

Effect of the Ultradrawing Behavior of Gel Films of Ultrahigh-Molecular-Weight Polyethylene and Low-Molecular-Weight Polyethylene Blends on Their Physical Properties

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ABSTRACT: This study examined the effect of the ultradrawing behavior of gel film specimens of ultrahigh-molecular-weight polyethylene (UHMWPE) and UHMWPE/low-molecular-weight polyethylene (LMWPE) blends on their physical properties. The concentration of a gel film approximated its critical concentration at a fixed drawing temperature; its achievable draw ratio was higher than that of other blend specimens with various concentrations. Noticeably, when about 5 wt % LMWPE was added to a UHMWPE/LMWPE gel film specimen, the achievable draw ratio of the gel film increased, and this contributed to an apparent promoting effect on its anticreeping properties and thermal stability. Therefore, when $UL_{B-0.9}$ was drawn to a draw ratio of 300, the anticreeping behavior was

improved to less than 0.026%/day. Moreover, with respect to the thermal stability, when the same specimen was drawn to a draw ratio of 300, the retention capability of its storage modulus could resist a high temperature of 150°C, which was obviously much higher than the temperature of an undrawn gel film specimen (70°C). To study these interesting behaviors further, this study systematically investigated the gel solution viscosities, anticreeping properties, dynamic mechanical properties, thermal properties, molecular orientations, and mechanical properties of undrawn and drawn UHMWPE/LMWPE gel film specimens. © 2007 Wiley Periodicals, Inc. *J Appl Polym Sci* 107: 854–862, 2008

Key words: polyethylene; drawing; gels; creep; films

INTRODUCTION

In recent years, after carbon and aromatic polyamide fibers, another important product in the field of high-performance fibers has been produced: high-strength, high-modulus polyethylene (PE) fibers. When DSM Corp. in Holland produced such an ultrahigh-molecular-weight polyolefin material through gel spinning and applied for a patent, it attracted great interest from related companies and research institutes in many countries. With respect to such an ultrahigh-molecular-weight polyolefin material, the melt viscosities of ultrahigh-molecular-weight polyethylene (UHMWPE) are too high to be applied to common processing methods. Besides being processed by gel solution processing,^{1–15} it can be produced only by compression molding or ram extrusion.^{16,17}

Almost all high-strength, high-modulus fibers, such as UHMWPE and UHMWPE/low-molecular-weight polyethylene (LMWPE), have one thing in common during the fiber-forming process: the polymer in an organic solvent can be in a kind of gel-like state. However, the maximum draw ratio of such a gel film has a direct relationship with the polymer concentration prepared in the solution.^{1,2,18–23} The major reason for such a phenomenon is that the number of entanglements of each polymer chain is reduced, being subject to the reduction of the concentration of the polymer gel solution, and the entanglement degree and crystallized gel intermolecular forms are directly related to the subsequent draw ratio and mechanical properties. For example, Darras et al.¹⁹ pointed out that with the reduction of the solution concentration, the draw ratio of a UHMWPE gel film increases progressively, but if the solution concentration is diluted to the critical concentration (C_c), its draw ratio decreases. They explained that with a decrease in the solution concentration, a reduction in the number of entanglements of the intermolecular polymer chains contrarily contributes to the draw ratio and mechanical

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properties after drawing. However, when the degree of intermolecular entanglements decreases to a limited value, the drawing of a gel film tends to cause slippage and damage of crystal boundaries very easily, and this further makes the draw ratio of such a gel film and its mechanical properties after drawing decrease drastically.

Because the molecular chain of PE is flexible, the creeping effect can occur when PE is in a high-temperature environment for a long time. To improve the anticreeping properties of common PE, the thermal stability of PE must be improved first. The applied method is the chemical crosslink method, which includes the radiation crosslink method^{24,25} and the peroxide crosslink method.^{26,27} The radiation method not only can produce the chemical crosslinks of polymer chains but also can break the polymer chains into shorter molecular chains to lower the tensile strength and modulus.^{24,25} The peroxide crosslink method introduces a crosslinking agent into PE and makes it into a specimen; through the hot-drawing procedure, it comes into contact with hot air and produces oxidation crosslinks. This crosslink method is mainly applied before PE molecular orientation. However, when it is applied after PE molecular orientation and crystallization, oxidation crosslinking^{26,27} is not easy to perform. Soo and Sik²⁸ dissolved dicumyl peroxide in decalin, coated it onto a UHMWPE gel, and applied zone-drawing technology to the prepared UHMWPE gel film to obtain an ultrahigh orientation. However, using this method and then making the film pass through a hot-drawing process resulted in chemical crosslinks on the surface, causing a weakness in the intermolecular crosslinking.

This study mainly examined the ultradrawing behavior of gel films of UHMWPE and UHMWPE/LMWPE blends. When a little LMWPE was added to a gel film of UHMWPE, it helped the disentanglement of the UHMWPE molecules to achieve a higher draw ratio to promote an increase in the UHMWPE molecular chain orientation and directly affected the anticreeping properties of the gel film. Such an interesting phenomenon was systematically examined through the gel solution viscosities, anticreeping properties, dynamic mechanical properties, thermal properties, molecular orientations, and mechanical properties of drawn and undrawn UHMWPE/LMWPE gel film specimens.

EXPERIMENTAL

Materials and specimen preparation

The UHMWPE resin used in this study had a weight-average molecular weight of 4.5×10^6 and is called resin U in the following discussion. On the other hand, the linear LMWPE used in this study is

TABLE I
Compositions and C_c Values of Resin U and UHMWPE/LMWPE Solutions and D_{ra} Values of the Corresponding Gel Films Drawn at 95°C

Sample	U/L weight ratio	Concentration (g/dL)	C_c	D_{ra}
U _{-0.6}		0.6		216
U _{-0.7}		0.7		240
U _{-0.8}		0.8		224
U _{-0.9}		0.9		221
U _{-1.0}	100/0	1.0	0.7	200
UL _{A-0.6}		0.6		295
UL _{A-0.7}		0.7		323
UL _{A-0.8}		0.8		352
UL _{A-0.9}		0.9		338
UL _{A-1.0}	98/2	1.0	0.77	283
UL _{B-0.6}		0.6		333
UL _{B-0.7}		0.7		343
UL _{B-0.8}		0.8		362
UL _{B-0.9}		0.9		371
UL _{B-1.0}	95/5	1.0	0.87	312
UL _{C-0.7}		0.7		263
UL _{C-0.8}		0.8		288
UL _{C-0.9}		0.9		320
UL _{C-1.0}		1.0		276
UL _{C-1.1}	90/10	1.1	0.91	261
UL _{D-0.8}		0.8		169
UL _{D-0.9}		0.9		178
UL _{D-1.0}		1.0		187
UL _{D-1.1}		1.1		175
UL _{D-1.2}	80/20	1.2	1.05	172
UL _{E-1.0}	70/30	1.0	1.2	113
UL _{E-1.1}		1.1		121
UL _{E-1.2}		1.2		158
UL _{E-1.3}		1.3		142
UL _{E-1.4}		1.4		121

called resin L; it was a linear high-density PE and had a weight-average molecular weight of 5.0×10^4 . Both the UHMWPE and LMWPE resins were kindly supplied by Bruce Lu of Yung Chia Chemical Industrial Corp. (Kaohsiung, Taiwan). Mixtures with various weight ratios of UHMWPE to LMWPE were dissolved in decalin at 135°C for 90 min, to which 0.1 wt % di-*t*-butyl-*p*-cresol was added as an antioxidant. The compositions of the gel solutions prepared in this study are summarized in Table I. The hot homogenized solutions were poured into an aluminum tray and cooled in an oven to form the gel films at 35°C, which yielded a cooling rate of about 25°C/min. The decalin was then evaporated from the gels in the oven. The prepared gel films had a thickness of approximately 250 μm.

Determination of the drawing and creep properties of the gel films of the UHMWPE and UHMWPE/LMWPE blends

The drawn specimens in the drawing test were cut from dry gel films and drawn with an RTA-1T

strength-testing machine (Taichang, Taiwan). The drawing speed of the crosshead was 20 mm/min, and an oven was used to control the temperature balance. The length of the specimen was 30 mm, and the width was 10 mm. The specimens were drawn at a fixed speed of 20 mm/min, and the optimal drawing temperature was 95°C.¹⁵ The draw ratio of each specimen was determined as the ratio of the marked displacement after and before drawing. This part of the drawing test was called the drawing procedure, and the marked displacement before drawing was 5 mm. The strength properties of the drawn and undrawn specimens were tested with the RTA-1T strength-testing machine at 26°C, and the crosshead speed was 20 mm/min. On the other hand, the length of the drawn and undrawn gel film specimens cut for the anticreeping test was 130 mm. Then, the striplike specimens were heated in an oven at $50 \pm 0.1^\circ\text{C}$, with both ends clamped in a stretching device; the central distance of the specimens was marked as 100 mm. The hanging stress of the film specimens was 0.106 GPa (the breaking strength was 10% of that of $UL_{B-0.9}$ drawn to a ratio of 40). The hanging time was 27 days. The creep strain was calculated from the percentage of the elongation after and before creeping. The creep strain percentage rate (CSPR) was calculated from the creep strain of the gel films every day.

Determination of the viscosities, birefringence, and dynamic mechanical and thermal properties

The viscosities of the polymer solutions were determined at 135°C with a Brookfield model LVDV-II⁺ viscometer (Oakville, Ontario, Canada). As reported in our previous publication,¹⁴ two distinct regions were found on plots of the reduced viscosities versus the concentrations of the polymer solutions. The reduced viscosities increased slightly with the concentration in region 1, and this was associated with low concentrations. However, the reduced viscosities increased dramatically as the concentrations of the solutions reached their critical values. The region associated with concentrations higher than C_c is called region 2. The value of C_c was determined as the intersection of the two straight lines drawn parallel to the two distinct regions shown in these plots. The values of C_c of solutions prepared in this study were determined in our previous studies¹⁴ and are described later in the Results and Discussion section. On the other hand, the birefringence properties of the drawn and as prepared gel films were measured with a model TFM-120 AFT polarizing microspectrometer. An Eplexor 150N dynamic mechanical analysis (DMA) unit (GABO Qualimeter Testanlagen GmbH) was used to study the mechanical relaxation

of all samples; all DMA experiments were performed at a frequency of 3 Hz, at a heating rate of 2°C/min, and in the temperature range of -50 to 180°C. The thermal behavior of all specimens was determined on a DuPont model 2000 differential scanning calorimeter (Wilmington, DE). All scans were carried out at a heating rate of 10°C/min under flowing nitrogen at a flow rate of 25 mL/min. Specimens weighing 0.5 mg were placed in standard aluminum specimen pans for the determination of their thermal behavior.

RESULTS AND DISCUSSION

Drawing properties of the gel films of the UHMWPE and UHMWPE/LMWPE blends

As shown in Table I, pure gel film specimens of the UHMWPE and UHMWPE/LMWPE blends could obtain an achievable draw ratio (D_{ra}). The data show that D_{ra} of the UHMWPE and UHMWPE/LMWPE gel film specimens was closely related to the concentration of the originally prepared gel solution. For example, the D_{ra} values of all gel films prepared near C_c after drawing at a constant temperature were higher than those of the gel films prepared at other concentrations (shown as Table I). D_{ra} of a gel film prepared near C_c is called the critical draw ratio (D_{rc}) hereafter. It is generally thought that a gel film prepared near C_c contains an optimum number of tie molecules and proper UHMWPE molecules buried in a crystalline region. Such a gel network structure helps the UHMWPE molecules to be unfolded in folded-chain lamellae more easily and pulled out more effectively during the sequence drawing process without causing a stress concentration in tie molecules. That is, it does not cause a broken state before the UHMWPE molecules are disentangled or unfolded and pulled out in the folded-chain lamellae.

On the other hand, a blended UHMWPE/LMWPE gel film had little LMWPE; D_{rc} increased noticeably. Therefore, when the concentration was less than 5 wt %, D_{rc} reached a maximum value approximating 371, and it was 50% higher than that of the $U_{-0.7}$ gel film specimen at least; however, when the concentration of LMWPE was over 5 wt %, D_{rc} decreased gradually, as shown in Figure 1. This result clearly suggests that when the optimum concentration of LMWPE is blended with a UHMWPE gel solution, D_{rc} of the gel film specimen increases. This interesting phenomenon may be caused by the addition of the optimum concentration of LMWPE to the UHMWPE gel film, which properly reduces the number of entanglements in the UHMWPE molecules and intermolecular entanglements; meanwhile, it helps the UHMWPE molecules to unfold properly during the drawing process and to be pulled out

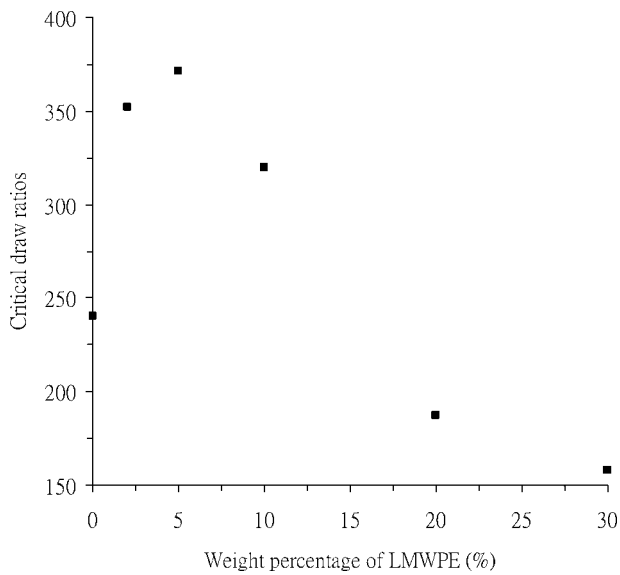


Figure 1 Plot of D_{rc} versus the weight percentage of LMWPE in UHMWPE/LMWPE gel films.

more easily from the folded-chain lamellae, so it creates a beneficial effect on the achievable drawing properties.

Creep properties of the gel films of the UHMWPE and UHMWPE/LMWPE blends

On the basis of the anticreeping behaviors of gel film specimens $U_{-0.7}$, $UL_{B-0.9}$, and $UL_{D-1.0}$ with various draw ratios (see Figs. 2 and 3 and Table II), it was found that the anticreeping behaviors of all the gel film specimens increased with increases in the draw ratios. For example, when stress was applied to the undrawn $U_{-0.7}$ gel film, it broke immediately, and its CSPR was 100,000%/day. When the $U_{-0.7}$ gel film was drawn to ratios of 20 and 40, its CSPRs were 3.56 and 2.05%/day, respectively. Furthermore, when the $U_{-0.7}$ gel film was drawn to ratios of 100 and 200, its CSPR was improved to about 0.076 and 0.037%/day, respectively (see Fig. 3 and Table II). Similarly, for the $UL_{B-0.9}$ and $UL_{D-1.0}$ gel film specimens containing 5 and 20 wt % LMWPE, respectively, the CSPRs were noticeably improved with increases in the draw ratios. Moreover, at any fixed draw ratio, the CSPR increased with an increase in the blended content of LMWPE. Therefore, if the draw ratio was 20, the CSPR of $U_{-0.7}$ was 4.9 and 13.1 times lower than those of $UL_{B-0.9}$ and $UL_{D-1.0}$, respectively. However, with an increase in the draw

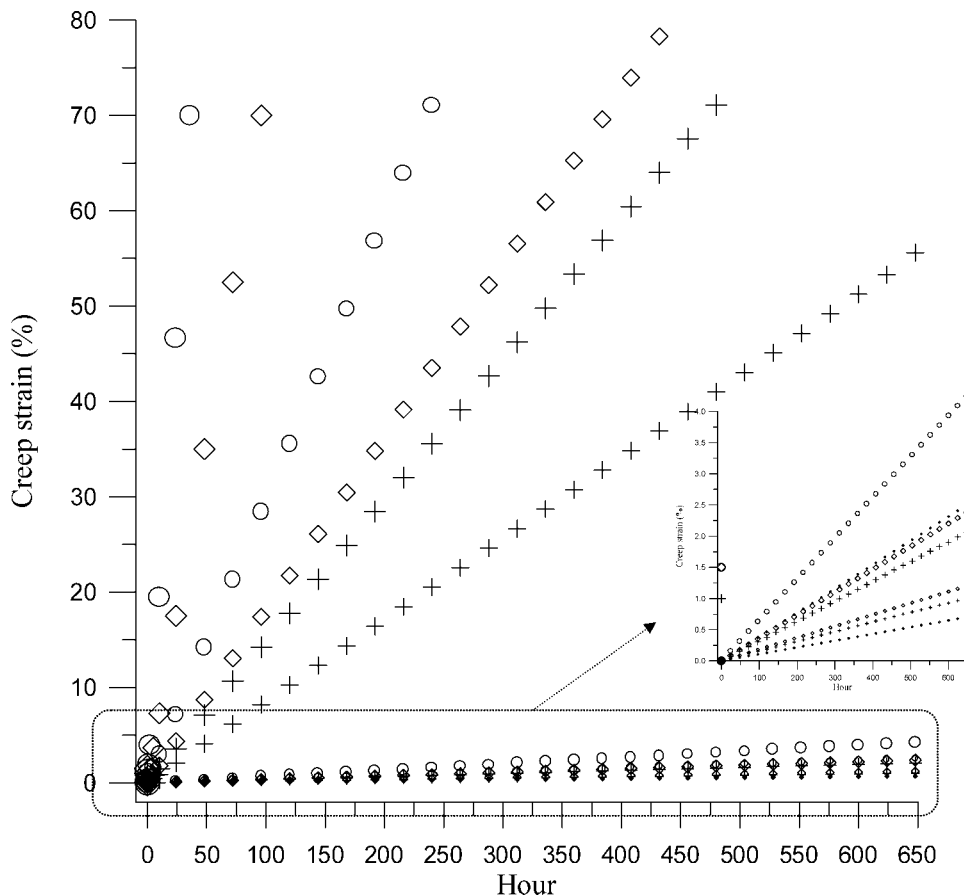


Figure 2 Creep strain of (+) $U_{-0.7}$ (draw ratio = 1, 20, 40, 100, or 200), (◇) $UL_{B-0.9}$ (draw ratio = 1, 20, 30, 100, 200, or 300), and (○) $UL_{D-1.0}$ (draw ratio = 1, 20, 30, 100, or 150) drawn gel films versus the time at 50°C.

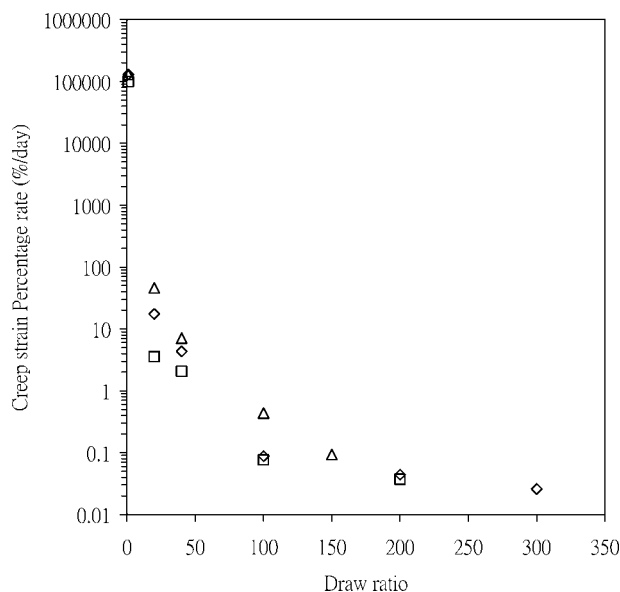


Figure 3 CSPR of (\square) $U_{-0.7}$, (\diamond) $UL_{B-0.9}$, and (\triangle) $UL_{D-1.0}$ drawn gel films with various draw ratios.

ratio, the anticreeping property was more greatly improved. For example, when $UL_{B-0.9}$ was drawn to a ratio greater than 300 (CSPR = 0.026%/day), its anticreeping property was better than that of $U_{-0.7}$, which was drawn to a ratio of 200 (CSPR = 0.037%/day; see Fig. 3 and Table II).

Thermal properties of the gel films of the UHMWPE and UHMWPE/LMWPE blends

From the thermal properties of the $U_{-0.7}$, $UL_{B-0.9}$, and $UL_{D-1.0}$ gel film specimens with various draw ratios in Figures 4–6, it was found that the melting temperatures of all the gel film specimens increased with increases in the draw ratios. For example, the melting temperature of the undrawn $U_{-0.7}$ gel film was 138.5°C (see Fig. 4). When the draw ratio reached 20, its melting temperature rapidly increased to 142°C. When the draw ratio was 40, the melting temperature of the main melting peak rose

TABLE II
CSPRs of Gel Film Samples Drawn at Various Draw Ratios

Draw ratio	CSPR (%/day)		
	$U_{-0.7}$	$UL_{B-0.9}$	$UL_{D-1.0}$
1	100,000	129,600	129,600
20	3.56	17.5	46
40	2.05	4.35	7.1
100	0.076	0.088	0.44
150	—	—	0.093
200	0.037	0.044	—
300	—	0.026	—

to 143°C, and the first split melting peak, whose melting point was 149.8°C, appeared at the right side of the main melting peak. The melting temperature and peak shape of the split melting peak gradually increased and grew with an increase in the draw ratio. When the draw ratio was 200, the melting temperatures of the two peaks were 143.9 and 152.9°C, respectively, and the split melting peak grew gradually and then replaced the original main melting peak (see Fig. 4). Similar results also occurred for the $UL_{B-0.9}$ and $UL_{D-1.0}$ gel film specimens, as shown in Figures 5 and 6. When the draw ratio of the $UL_{B-0.9}$ gel film specimen reached 100, the first split melting peak appeared with the second split melting peak (see Fig. 5). The melting temperatures of the three peaks were 142, 150, and 156.3°C, respectively. When the draw ratio was 300, the melting temperature and peak shape of the first and second split melting peaks continued growing, and the melting temperatures rose to 152.3 and 156.6°C, respectively, but the endothermic enthalpy of the main melting peak decreased, and its melting temperature was 142.7°C (see Fig. 5). The melting temperature of the undrawn $UL_{D-1.0}$ gel film specimen

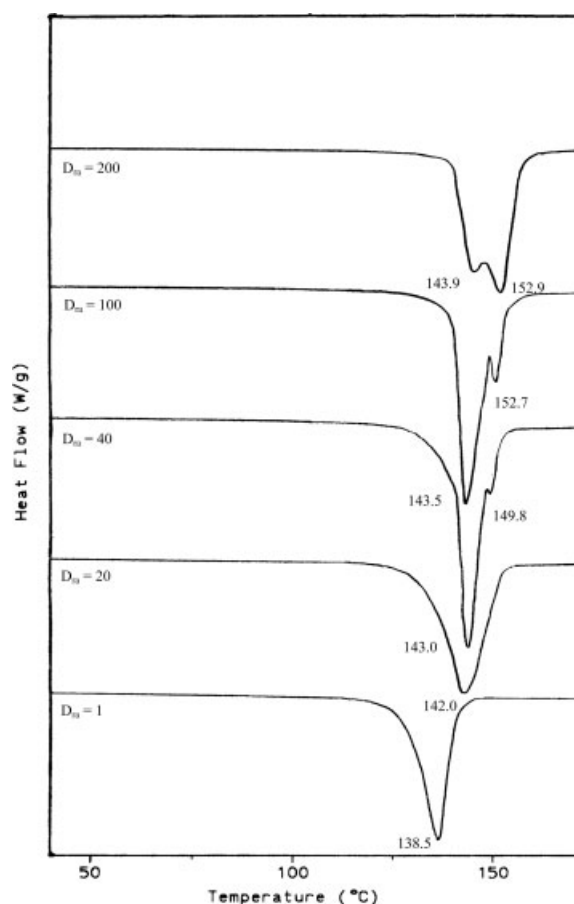


Figure 4 DSC thermograms of $U_{-0.7}$ gel films with various draw ratios.

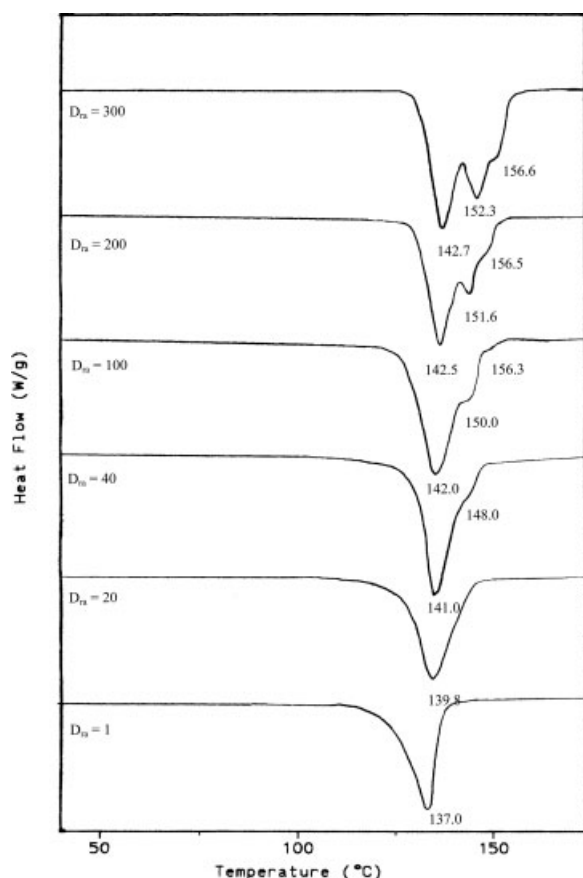


Figure 5 DSC thermograms of $UL_{B-0.9}$ gel films with various draw ratios.

decreased to 136°C (see Fig. 6). Three melting peaks were presented in the differential scanning calorimetry (DSC) thermograms when the draw ratio was 40. Their melting temperatures were 140.6, 151.1, and 156.1°C, respectively, and the melting temperatures of the three peaks increased with an increase in the draw ratio. When the draw ratio was 150, their melting temperatures were 142, 152, and 157.9°C, respectively (see Fig. 6). This phenomenon was attributable to the increase in the draw ratio of the gel films. The increases in the melting temperature between the undrawn samples and samples drawn to a ratio of 20 were probably due to an increase in the orientation of the molecular chains in the amorphous region, which promoted the anticreeping property and thermal stability. The first split peak was formed from the main melting peak at a draw ratio of 40. It is possible that the folded chains in the crystalline region were pulled out and arranged in an orientation or the crystal thickness increased. Besides, when the draw ratio was increased to 200, more folded chains were pulled out, and the crystal thickness and numbers of crystals also increased; this caused the melting temperature to increase a lot and

improved the anticreeping property and thermal stability accordingly (see Figs. 3 and 4). When 5% LMWPE was added to UHMWPE, the melting temperature decreased because the molecular weight of LMWPE was so much lower that the crystal structure was destroyed. In comparison, when the optimum concentration of LMWPE was added to a UHMWPE gel film, it could help the disentanglement of UHMWPE molecules after drawing, and so a higher D_{ra} value was obtained. When the draw ratio was 100, the first split melting peak could be formed, and when the draw ratio increased to 300, the second split melting peak tended to grow (see Fig. 5). As mentioned previously, the thermal properties have a great relation with the anticreeping property (see Figs. 3 and 5).

Dynamic mechanical properties of the gel films of the UHMWPE/LMWPE blends

From the storage modulus (E') values of the $UL_{B-0.9}$ gel film specimens that were undrawn or drawn with various draw ratios (Fig. 7), it was found that E' of the undrawn $UL_{B-0.9}$ gel film slowly decreased with an increase in the temperature and drastically

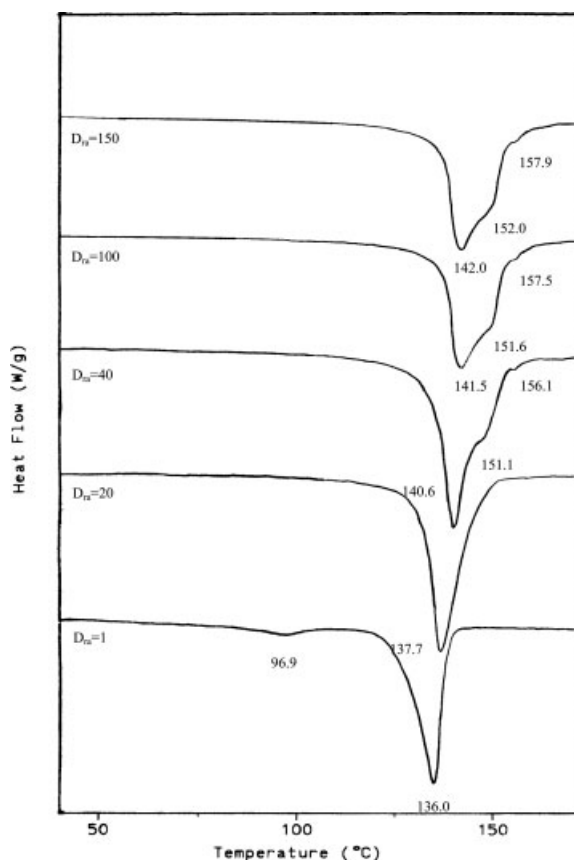


Figure 6 DSC thermograms of $UL_{D-1.0}$ gel films with various draw ratios.

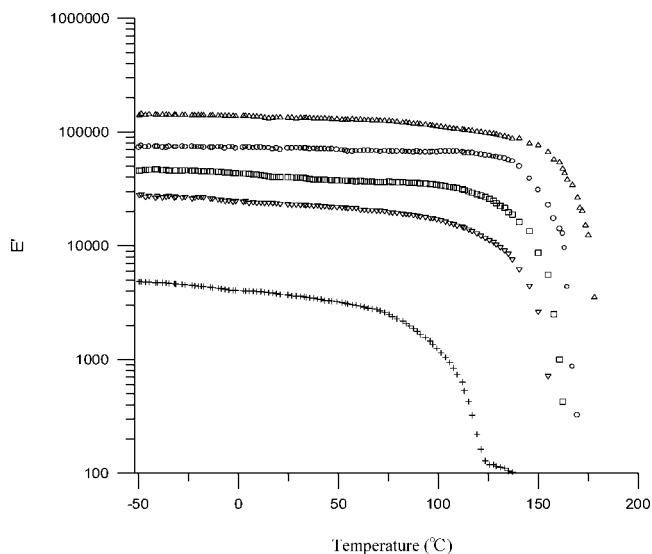


Figure 7 Plot of E' as a function of temperature for (+) an undrawn $UL_{B-0.9}$ specimen and $UL_{B-0.9}$ specimens drawn at 95°C with various draw ratios: (∇) 20, (\square) 40, (\circ) 100, and (\triangle) 300.

decreased at 70°C . E' of the drawn $UL_{B-0.9}$ gel film noticeably increased with an increase in the draw ratio. However, E' of the drawn $UL_{B-0.9}$ gel film slowly decreased with an increase in the temperature, and the curve of E' shifted to the high-temperature region; this helped to improve the thermal stability of the gel film specimens. For example, when the draw ratio of the $UL_{B-0.9}$ gel film specimen was 300, its temperature of thermal stability was about 150°C , much higher than that of the undrawn gel film specimen. Furthermore, the $\tan \delta$ values of the $UL_{B-0.9}$ gel film specimens that were undrawn or drawn with various draw ratios are shown in Figure 8. The α -transition temperature of the undrawn $UL_{B-0.9}$ gel film specimens was about 95°C , and it shifted to a high-temperature region with an increase in the draw ratio. When the draw ratio reached 300, the α -transition temperature rose to 150°C . The $\tan \delta$ value of the specimen decreased noticeably with an increase in the draw ratio. The aforementioned interesting phenomenon possibly had something to do with this: the high draw ratios of the gel film specimen caused the increase in the molecular chain orientation in the amorphous region and in the crystal thickness of the folded-chain lamellae. Therefore, both the E' curve and α -transition temperature curve of the specimens apparently shifted to the high-temperature region, but the curve of $\tan \delta$ apparently decreased; this meant that the loss modulus of the gel film specimen was lower. This explains why a decrease in the molecular mobility of UHMWPE molecules benefits the anticreeping behavior of UHMWPE/LMWPE specimens.

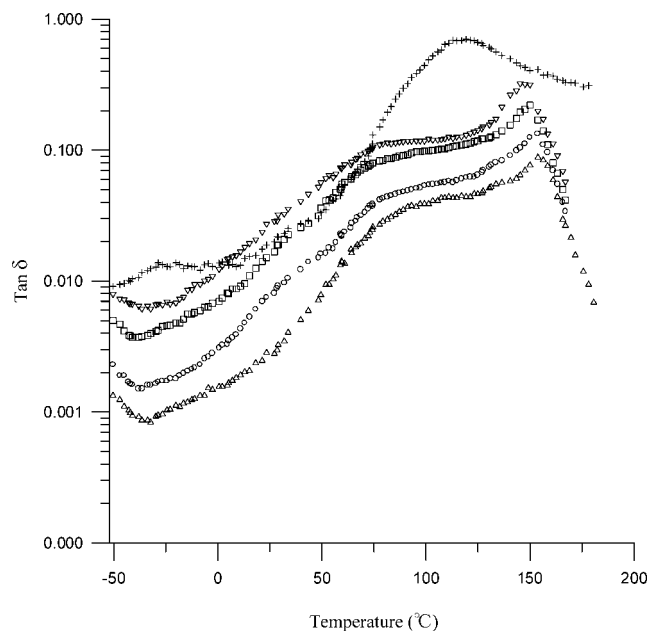


Figure 8 Plot of $\tan \delta$ as a function of temperature for (+) an undrawn $UL_{B-0.9}$ specimen and $UL_{B-0.9}$ specimens drawn at 95°C with various draw ratios: (∇) 20, (\square) 40, (\circ) 100, and (\triangle) 300.

Birefringence and tensile properties of the gel films of the UHMWPE and UHMWPE/LMWPE blends

From the birefringence of the $U_{-0.7}$, $UL_{B-0.9}$, and $UL_{D-1.0}$ gel film specimens that were undrawn or drawn with various draw ratios (Fig. 9), it was found that the increasing rate of birefringence increased rapidly when the specimens were at a low

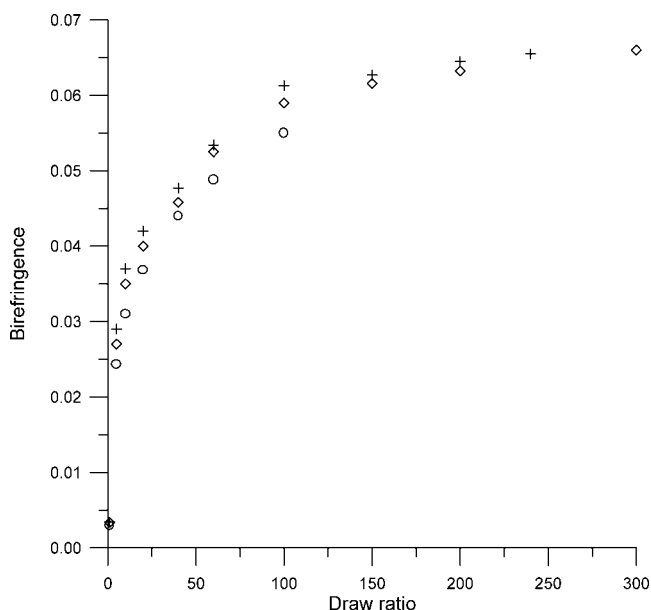


Figure 9 Birefringence of (+) $U_{-0.7}$, (\diamond) $UL_{B-0.9}$, and (\circ) $UL_{D-1.0}$ gel films drawn at different draw ratios.

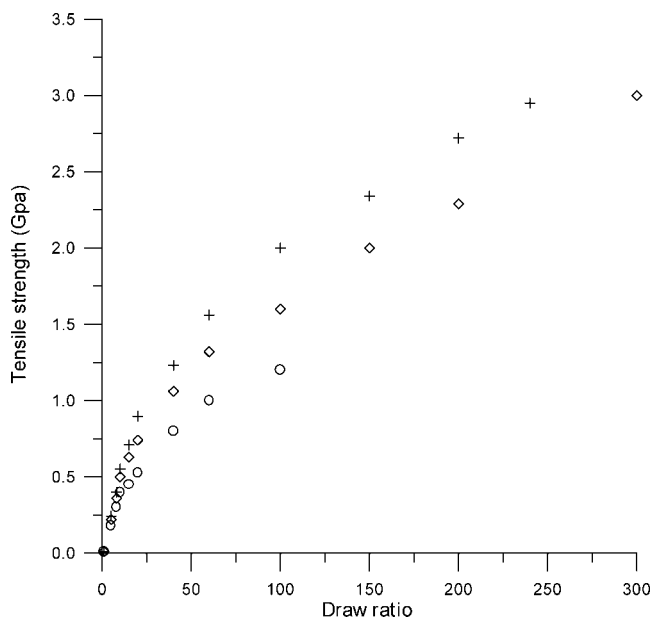


Figure 10 Tensile strength of (+) $U_{-0.7}$, (◇) $UL_{B-0.9}$, and (○) $UL_{D-1.0}$ gel films drawn at different draw ratios.

draw ratio. When the draw ratio increased to 20, the increasing rate of birefringence slowly decreased. After the draw ratio reached 100, the increasing rate of birefringence became slower. After the draw ratio reached 200, the increasing rate of birefringence became very slow and was almost close to a fixed value. Besides, at any of the same draw ratios, the birefringence decreased with an increase in the blended content of LMWPE. For example, when the draw ratio was 100, the birefringence of the $U_{-0.7}$ gel film was 7 and 11% higher than those of $UL_{B-0.9}$ and $UL_{D-1.0}$, respectively. When the draw ratio of the UHMWPE/LMWPE gel film specimen with about 5 wt % LMWPE added was 300, the birefringence could reach the maximum value. As for the tensile strength and moduli of the $U_{-0.7}$, $UL_{B-0.9}$, and $UL_{D-1.0}$ gel film specimens that were undrawn and drawn with various draw ratios (Figs. 10 and 11), it was found that the tensile strength and moduli increased rapidly when the specimens were at low draw ratios; when the draw ratio increased to 20, the increasing rate of the tensile strength and moduli began to slowly drop. After the draw ratio reached 100, the increasing rate of the tensile strength and moduli increased very slowly and was almost close to a fixed value. Another interesting phenomenon is that, at any of the same draw ratios, the tensile strength and moduli decreased with an increase in the blended content of LMWPE. For example, when the draw ratio was fixed at 100, the tensile strength and moduli of the $U_{-0.7}$ gel film were 25 and 40% higher than those of $UL_{B-0.9}$ and $UL_{D-1.0}$, respectively. When the draw ratio of the

UHMWPE/LMWPE gel film specimen with about 5 wt % LMWPE added was 300, the tensile strength and moduli could reach the maximum values. The aforementioned interesting phenomenon occurred because a low draw ratio for the gel film specimens caused the orientation of the molecular chains in the amorphous region; therefore, the increasing rate of birefringence increased rapidly, and so did the increasing rate of the tensile strength and moduli. This phenomenon could improve the anticreeping property effectively. After the draw ratio increased to 20, the increasing rate of the birefringence, tensile strength, and moduli began to decrease. This happened because parts of the folded chains in the crystalline region began to be pulled out, and when the draw ratio increased to 100, the increasing rate of the birefringence, tensile strength, and moduli increased even more slowly; this indicated that most of the folded chains in the crystalline region had been pulled out and formed a structure with extended chains and a thickened crystal size. At this time, the orientation arrangement of the molecular chains in the amorphous region could not supply a high enough rate for the birefringence. This interesting phenomenon was the major reason that the anti-creeping property was affected in the gel film specimens. Furthermore, at any of the same draw ratios, the birefringence decreased with an increase in the blended content of LMWPE. This occurred because when LMWPE was blended into a UHMWPE gel film, it resulted in a decrease in the orientation arrangement of the molecular chains when the UHMWPE molecules were drawn. Therefore, at any of the same draw ratios, both the tensile strength

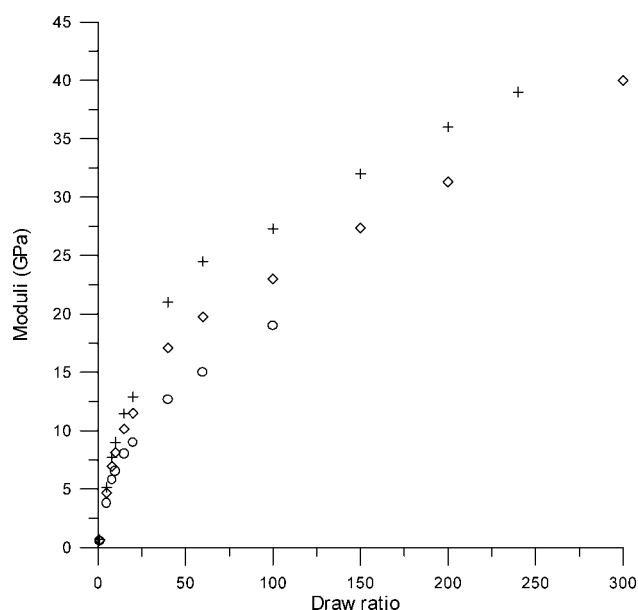


Figure 11 Moduli of (+) $U_{-0.7}$, (◇) $UL_{B-0.9}$, and (○) $UL_{D-1.0}$ gel films drawn at different draw ratios.

and moduli decreased and affected the anticreeping property. However, when about 5 wt % LMWPE was added, D_{ra} could reach the maximum value of 371. Consequently, the birefringence, tensile strength, and moduli all increased and were higher than those of the $U_{-0.7}$ specimens, so the anticreeping property was improved accordingly.

CONCLUSIONS

After drawing, the D_{ra} values of the UHMWPE and UHMWPE/LMWPE gel film specimens prepared near C_c (i.e., the D_{rc} values) were higher than those of the gel film specimens prepared at other concentrations. When 5 wt % LMWPE was properly added to UHMWPE, the maximum draw ratio, 371, was obtained. Therefore, after the optimum concentration of 5 wt % LMWPE was exceeded, D_{ra} decreased gradually. To improve the anticreeping property and thermal stability of common PE, the most important thing is to increase D_{ra} . The draw ratio of the $UL_{B-0.9}$ specimens increased to 300. Their anticreeping property was improved over that of the undrawn gel specimens (CSPR was ca. 0.026%/day) and was even better than that of pure $U_{-0.7}$, the draw ratio of which was 200 (CSPR was ca. 0.037%/day). Besides, with an increase in the draw ratio, the curve of E' shifted to a high-temperature region, and this helped to improve the thermal stability of the gel film specimens. For example, when the $UL_{B-0.9}$ gel film specimens were drawn to a ratio of 300, the temperature was about 150°C, which was obviously much higher than that of the undrawn gel film specimens (70°C). The α -transition temperature, thermal properties, degree of orientation, dynamic properties, and mechanical properties of the gel film specimens continued increasing with an increase in the draw ratio, but the $\tan \delta$ curve decreased noticeably with the increase in the draw ratio; this meant that the loss modulus of the gel film specimens was lower. This explains why the molecular mobility of UHMWPE molecules decreases. The aforementioned phenomenon can clearly explain why ultrahigh-drawn UHMWPE and UHMWPE/LMWPE gel

specimens have a significant influence on the anticreeping property and thermal stability.

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