Flow Temperature of Poly(Lactic Acid) Gel in Solvents with Different Solubility

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Poly(L-lactic acid) (PLLA) forms complex crystals (ε-crystal) with some solvents including N,N-dimethylformamide (DMF), and can be easily gelled in such solvents. The solvent of these gels can be exchanged to some other solvents which do not form ε-crystal with PLLA. The flow temperatures of PLLA gels after exchanging DMF to various solvents were investigated to clarify the relation between the exchangeability and the solubility of solvents to PLLA. After changing the ε-crystals to α-crystals (crystal form of PLLA in films without special treatments) by immersing the gels into 1-propanol, the flow temperatures of PLLA gels could be expected by Hansen solubility parameters. The results suggest that the exchangeability of the solvent of the PLLA gel is determined both by the solubility to PLLA and the ability of the new solvent to induce the change from ε-crystals to α-crystals.

Key Words: Poly(L-lactic acid) / Gel / Complex crystal / Hansen solubility parameter

1. INTRODUCTION

Poly(L-lactic acid) (PLLA) attracts interests as an environmentally friendly and biocompatible polymer materials.1, 2) Whereas PLLA forms α-crystals in film without special treatments, it can also form some other crystal forms under some sample preparation conditions. Marubayashi et al.3, 4) reported that PLLA forms complex crystals with some solvents including N,N-dimethylformamide (DMF), and designated these crystals as “ε-crystal”. Guenet, Daniel and their co-workers5-8) reported that syndiotactic polystyrene also form complex crystals with some solvents such as 1,2-dichloroethan and 1-chloropropane, and gels in these solvents.

We found that PLLA can easily form gels in the solvents inducing ε-crystal, and investigated the structure of PLLA in these gels.9-13) PLLA formed a fibrous structure in the gels. The ε-crystals changed into α-crystals by heating the gel.9, 11) The PLLA gel formed in DMF began to flow not at the temperature at which the ε-crystals changed into α-crystals (~45 °C), but the temperature at which α-crystals dissolved into DMF (~65 °C). This result indicates that once the fibrous structure is formed with ε-crystals, the gel does not flow below the temperature at which the fibrous structure dissolved.

Because the number of the solvents which can induce PLLA to form the ε-crystals is limited, we tried to prepare PLLA gels in solvents not inducing ε-crystals by immersing the DMF gels into these solvents.11) PLLA was first dissolved in DMF at 110 °C. The solution was poured into a breakable container, and allowed to stand in a freezer controlled at −18 °C for gelation. The gel was picked up by breaking the container, and put directly into various solvents. In some solvents, the solvent was successfully exchanged from DMF to a new solvent without disintegrating the gel. The absence of DMF and presence of the new solvent were confirmed by infrared spectroscopy. In the other solvents, the gel was disintegrated by immersing in a new solvent. We tried to discuss the exchangeability of the solvents based on the solubility of the solvents investigated by Hansen solubility parameters (HSP). Although the solvent was successfully exchanged into non-solvents, and very good solvents disintegrated the gels by immersion, the solvent was successfully exchanged into some solvents which HSP predicts to be fairly good solvents, and some poor solvents disintegrated the gels by immersion.

We thought that the indistinct dependence of the exchangeability on the solubility might be caused that the exchangeability was determined not only by the solubility, but also the speed of the solvents to change the ε-crystals to
α-crystals. In this paper, PLLA gel formed in DMF was first immersed into 1-propanol, which change the ε-crystals to α-crystals without disintegrating the gel, then immersed into other solvents. When the solvent was successfully exchanged, the flow temperatures of the gels were estimated by viscoelastic measurements by heating the gels.

2. EXPERIMENTAL

The PLLA sample used in this study and preparation procedure of the gels in DMF are same as those in our previous study of which details are described in our previous paper.11) The PLLA sample was purchased from Polymersciences, which reports the molecular weight to be $7 \times 10^5$. The PLLA was dissolved in DMF at 110 °C, and the solution was poured into a breakable container. After cooling in a freezer controlled at $-18$ °C overnight, the gel was picked up by breaking the container, and immersed into 1-propanol to change the ε-crystals to α-crystals. The 1-propanol where the gel was immersed, was changed to fresh 1-propanol three times, and the gel was allowed to stand overnight. The X-ray diffraction patterns of the gel before and after immersing 1-propanol were measured to investigate the crystal forms of the gel. Only the peaks assigned as those of α-crystals14) were detected for all the samples after immersing into 1-propanol.

The gels were picked up from 1-propanol, and immersed into a new solvent that is listed in Table I. The gels were immersed in the new solvent which was changed to fresh solvent three times (five times only for acetone), and allowed to stand overnight. The absence of old solvent and existence of the new solvent were checked by infrared spectroscopy.

When the solvent of the gel was successfully exchanged without disintegrating the gel, the viscoelastic behavior of the gel was measured with a PZ-Rheo NDS-1000 rheometer manufactured by Taise at a frequency of 1 Hz, and heating rate of 5.0 °C/min. The details of the instruments and measuring conditions of the viscoelastic and XRD measurements and infrared spectroscopy are described in our previous paper.11)

The intrinsic viscosity $[\eta]$ was estimated to the quality of the solvents for poly(D,L-lactic acid) (PDLLA), because the number of the solvents which dissolve PLLA completely at room temperature is limited for the crystallinity of PLLA. The sample used in this study was purchased from Aldrich. The weight average molecular weight and molecular weight distribution index were measured to be $7.7 \times 10^4$ and 4.1, respectively by gel permeation chromatography, of which experimental details are described in our previous paper.15) An Ubbelohde type capillary viscometer was used to determine $[\eta]$ of this PDLLA sample in various solvents. The details of the $[\eta]$ estimation are described in our previous paper.16)

3. RESULTS AND DISCUSSION

Table I summarizes the exchangeability of solvents for the gel which was directly immersed in a new solvent, which was conducted in our previous study.11) The solvent solubility to PLLA was estimated from the distances between the Hansen solubility parameters (HSPs) of PLLA and those of solvents. The distance of HSP between PLLA17) and solvents is calculated from the HSP in the literatures. A solvent with a larger distance is a poorer solvent to PLLA. The solvent was successfully exchanged to all the solvents listed in Table I by first immersing into 1-propanol, then immersing into a new solvent at room temperature in this study, except for 1,3-dioxolane and 1,4-dioxane. The gel was disintegrated by immersing into 1,3-dioxolane at room temperature, which indicates that the flow temperatures in 1,3-dioxolane and 1,4-dioxane were lower than room temperature. To estimate the flow temperature in 1,3-dioxolane, which is expected to be lower than room temperature, the solvent of the gel was exchanged from 1-propanol to 1,3-dioxolane by immersing in a freezer controlled at $-18$ °C. The gel was also disintegrated by immersing into 1,4-dioxane cooled at 13 °C. Because the freezing temperature of 1,4-dioxane is 12 °C, we gave up exchanging the solvent to 1,4-dioxane.

Figure 1 shows the temperature dependence of storage modulus $G'$ and loss tangent tanδ for the gels of which solvents were exchanged to other solvents. The flow temperatures determined by the measurements as shown in Fig. 1 are listed in Table I. In dimethylacetamide, which has sufficiently high boiling temperatures, $G'$ of the gels decreased drastically, and tanδ increased drastically at 70 °C. Strictly speaking, the flow temperature is defined to be the temperature at which the finite equilibrium modulus disappears. To determine the temperature at which the finite equilibrium modulus disappears, the frequency dependence of $G'$ needs to be measured at a wide range of temperature for the many samples with various solvents. So, we approximated the temperatures when the $G'$ of the gels decreased drastically, and tanδ increased drastically, to be the flow temperatures in this paper. For the gels composed of solvents with low boiling temperatures, such as 2-propanol, $G'$ decreased drastically when the samples were dried and came off from the plunger.

Figure 2 shows the relation between the solvent solubility to PLLA and the flow temperatures determined by the
Table I. Summary of HSP distance to PLLA, flow temperature of the PLLA gel after exchanging the solvents, and intrinsic viscosity of PDLLA. The solvent exchangeability by immersing directly into new solvent, which was confirmed in our previous study, is also shown in the table. The numbers in the parentheses in the column of “flow temperature” indicates the dry temperatures. For 1,4-dioxane, the lowest temperature at which we tried to exchange DMF to 1,4-dioxane is shown in this table.

| solvent          | HSP distance / \(\text{MPa}^{1/2}\) | direct exchangeability | flow temperature / °C | \([\eta]/\text{cm}^3\cdot\text{g}^{-1}\) |
|------------------|--------------------------------------|------------------------|------------------------|----------------------------------|
| cyclopentanone   | 2.6                                  | N                      | 55                     |                                  |
| nitrobenzene     | 3.6                                  | Y                      | 65                     | 50.1                             |
| 1,3-dioxolane    | 4.8                                  | N                      | 10                     | 62.6                             |
| dimethylacetamide| 5.8                                  | Y                      | 70                     | 52.7                             |
| tetrahydrofuran  | 5.9                                  | Y                      | (52)                   | 56.6                             |
| acetone          | 6.3                                  | N                      | (57)                   | 49.4                             |
| \(\gamma\)-butyrolactone | 6.9                              | Y                      | 65                     | 50.2                             |
| acetic anhydride | 6.9                                  | Y                      | 70                     | 48.2                             |
| DMF              | 6.9                                  |                        | 60                     | 52.1                             |
| dimethyl sulfoxide| 7.7                                 | N                      | 92                     | 44.2                             |
| methyl salicylate| 8.2                                  | N                      | 82                     |                                  |
| 1,4-dioxane      | 8.3                                  | N                      | <13                    | 62.9                             |
| propylene carbonate| 8.8                               | Y                      | 87                     | 44.1                             |
| toluene          | 9.5                                  | N                      | (93)                   | 51.2                             |
| cyclohexanol     | 9.8                                  | N                      | 104                    |                                  |
| 2-butanol        | 11.0                                 |                        | (90)                   |                                  |
| acetic acid      | 11.3                                 | Y                      | 70                     |                                  |
| 1-butanol        | 11.9                                 | Y                      | (71)                   |                                  |
| 2-propanol       | 12.7                                 | Y                      | (85)                   |                                  |
| 1-propanol       | 13.1                                 | Y                      | (90)                   |                                  |
| ethanol          | 14.6                                 | Y                      | (65)                   |                                  |
| ethylene glycol  | 20.3                                 | Y                      | 134                    |                                  |
| formamide        | 21.0                                 | Y                      | 137                    |                                  |
| glycerine        | 23.5                                 | Y                      | 139                    |                                  |
| water            | 37.3                                 | Y                      | (100)                  |                                  |

Fig. 1. Typical results of viscoelastic measurements for PLLA gel after exchanging solvents. The boiling temperature of \(\gamma\)-butyrolactone was high enough to determine the flow temperature, whereas that of 2-propanol was too low to determine the flow temperature before drying.

Fig. 2. The relation between the distance of HSP between PLLA and solvents, and the flow temperature. For the solvents of which boiling temperature was too low, drying temperatures are plotted in this figure. For 1,4-dioxane, the lowest temperature at which we tried to exchange DMF to 1,4-dioxane is plotted in this figure.
viscoelastic measurements as shown in Fig. 1. The circles and triangles in the figure indicate the flow temperatures and dry temperatures, respectively. The lowest temperature at which we tried to exchange DMF to 1,4-dioxane is plotted in a square to indicate the flow temperature in 1,4-dioxane, which is expected to be lower than this temperature. The flow temperatures increase with an increase of the distance, and most of the data points are on the single line as shown in Fig. 2, while the dry temperatures are below this line. Only the flow temperature of 1,3-dioxolane is significantly below the line.

This result indicates that the flow temperature is dominated by the solvent solubility to PLLA after the $\varepsilon$-crystals were changed to $\alpha$-crystals by immersing the gels into 1-propanol. The indistinct dependence of the solvent exchangeability by immersing the gel directly into a new solvent, which was found in our previous study\(^{11}\), was caused that the solvent exchangeability was dominated by not only the solvent solubility, but also the ability of the solvents to change $\varepsilon$-crystals to $\alpha$-crystals. In solvent with low solubility to PLLA, but low ability to change $\varepsilon$-crystals to $\alpha$-crystals, PLLA gel composed by $\varepsilon$-crystals disintegrated before changing to $\alpha$-crystals.

To discuss the deviation of the flow temperatures of 1,3-dioxolane and 1,4-dioxane, the $[\eta]$ of PDLLA in various solvents including these two solvents were measured and summarized in Table I. Because $[\eta]$ represents the dimension of polymer chains in solution, a polymer sample has larger $[\eta]$ in a better solvent. Typical results to determine $[\eta]$ are shown in Fig. 3, and the $[\eta]$ in various solvents are

summarized in Table I. The values of $[\eta]$ in 1,3-dioxolane and 1,4-dioxane are significantly higher than those in the other solvents. These results indicate that 1,3-dioxolane and 1,4-dioxane are very good solvents.

To determine HSP of polymers, three components (dispersion, polar, and hydrogen bond) of HSP of solvents are plotted in a three dimensional coordinates. The center of a sphere which includes the solvents in which the polymer is soluble, and excludes the solvents in which the polymer is insoluble, is defined to be the HSP of the polymer.\(^ {17}\) Because HSP focuses to predict whether a polymer is soluble or insoluble in a solvent, it is not necessarily suitable to predict a good solvent is better than another good solvent.

The discrepancy of the flow temperature for 1,3-dioxolane and 1,4-dioxane as shown in Fig. 2 can be explained that these solvents are very good solvents, which can be estimated by measuring $[\eta]$, but cannot be predicted by HSP.

The melting temperature of mixture of two crystallizable materials is lower than those of the pure materials for the eutectic effect. This effect is well known for metallic alloys, but also known for polymers and solvents, such as polyethylene and 1,2,4,5-tetraclorobenzen.\(^ {18}\) For 1,4-dioxane, its melting temperature (12 °C) is very near to room temperature, this effect could lower the flow temperature of the gel in 1,4-dioxane and prevented the exchange of the solvent from DMF to 1,4-dioxane.

4. CONCLUSION

The flow temperatures of PLLA gels which were formed by the $\varepsilon$-crystals in DMF, immersing into 1-propanol to change the $\varepsilon$-crystals to $\alpha$-crystals, then immersing into various solvents, were estimated by viscoelastic measurements. Although the solvent exchangeability of the PLLA gel by immersing directly into a new solvent, could not be predicted by the solubility of solvents to PLLA, the flow temperature of the PLLA gel after immersing into 1-propanol, increased with an increase of the distance of HSPs between PLLA and solvents, except for the solvents with low boiling temperatures. The indistinct dependence of the solvent exchangeability of the gel by immersing directly into a new solvent was caused that the solvent exchangeability was dominated by not only the solvent solubility, but also the ability of the solvents to change the $\varepsilon$-crystals to $\alpha$-crystals.
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