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Flexible and colorless shape memory polyimide films with high visible light transmittance and high transition temperature

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Colorless shape memory polyimide (CSMPI) has potential applications in broad fields, especially in advanced optoelectronics due to the excellent optical transparency, shape memory effect and high temperature resistance. In this work, high flexible dianhydrides and fluorine-containing diamines were used to synthesize CSMPI, which simultaneously combined great shape memory performance with high optical transparency. The effects of monomer ratios and imidization temperatures on the molecular structure and properties were investigated. Moreover, the CSMPI film possesses a higher glass transition temperature (T_g) of 234 °C, compared with the reported transparent shape memory polymers. Most importantly, the transmittance of CSMPI film is 87%–90% at 450–800 nm, meeting the requirements of heat resistance and transmittance of the substrate. Both shape recovery and shape fixity are over 97%. Flexible and colorless CSMPI films severed as substrates provide more potential in optoelectronic devices such as OLED and OPV, etc.

Supplementary material for this article is available online

Keywords: colorless shape memory polyimide, high visible light transmittance, high transition temperature, shape memory behavior

(Some figures may appear in colour only in the online journal)

1. Introduction

Shape memory polymers (SMPs) are a novel class of smart materials that have been developed rapidly and well in recent years [1–4]. It can memorize a temporary shape and return to the original shape exposed to external stimuli, such as heat, light, solvent, electric and magnetic field [3–7]. SMPs have been used in many areas, including biomedical science, deployable structures, actuators, sensors, optical and electrical devices, as well as smart fabrics [8–12].

Aromatic polyimide (PI) films have been widely applied in aerospace, automobile, microelectronic and optoelectronic applications for many decades due to the excellent mechanical properties, dielectric features, high thermal and chemical resistance [13–15]. Because of the formation of the chargetransfer complex (CTC) in the highly conjugated molecular structure, traditional PI films possess dark color and poor optical transparency, greatly limiting the application in optoelectronic engineering [16, 17]. The synthesis strategy of colorless polyimide (CPI) is mainly to introduce substituents



for destroying the highly conjugated molecular structure and inhibiting the formation of CTC [18–20].

The optoelectronic devices are favorable in manifesting more lightweight, ultrathin and flexible in the future. The traditional glasses and other brittle substrate materials are not able to meet these requirements. Therefore, optical transparent polymer is the preferred substrate for future optoelectronic devices due to the high transparency, flexibility, light weight and high impact resistance [21–25]. Compared with traditional optical polymer films such as polyethylene terephthalate and poly(methyl methacrylate), CPI with optical transparency, high thermal stability, and excellent mechanical properties has been used for flexible thin film transistors, flexible organic electroluminescent devices and flexible solar cells [26–29].

The UV curable shape memory polyesters have been used as substrates for the preparation of flexible organic lightemitting diodes (OLEDs), deformed to various stable shapes and recovered the initial plane shape, at the same time, the deformation caused little loss of the electroluminescent property [30, 31]. However, the glass transition temperature (T_g) of shape memory polyesters were lower than 150 °C and their mechanical and optical properties can deteriorated significantly at a high temperature due to the poor thermal resistance. It cannot meet the requirements of advanced optoelectronic devices for high heat resistant optical films [32, 33]. Xiao *et al* [34] reported a transparent shape memory polyimide with $T_{\rm g}$ of 171 °C and the transmittance at 450 nm was only 82%. Heat resistance had been greatly improved compared with polyester and polystyrene. However, the transmittance and heat resistance need to be improved. The performance comparison of the reported transparent SMPs is shown in table S1 is available online at stacks.iop.org/SMS/ 28/055031/mmedia.

To date there is no report on highly transparent SMPs with T_g higher than 200 °C and visible light transmittance over 90% [30, 32, 34–38]. Our motivation is to prepare a kind of SMP with high transparency and high heat resistance. Due to its high visible light transmittance and high heat resistance, in addition to being applied to actuators, deployable structures, sensors [8–12], it also meets the requirements of advanced optoelectronic devices for high heat resistant optical films [32, 33]. Optoelectronic devices based on transparent SMPs are deformable and adaptive, being converted from simple two-dimensional structure into complex three-dimensional structure.

Compared with other researches, high heat resistant polyimide as the research object, suitable monomers were selected in consideration of light transmittance and shape memory properties. In this work, flexible dianhydride and fluorine-containing diamine were chosen to synthesize colorless shape memory polyimide (CSMPI). The effect of monomer molar ratio and imidization temperature on CSMPI and its mechanism were discussed. Moreover, the effect of imidization temperature on shape memory polyimide was firstly reported.



Figure 1. Schematic of synthesis of colorless shape memory polyimide.

2. Experimental

2.1. Materials

Both 4, 4'-(4, 4'-Isopropylidenediphenoxy) diphthalic Anhydride (BPADA) (\geq 98%) and 2, 20-bis(trifluoromethyl)-4, 40diaminobiphenyl (TFDB) (98%) were purchased from Aladdin Co.. High flexible dianhydride can make the macromolecule chain more easily twist and tangle to create physical crosslinking points as the fixed phase of shape memory effect. The strongly electron-withdrawing, bulky, *meta*-substituted –CF₃ in TFDB can effectively destroy the highly conjugated molecular structure and inhibit the formation of CTC [19], ensuring CSMPI with excellent optical transparency. Chromatographically pure dimethylacetamide (DMAc) was purchased from Tianjin Guangfu Fine Chemicals Institute. All the raw materials were used as received. All the glassware for the synthesis was strictly dried before use.

2.2. Preparation of CSMPI

The schematic diagram of polycondensation reaction of CSMPI is shown in figure 1. The preparation step of CSMPI with a molar ratio of 0.95 (TFDB/BPADA) was described as follows: 3.8 mmol TFDB and 20 ml DMAc were simultaneously added to the flask and stirred for 15 min 4 mmol BPADA was added in two batches at intervals of 20 min, and the colorless polyamic acid (PAA) solution was obtained by magnetically stirring 24 h at room temperature. The flask was dried in a vacuum drying oven at 45 °C for 2 h for defoaming treatment. The defoamed PAA solution was cast onto the glass slide placed on the adjustable horizontal plate to ensure film thickness uniformity, and underwent a step-wise imidization curing process at 80 $^{\circ}C/2$ h, 120 $^{\circ}C/2$ h, 160 $^{\circ}C/2$ h, 200 °C/2 h, 250 °C/2 h and 300 °C/1 h, respectively. The polyimide was placed in deionized water in order to separate the film from the slide.

2.3. Characterization

The molecular weight of the polymer directly influenced its performance, such as mechanical properties and solubility. The molecular weight distribution of polyimide was characterized by gel permeation chromatography using Agilent 1260 Infitiny with tetrahydrofuran (THF) as an eluent at 30 °C.

The modulus, T_g and shape memory properties of CSMPI were characterized by conventional dynamic mechanical analysis (DMA) (TA Instruments Q800). The DMA test was performed in the tensile mode with a frequency of 1 Hz, at a heating rate of 3 °C min⁻¹. The film size was 40 × 3 × 0.08 mm.

The thermal stability of the CSMPI was performed by thermogravimetric analysis (TGA) under a N_2 environment on the Mettler-Toledo TGA/DSC 1 STARe System at a heating rate of 10 °C min⁻¹.

Differential scanning calorimetry (DSC, Mettler-Toledo TGA/DSC 1 STARe System) measurements were used to characterize thermal changes of polyimide at a heating rate of $10 \,^{\circ}$ C min⁻¹. The temperature at the endothermic glass transition was measured by DSC, and the test data obtained by DMA was verified from the side.

Mechanical properties were essential for the application of polymer films in advanced optoelectronic devices. Mechanical properties of the CSMPI samples were tested at room temperature on an Instron 5500 R instrument and sample size used for the tensile test was tailored to the standard (ISO 527-3-2003, Type I). The extensional strain rate was controlled at 5 mm min⁻¹.

The optical transmittance (200–800 nm) was measured by a Perkin Elmer Lambda 1050 UV/Vis/NIR spectrophotometer at a resolution of 1 nm. The film thickness for transmittance characterization was about 70–80 μ m. The yellowness index (YI) was calculated from the hemispherical transmittance at 380–780 nm according to ASTM E313 [39]. Both transmittance and YI were necessary indicators for characterizing the optical properties of transparent polymer films. 1 × 10⁻⁶ mol1⁻¹ polyimide TFH solution was prepared for UV absorption spectroscopy, characterized using Agilent Cary 5000 UV/Vis/NIR spectrophotometer at a resolution of 1 nm.

Wide angle x-ray diffraction (WAXD) was determined by Bruker D8 Advance Plus under Cu K α radiation ($\lambda = 0.15406$ nm), and the accelerating voltage and emission current were 40 kV and 150 mA, respectively. WAXD was used to characterize the aggregation morphology of polymer molecular chains.

The characteristic functional groups and imidization degree (ID) of polyimide were characterized by Fourier transform infrared (FT-IR) spectra. The FT-IR spectra was measured by Perkin-Elmer Spectrum II under the attenuated total reflectance module from 650 to 4000 cm⁻¹ at a resolution of 4 cm⁻¹. The CSMPI underwent final imidization temperature of 300 °C was defined as fully imidized, and the relative ID of other samples can be calculated using equation (1) [40]. A_{1365} and A_{1480} represented the infrared

absorption peak area at 1365 cm^{-1} and 1480 cm^{-1} respectively, and 1480 cm^{-1} was the characteristic peak of benzene ring with constant content before and after imidization

$$ID(\%) = \frac{(A_{1365}/A_{1480})_{sample}}{(A_{1365}/A_{1480})_{(300 \circ C)}} \times 100\%.$$
(1)

Shape-memory cycles to obtain shape fixity and recovery were carried out with consecutive stretch contraction processes using the controlled force mode on a TA Instruments Q800. The procedure included the following steps: (a) heating a sample to $T_g + 10$ °C, (b) applying a force to prolong the sample, (c) reducing the temperature to 25 °C, (d) unloading the force, (e) heating the sample to $T_g + 10$ °C again. When the tensile deformation of the sample recovered a constant value, the cycle process was repeated by applying the same force used in step (b). The shape recovery rate (R_r) is calculated according to equation (2), where ε_m is the tensile strain after the stretching process, ε_p is the strain after recovering original shape, N denotes cycle time. The shape fix rate (R_f) can be expressed as equation (3), where ε_u is the strain of temporary deformation fixed [34]

$$R_{\rm r}(N) = \frac{\varepsilon_{\rm m}(N) - \varepsilon_{\rm p}(N)}{\varepsilon_{\rm m}(N) - \varepsilon_{\rm p}(N-1)} \times 100\%, \tag{2}$$

$$R_{\rm f}(N) = \frac{\varepsilon_{\rm u}(N)}{\varepsilon_{\rm m}(N)} \times 100\%. \tag{3}$$

3. Results and discussion

3.1. Molecular structure

CSMPI films with different molar ratios (BPADA/TFDB) and different final imidization temperatures are listed in table 1. As shown in figure 2(a), molecular weight distribution shifts toward the high molecular weight with the increase of the molar ratios, similar to other thermoplastic polyimides [41]. Figure 2(b) shows that the decrease in final imidization temperature has no significant effect on the molecular weight distribution. The number of average molecular weight (M_n) values is listed in table 2.

The FTIR spectra of polyamide acid (PAA) and CSMPI at $600-2700 \text{ cm}^{-1}$ undergoing different final imidization temperatures are shown in figure 2(c), and the FTIR spectra of CSMPI with different molar ratios are shown in supporting information (figure S1). The characteristic peaks of PAA at 1683 cm⁻¹ and 1415 cm⁻¹, respectively corresponding to stretching vibration of C=O in -COOH and stretching vibration of C=N in -CONH. The characteristic peaks of CSMPI were 1365 cm⁻¹, 1720 cm⁻¹, and 1779 cm⁻¹, respectively corresponding to stretching vibration of C=O, and asymmetric stretching of C=O.

The changing trend of ID is shown in figure 2(d). The ID of CPI200 was only 81%, while the ID of the other samples exceeded 90%. The WAXD spectra are shown in ESI



Figure 2. (a) Molecular weight distribution curves of CSMPI with different molecular ratios, (b) molecular weight distribution curves of CSMPI at different temperatures, (c) FTIR spectra of PAA and CSMPI, (d) imidization degree varies with imidization temperature.

Table 1. CSMPI with different preparation processes.

| | CPI1.0 | CPI0.97 | CPI0.95 | CPI0.93 | CPI300 | CPI270 | CPI235 | CPI200 |
|------------------------------|--------|---------|---------|---------|--------|--------|--------|--------|
| Molar ratio | 1.0 | 0.97 | 0.95 | 0.93 | 0.95 | 0.95 | 0.95 | 0.95 |
| Imidization temperature (°C) | 300 | 300 | 300 | 300 | 300 | 270 | 235 | 200 |

(figure S2), and all samples have a broad peak near 15°. It indicated that CSMPI was amorphous in morphological structures, due to loosing chain stacking caused by high flexible BPADA and bulky, *meta*-substituted –CF₃. Moreover, the UV absorption spectra of CSMPI with different imidization temperature are shown in ESI (figure S3). UV absorption spectra give an initial ultraviolet absorption wavelength (λ_{onset}) of 303 nm, far lower the fully aromatic polyimide. Because of the highly flexible dianhydride and strongly electron-withdrawing, bulky –CF₃ greatly destroy the degree of conjugation of molecular, making CSMPI exhibit colorless and high optical transmittance.

3.2. Thermomechanical and thermal properties

DMA images of CSMPI are shown in figure 3. T_g increases from 227 °C to 250 °C with the molar ratio increasing from 0.93 to 1.0, mainly due to the increase in M_n (figure 2(a)). Higher molecular weight possesses a higher degree of macromolecular entanglement and more intermolecular CTC, resulting in an increase of T_g (figure 3(a)) [42]. The internal friction caused by the slip of molecular chains also decreased with the increase of M_n , resulting in the decrease of loss factor value (Tan δ).

 $T_{\rm g}$ showed no substantial change at the imidization temperature of 235 °C–300 °C, however, the Tan δ peak of CPI200 shifted slightly to the left and became broader (figure 3(b)). The reduction in the final imidization temperature leads to a lower ID (figure 2(d)), and residual amic acid on the molecular chain may weaken the interaction between the macromolecules. The residual amic acid also leads to a sharp drop in the storage modulus (*E'*) of CPI200 at 200 °C (figure 3(d)). CSMPI possessed great shape memory performance by virtue of a great difference in *E'* between glassy state and rubber state. The *E'* of other samples is listed in table 2.

TGA results indicated the thermal stability of samples, which are shown in figures 4 and S4. The change of mole ratio has no effect on thermal stability. The temperature of 5% mass loss ($T_{5\%}$) is about 520 °C, and the tiptop temperature of pyrolysis (T_P) is 540 °C (figure S4), demonstrating that CSMPI cured at 300 °C has excellent thermal stability. Figure 4(b) shows that PAA has a significant mass loss in the range of 100 °C–270 °C, caused by the evaporation of the



Figure 3. (a) Loss factor of CSMPI with different molecular ratios, (b) loss factor of CSMPI at different temperatures, (c) storage modulus of CSMPI with different molecular ratios, (d) storage modulus of CSMPI at different temperatures.



Figure 4. (a) TGA spectra of the weight loss of CSMPI with different molecular ratios, (b) TGA spectra of the weight loss of CSMPI at different temperatures.

solvent and the small molecules of water released from the imidization reaction. CPI270 and CPI235 present the same excellent thermal stability as CPI300, while the $T_{5\%}$ of CPI200 drops to 505 °C and a slight mass loss occurs at 250 °C–300 °C, due to further imidization of residual amic acid to release small molecules of water. In addition, the DSC curves of CSMPI are shown in ESI (figure S5). DSC results reveal that the variation of T_g with molar ratio is similar to DMA results. Typical tensile stress–strain curves of CSMPI are shown in ESI (figure S6). Both the reduction of molar ratio and imidization temperature impair the mechanical properties of CSMPI, especially for the decrease of elongation at break (δ).

3.3. Optical properties

The optical properties of CSMPI were characterized by light transmittance in visible range and the YI. The strongly electron-withdrawing, bulky, and *meta*-substituted –CF₃ in TFDB effectively destroyed the highly conjugated molecular structure and inhibited the formation of CTC [19], ensuring the CSMPI with excellent optical transparency. As shown in figure 5(a), with the decrease of the molar ratios, the transmittance in the range of 400–600 nm had been greatly improved, especially for the transmittance at 450 nm (T_{450}) increased from 80% to 87%, while the UV cutoff wavelength (λ_{cutoff}) was not changed to about 378 nm. YI is significantly reduced from 11.2 to 3.7, and figure 5(c) show that the film



Figure 5. (a) UV–vis spectra of CSMPI with different molecular ratios, (b) UV–vis spectra of CSMPI at different temperatures, (c) optical photographs of CSMPI with different molecular ratios, (d) optical photographs of CSMPI at different temperatures.

 $(80 \,\mu\text{m})$ color becomes more colorless. According to the foregoing, the decrease of the molar ratio causes weakening of the entanglement between the molecular chains, inhibiting the formation of intermolecular CTC and improving the transmittance [42].

In figure 5(b), the transmittance at 400–500 nm increases slightly with the decrease of imidization temperature, and T_{450} increases from 86% to 88% with no change in cutoff wavelength. YI decreases from 4.2 to 1.7, and figure 5(d) shows a slight lightening of film color. Compared with imide rings, residual amic acid groups may inhibit the formation of CTC. In summary, the decrease of the molar ratio and imidization temperature were favorable for improving the optical properties of CSMPI.

3.4. Shape memory properties

For the sake of gaining more intuitive demonstration of excellent shape memory performance, the rectangular film was curled as a circle on a flat heater, the deformed shape was fixed by removing the curled film from the flat heater. The shape recovery process is shown in figure 6(a), and the deformed shape (circle) returns to the original shape (flat) within 25s.

The physical cross-linking formed by molecular chain entanglement is necessary for the shape memory effect of thermoplastic PI [43]. PMDA/TFDB as a comparison group, optimized 3D model structure of BPADA/TFDB (CSMPI) and PMDA/TFDB consisted of 20 repeating units are shown



Figure 6. (a) Deployable shape memory recovery process of winding CSMPI film (CPI270). (b) optimized 3D model structure of CSMPI and (c) PMDA/TFDB consisting of 20 repeating units.

in figures 6(b) and (c). BPADA with flexible ether linkages provides molecular chains greater flexibility than PMDA/TFDB. The bending conformation of CSMPI can make the molecule chains more easily twisted and tangled to form



Figure 7. Stretchable shape memory cycles of (a) CPI300, (b) CPI270, (c) CPI235 and (d) CPI200; (e) shape recovery rate and (f) shape fix rate of CSMPI at different cycle times.

physical crosslinking points with greater shape memory property.

The decrease of the molar ratio impairs the shape memory performance of CSMPI [34]. Shape memory cycling results of tensile deformation-recovery were carried out by DMA are shown in figure 7. The curve of CPI200 (figure 7(d)) is different from others. The tensile strain decreased as the number of cycles increased under the condition of constant deformation temperature and constant applied stress, indicating the higher modulus. It may be related to the residual amic acid in CPI200, the deformationrecovery process at a high temperature (>200 $^{\circ}$ C) in the shape memory cycle was equivalent to heat treatment of the specimen for the imidization reaction of residual amic acid. Thus the modulus of CSMPI increased with the decreases of residual amic acid. The E' at high temperature (≥ 200 °C) increased with the imidization temperature increasing (figure 3(d)), confirming this phenomenon from the other side.

The R_r (1) of all CSMPI were relatively lower than R_r (2–4), caused by the residual strain resulting from the processing history. The lower imidization temperature has little influence on R_f (\geq 97%), however, R_r decrease significantly (figure 7(f)). As the cycle continues, the R_r of CPI200 increased significantly, and the R_r (4) increased to 96%, which was approximate to the 97% of CPI300. It may be

caused by high temperature heat treatment during the cycles, and residual amic acid groups were further imidized. Therefore, the imidization temperature should not be lower than $270 \,^{\circ}$ C in consideration of shape memory performance.

The key performance data is shown in table 2. The decrease of molar ratios can increase the transmittance while impairing the mechanical properties. The decrease of imidization temperature improved the optical performance to a certain extent, causing the damage to the shape memory performance, heat stability and mechanical properties. Comprehensively, CPI270 shows more excellent comprehensive performance marked as the red star, and the performance comparison with the transparent SMP of other literature is shown in figure 8. In this work, we obtained the first optical transparent SMP (CPI270) with the transmittance (550 nm) of 90% and T_g over 200 °C, meeting the requirements of optoelectronic devices such as OLED and OPV on heat resistance and transmittance of the substrate [32, 33], and the R_f and R_r are over 97%.

4. Conclusion

In summary, CSMPI prepared by BPADA and TFDB has excellent optical transparency, shape memory properties and a high temperature resistance. High flexible of BPADA making

| | | | | | | ······································ | , P | | | | |
|---------|---------|-----------------------|----------------------------|---------------------|-----------------|--|------|--------------|------------------------|---------------------|-------------|
| Title | M_n^a | $T_{\rm g}^{\ \rm b}$ | E' at 25 °C ^{c,d} | E' at $T_{g}^{c,d}$ | ID ^e | $T_{450}^{\mathrm{d,e}}$ | YI | δ^{e} | $T_{5\%}^{\mathbf{b}}$ | $R_{\rm f}^{\rm e}$ | $R_{\rm r}$ |
| CPI1.0 | 55.6 | 250 | 1706 ± 40 | 26.7 ± 1.8 | 100 | 80.5 ± 0.5 | 11.2 | 9.0 | 520 | _ | |
| CPI0.97 | 31.8 | 240 | 1695 ± 32 | 29.5 ± 2.5 | 100 | 83.7 ± 0.6 | 7.2 | 8.5 | 523 | — | |
| CPI0.95 | 18.4 | 233 | 1739 ± 43 | 27.4 ± 2.9 | 100 | 86.2 ± 0.5 | 4.2 | 8.1 | 520 | 98 | 98 |
| CPI0.93 | 15.4 | 227 | 1780 ± 47 | 28.5 ± 2.3 | 100 | 87.5 ± 0.8 | 3.7 | 6.1 | 522 | — | |
| CPI270 | 18.9 | 234 | 1814 ± 38 | 27.7 ± 3.1 | 96.6 | 87.3 ± 0.8 | 2.5 | 7.9 | 521 | 98 | 97 |
| CPI235 | 18.2 | 231 | 1875 ± 42 | 26.5 ± 2.5 | 90.5 | 87.5 ± 0.6 | 2.1 | 7.4 | 511 | 98 | 95 |
| CPI200 | 17.8 | 228 | 1783 ± 36 | 10.2 ± 1.7 | 81.2 | 88.4 ± 0.5 | 1.7 | 6.3 | 498 | 98 | 92 |
| | | | | | | | | | | | |

Table 2. The key performance of colorless shape memory polyimides

In kg mol⁻¹.

In °C.

° In MPa.

^d Average values and standard deviations.

ໍ In %. ັ



Figure 8. The performance comparison with the transparent SMP of other literatures.

the molecule chains more easily twisted and tangled to form physical crosslinking points is favorable for possessing great shape memory property. The strongly electron-withdrawing, bulky -CF₃ effectively destroyed the highly conjugated molecular structure and inhibited the formation of CTC, ensuring the CSMPI with excellent optical transparency. The effects of monomer ratio and imidization temperature on the molecular structure and properties were discussed. The decrease of the molar ratio can increase the transmittance while impairing the mechanical properties. The decrease of imidization temperature improved the optical performance to a certain extent, causing the damage to the shape memory performance, heat stability, and mechanical properties. CPI270 possessed a higher T_g of 234 °C, compared with the reported transparent SMPs, the transmittance of CPI270 is 87%-90% at 450-800 nm and the $R_{\rm f}$ and $R_{\rm r}$ are over 97%. CSMPI film has potential applications in broad fields, especially in advanced optoelectronics, such as flexible substrates for OLED and OPV devices, etc

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Appendix. List of abbreviations

| CSMPI | Colorless shape memory polyimide |
|-------|--|
| SMPs | Shape memory polymers |
| OLED | Organic light emitting diode |
| OPV | Organic photovoltaics |
| CTC | Charge-transfer complex |
| BPADA | 4, 4'-(4, 4'-Isopropylidenediphenoxy) diphthalic anhydride |
| TFDB | 2, 20-bis(trifluoromethyl)-4, 40-diaminobiphenyl |
| DMAc | Dimethylacetamide |
| PAA | Polyamic acid |
| GPC | Gel permeation chromatography |
| DMA | Dynamic mechanical analysis |
| TGA | Thermogravimetric analysis |
| DSC | Differential scanning calorimetry |
| YI | Yellowness index |
| WAXD | Wide angle x-ray diffraction |
| FTIR | Fourier transform infrared |
| ID | Imidization degree |

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