L sodium lauryl sulfate	62.7
PLLGA (80 : 20) + 0.01 g/L sodium lauryl sulfate	56.3
PLLGA (80 : 20) + 0.1 g/L sodium lauryl sulfate	38.2
PLLGA (80 : 20) + 0.5 g/L sodium lauryl sulfate	13.4
PLLGA (80 : 20) + 0.1 g/L SDBS	64.2

incompatibility of the organic solvent and water, as well as the hydrophilic/hydrophobic balance of the polymer solution, water droplets are closely packed at the surface of the solution. (3) After the water and the solvent evaporate completely, honeycomb films are prepared.

Influence of hydrophilicity and surface tension of the materials

It has taken a long time to find out the materials which can form honeycomb films. François and coworkers[9–11] thought that the polymers must contain some polar groups, which could increase the hydrophilicity of the polymers. Stenzel et al.[15,16] concluded that the polymers, which could form spherical-shaped structure in proper solvents, might fabricate honeycomb films. Peng et al.[17,28] pointed out that a suitable viscosity of the polymer solutions was important to form an ordered porous structure. Chen and Zeng[29] considered that the polymers, which could form a special structure at the interface of the binary phases and decrease the surface tension of the two phases, could form a honeycomb structure.

Tables I and II show the contact angles of PLLGA and PLGA. It is easy to find that when the fraction of GA increases in the PLGA, the contact angle of PLGA decreases (Table II), which means the PLGA becomes more hydrophilic. When one increases the additions of the sodium lauryl sulfate, the contact angle of PLLGA decreases (Table I), which means the hydrophilicity of PLLGA increases too. However, the hydrophilicity of PLLGA does not change much when some SDBS is added (Table I). Figures 2 and 3 show the optical microscopy (OM) images and scanning electron microscopy (SEM) images of the copolymers of PLGA and PLLGA. On comparing these figures and tables, it was found that when the contact angles are between 59° and 38°, regular porous films can be obtained [Figs. 2(c), 3(d), and 3(e)].

Figures 3(a) and 3(b) show the films that have been prepared by the same materials but with different concentrations. It is easy to find that Figure 3(a) (1 g/L) has porous structures and Figure 3(b) (15 g/L) has almost no pore. This may be caused by the different surface tensions, which are influenced by many factors, such as concentration, viscosity, molecular weight, and so on. The films, which are shown in
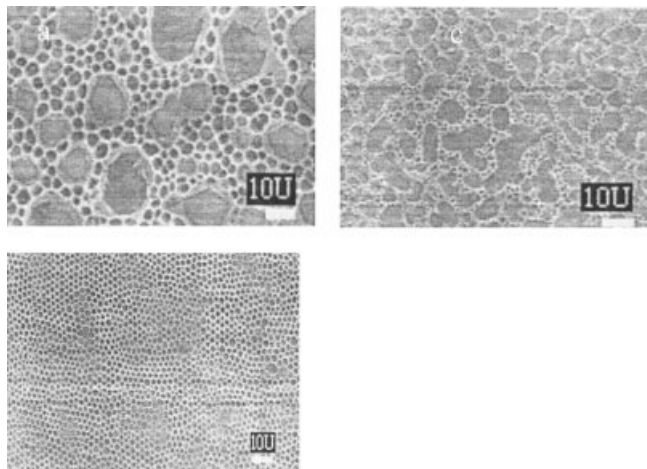
Figure 2 SEM images (a), (b), (c) of porous films prepared by PLGA/CHCl₃ solution. Conditions: temperature, 25°C; relative humidity, 95%; concentraion, 1 g/L; spreading volume, 80 μm.

Figures 3(a) and 3(b), have same hydrophilicity because of the same materials, but the different concentrations of the solutions lead to different surface tensions and showed different results. The morphology of the film fabricated by the low concentration solution [Fig. 3(a)] can be explained as follows: when the hydrophilicity of the PLLGA (80 : 20) is low, the water droplets cannot immerge into the polymer solution easily, and so the pitch of the holes is large; moreover, because of low concentration the solution's viscosity is low, and the polymer film cannot prohibit the coalescence of the water droplets, which have immerged into the solution, and so the shape of the holes is multifarious. On the contrary, the high concentration solution has a large viscosity, which leads to large surface tension, and so it is not easy to form pores [Fig. 3(b)]. If we add some surfactants to the polymer solution, the solution surface tension will be reduced, and porous films can be obtained [Figs. 3(c), 3(d), 3(e), and 3(f)].

Therefore, here we consider that the polymers that have certain hydrophilicity and whose solutions have appropriate hydrophile–lyophile balance and proper surface tensions easily form honeycomb films.

Functional principle and influence of the surfactant

It is found that the PLLGA/CHCl₃ solution containing some surfactants [Figs. 3(d) and 3(e)] can fabricate honeycomb structures. The surfactants have asymmetric molecule structure, which consists of nonpolar groups (hydrophobic groups) and polar groups (hydrophilic groups). Because of this molecule structure, the surfactants can gather and arrange accordingly at the surface of the solution. This special character of the

surfactants can not only increase the hydropholicity but also decrease the surface tension of the solutions.

Figure 4 shows the PLLGA films whose solutions contain different surfactants (Fig. 4(a) PLLGA/CHCl₃ solution containing SDBS and Fig. 4(b) PLLGA/CHCl₃ solution containing sodium lauryl sulfate). It is found that the PLLGA/CHCl₃ solution with sodium lauryl sulfate [Fig. 4(b)] has formed honeycomb structure, but the film that is formed by PLLGA/CHCl₃ solution with SDBS [Fig. 4(a)], is not so regular. Different surfactants have different characters, and so choosing a proper surfactant is a key step to obtain the honeycomb structure. Nonionic surfactants have good hydrophilic property at room temperature, but most of the nonionic surfactants are very ropy, which will increase the viscosity of the polymer solution, so that
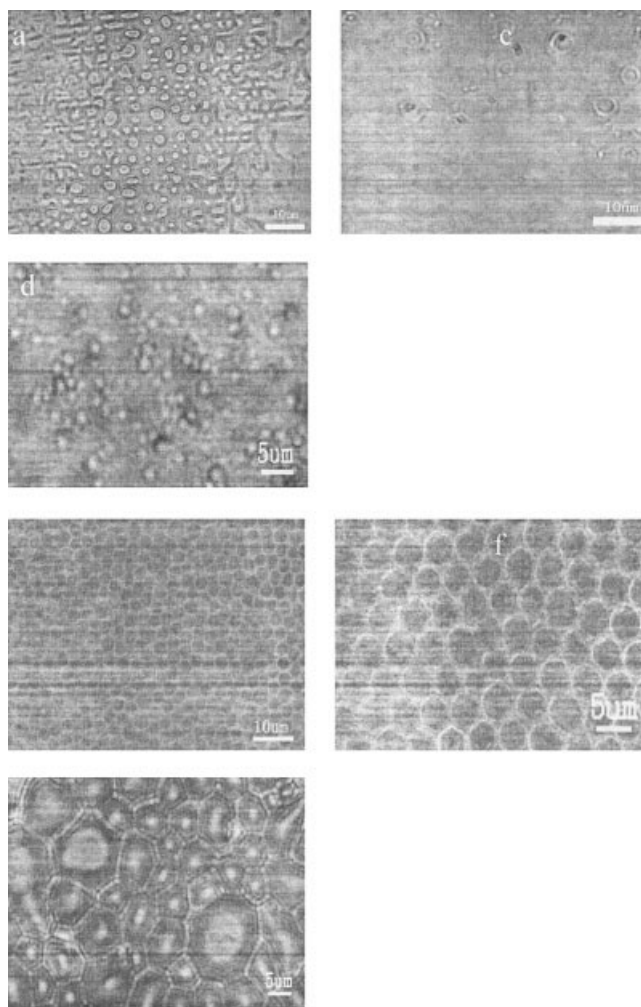
Figure 3 Optical microscopy images (a), (b), (c), (f) and SEM images (d), (e) of porous films prepared by PLLGA/CHCl₃ solution. (a) 1 g/L, (b) 15 g/L, (c) 15 g/L (contained 0.001 g/L sodium lauryl sulfate), (d) 15 g/L (contained 0.0l g/L sodium lauryl sulfate), (e) l5 g/L (contained 0.0l g/L sodium lauryl sulfate), (f) 15 g/L (contained 0.5 g/L sodium lauryl sulfate). Other conditions: temperature, 17°C; relative humidity, 95%; spreading volume, 80 μm.
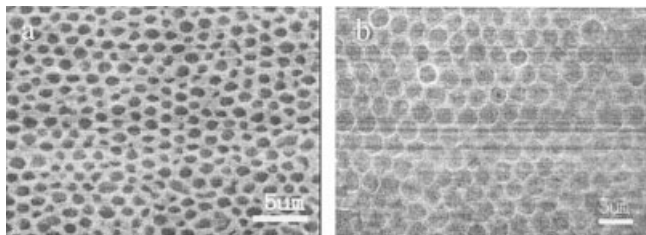
Figure 4 SEM images of porous films prepared by PLLGA/CHCl$_3$ solution in high humid. (a) PLLGA/CHCl$_3$ solution with sodium dodecyl benzene sulfonte, (b) PLLGA/CHCl$_3$ solution with sodium buryl sulfate. Other conditions: temperature, 17°C; relative humidity, 95%; concentraion, 15 g/L; spreading volume, 80 μm.

the films do not easily form pores. Ionic surfactants can decrease the surface tension of the polymer solution. At the same time, only the ionic surfactant can mix with water at will when the temperature reaches a certain high point, which is called "Krafft point". If the temperature is higher than this point, the ionic surfactant will have a good hydrophilic property; otherwise, the hydrophilicity of the ionic surfactants is low. Most of the ionic surfactants' Krafft points are higher than room temperature except sodium lauryl sulfate, whose Krafft point is 9°C. Sodium lauryl sulfate has good hydrophilicity at room temperature. From the results of the contact angle test (Table I), it is easy to say that adding SDBS to the polymer solution almost does not change the hydrophilicity of the solution, but the sodium lauryl sulfate can change the hydrophilicity obviously. This is the reason why the copolymer solution with SDBS can form only small pores (4a), but with sodium lauryl sulfate can form honeycomb structure.

Figures 3(c), 3(d), 3(e), and 3(f) show the results of the PLLGA films with the different additions of sodium lauryl sulfate. With the increasing additions of sodium lauryl sulfate, the shape of the holes changes from round to hexagon, and the pitch of holes becomes small, but when the content of the sodium lauryl sulfate is more than 0.5 g/L, the regular holes disappear. Different additions of sodium lauryl sulfate cause different hydrophilic and different surface tension of the polymer solutions, and lead to different results. It has been considered that the shape of the water droplets, which are dropped on the surface of the solution, was determined by the surface tension between the polymer and water droplets, and the repellent force among the water droplets, together.[20,30] The surface tension leaned to keep the roundness of the water droplets, and the repellent force tended to maintain the hexagonal shape of the water droplets. When the polymer solution contains 0.001 g/L sodium lauryl sulfate, the additions of the sodium lauryl sulfate is too low to improve the hydrophilicity of the polymer solution so much, which is proved by the

contact angle test (Table I). Also, the surface tension does not change so much, which can be deduced from the fact that the polymer solution is spread slowly on the substrate. Because of low hydrophilicity and large surface tension, the polymer solution finally forms small amounts of rounded holes [Fig. 3(c)]. With the increasing of the additions of the sodium lauryl sulfate, the hydrophilicity of the polymer solution is strengthened and the surface tension has less change, and so the shape of the holes changes into a hexagon, and the pitch of holes become small. But when the solution contains 0.5 g/L sodium lauryl sulfate, the solution's hydrophilicity is too strong and the surface tension becomes too little; and the polymer solution cannot prohibit the coalescence of the water droplets, and this leads to the various shapes of the big pores.

Influence of the solution concentration and environment humidity

Figure 5 shows the SEM images of honeycomb structures of PLLGA films with different concentrations. It can be seen clearly that high concentration solutions [Fig. 5(a)] form small pores, whose sizes are smaller than the low concentration solutions [Fig. 5(b)].

Using higher concentration solution to form porous films needs higher environment humidity, because high concentration causes high surface tension, and it is not easy for the water droplets to immerse into the polymer solutions. By adding some surfactants to the solutions, the porous structure can be formed in low environment humidity. PLLGA/CHCl$_3$ solution (5 g/L) cannot form a porous structure when the relative humidity is less than 85%. But when the solution contains 0.1 g/L sodium lauryl sulfate, it can fabricate
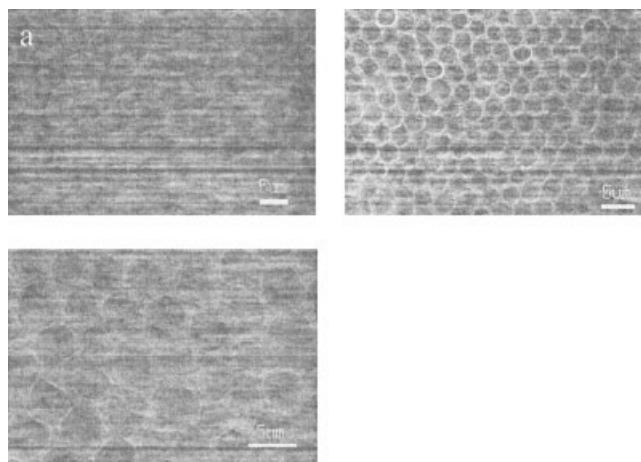
Figure 5 SEM images of porous films prepared by PLLGA/CHCl$_3$ solutions in high humidity. (a) 10 g/L, 95%, (b) 15 g/L, 95%, (c) 5 g/L, 70%. Other conditions: temperature, 17°C; concentraion: 15 g/L; spreading volume: 80 μm; 0.1 g/L sodium lauryl sulfate.
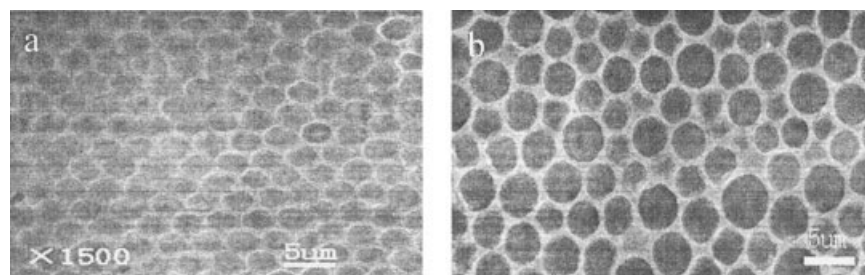
Figure 6 SEM images of porous films prepared by PLLGA/CHCl$_3$ solution in high humidity with different temperatures: (a) 17°C, (b) 20°C. Other conditions: relative humidity, 95%; concentraion, 15 g/L; spreading volume, 80 μm; 0.1 g/L sodium lauryl sulfate.

porous structure at a relative humidity of 70% [Fig. 5(c)].

Influence of the environment temperature and the volume of the solution

The spreading volume of the solution and the environment temperature mainly influence the volatilization time of the solvent, which is important for the formation of the shape of the pores. By controlling the volume of the solution and the environment temperature, the shape of the pores can be changed from round to hexagon. The more time the solvent needs to volatilize, the more time water droplets need to precipitate and coalesce, so that the pores become bigger, and the shape of pores is hexagonal. On the contrary, if the volatilization time of the solvent decreases, the pores are small and the shape of the pores is round.

When the volatilization time decreases, the curing time of the solution is reduced, and the precipitation time of water droplets is cut down too, and some of the water droplets cannot precipitate completely, so that the films form some nonpenetrated pores. The 15-g/L PLLGA/CHCl$_3$ solution (containing 0.1 g/L sodium lauryl sulfate) formed honeycomb structure at the environment temperature of 17°C [Fig. 6(a)], but when the temperature reached 20°C, the pores shape was round, and some pores were not penetrated [Fig. 6(b)].

CONCLUSIONS

It is a key factor to keep the water droplets stable at the surface of the polymer solutions. The solutions that have appropriate hydrophilicity and proper surface tension can stabilize the water droplets and obtain the regular porous structures more easily. Adding surfactants to the polymer solutions can change the hydrophilicity and surface tension of the solutions. Without changing the solution concentration and increasing the additions of the surfactant, the size of the holes becomes large, the pitch of the holes becomes small, and the shape of holes changes from round to

hexagon. However, if the content of the surfactant is too large, regular porous structures cannot be obtained; by the addition of the surfactant and increasing the concentration of the solutions or decreasing the atmosphere humidity, the size of the holes becomes small, and the pitch of the holes becomes large; by increasing the volume of the spreading solution or decreasing the environment temperature, the shape of holes changes from round to hexagon, and the penetrated pores will be easy to form.

By adding some surfactants to the polymer solutions, the hydrophobic polymer materials can form honeycomb structures via water-assisted method. This breaks through the limit of the materials' character and enlarges the sources of the materials.

References

1. Shimomura, M.; Sawadaishi, T.; Curr Opin Collid Interface Sci 2001, 6, 11.
2. Shimomura, M. Supramolecular Polymerization; Marcel Dekker: New York, 2000, 471.
3. Nishikawa, T.; Nonomura, M.; Arai, K.; Hayashi, J.; Sawadaishi, T.; Nishiura, Y.; Hara, M.; Shimomura, M. Langmuir 2003, 19, 6193.
4. Nishikawa, T.; Nishida, J.; Ookura, R.; Nishimura, S.; Wada, S.; Karino, T.; Shimomura, M. Mater Sci Eng C 1999, 8/9, 495.
5. Nishikawa, T.; Arai, K.; Hayashi, J.; Hara, M.; Shimomura, M. Mater Res Soc Symp Proc 2002, 72, 229.
6. Yabu, H.; Shimomura, M. Langmuir 2005, 21, 1709.
7. Gover, L. V.; Bashmakov, I. A.; Kaputski, F. N.; Pientka, M.; Parisi, J. Macromol Chem Phys 2000, 201, 1721.
8. Gover, L. V.; Bashmakov, I. A.; Kiebooms, R.; Dyakonov, V.; Parisi, J. Adv Mater (Weinheim, Ger) 2001, 13, 588.
9. Pitois, O.; François, B. Eur J Phys 1999, 138, 225.
10. François, B.; Pitois, O.; François, J. Adv Mater (Weinheim, Ger) 1995, 7, 1041.
11. Pitois, O.; François, B. J Polym Sci 1999, 277, 574.
12. Widawski, G.; Rawiso, B.; François, B. Nature 1994, 369, 387.
13. Jenekhe, S. A.; Chen, X. L. Science 1999, 283, 272.
14. Boer, B. D.; Stalmach, U.; Nijland, H.; Hadziioannou, G. Adv Mater (Weinheim, Ger) 2000, 12, 1581.
15. Stenzel, M. H. Aust J Chem 2002, 55, 239.
16. Stenzel, M. H.; Davis, T. P.; Fane, A. G.; Chen, V. Angew Chem Int Ed Engl 2001, 40, 3428.

17. Peng, J.; Han, Y. C.; Yang, Y. M.; Li, B. Y. Polymer 2004, 45, 447.

18. Xu, Y.; Zhu, B. K.; Xu, Y. Y. Polymer 2005, 46, 713.

19. Peng, J.; Han, Y. C.; Fu, J.; Yang, Y. M.; Li, B. Y. Macromol Chem Phys 2003, 204, 125.

20. Zhao, X. Y.; Cai, Q.; Shi, G. X.; Shi, Y. Q.; Chen, G. W. J Appl Polym Sci 2003, 90, 1846.

21. Nishikawa, T.; Nishida, J.; Ookura, R.; Nishimura, S.; Scheumann, V.; Zizlsperger, M.; Lawall, R.; Knoll, W.; Shimomura, M. Langmuir 2000, 16, 1337.

22. Karthaus, O.; Cieren, X.; Maruyama, N.; Shimomura, M. Mater Sci Eng C 1999, 10, 103.

23. Maruyama, N.; Koito, T.; Nishida, J.; Sawadaishi, T.; Cieren, X.; Ijiro, K.; Karthaus, O.; Shimomura, M. Thin Solid Films 1998, 327–329, 854.

24. Yabu, H.; Tanaka, M.; Ijiro, K.; Shimomura, M. Langmuir 2003, 19, 6297.

25. Cheng, R.; Qian, X. Chem Ind Eng Prog 2002, 21, 824. (Chinese).

26. Nishida, J.; Nishikawa, K.; Nishimura, S.-I.; Wada, S.; Karino, T.; Nishikawa, T.; Ijiro, K.; Shimomura, M. Polym J 2002, 34, 166.

27. Shimomura, M.; Sawadaishi, T. Curr Opin Colloid Interface Sci 2001, 6, 11.

28. Park, M. S.; Kim, J. K. Langmuir 2004, 20, 5347.

29. Chen, G. W.; Zeng, Y. M. Membr Sci Technol 2003, 23, 116. (Chinese).

30. Bruno, B.; Adam, J. S.; Albert, L. Phys Rev A : At Mol Opt Phys 1990, 41, 6893.