Journal of Applied Polymer Science

Fluorescently labeled degradable thermoplastic polyurethane elastomers: Visual evaluation for the degradation behavior

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ABSTRACT: Thermoplastic polyurethane elastomers (TPU) were synthesized with isophorone diisocyanate (IPDI) as the rigid segment, poly(lactic-co-glycolic acid) (PLGA-PEG-PLGA) diol as soft segment, and 1,4-butanediol (BDO) as the chain extender. During the chain extension process, three kinds of fluorescent monomers 4-(2-hydroxyethylamino)−1,8-naphthoyl-(2-hydroxyethyl)imide (HNHI), 1,5-dihydroxy naphthalene (DHN), and dicoumarin (DIC) were introduced to get the fluorescently labeled degradable TPUs. The structure and degradation properties of the TPUs were characterized in detail. The results showed that there was no significant effect found on average molecular weight, mechanical properties, and glass transition temperature of polyurethane by introducing 0.001% (wt) weight percent of fluorescence monomers. The degradation behavior of fluorescent-tagged thermoplastic elastomer has been characterized with fluorescence microscopy. Results showed that polyurethane elastomers, in which fluorescence monomers especially HNHI were introduced by chemical reaction, had more homogeneous and stable fluorescence intensity than that with fluorescence monomers introduced by post blending. This work also provides a promising visual characterization approach to monitor degradation behavior of degradable TPUs for tissue engineering applications or drug delivery system. © 2015 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2015**, *132*, 42519.

KEYWORDS: biomaterials; degradation; polyurethanes

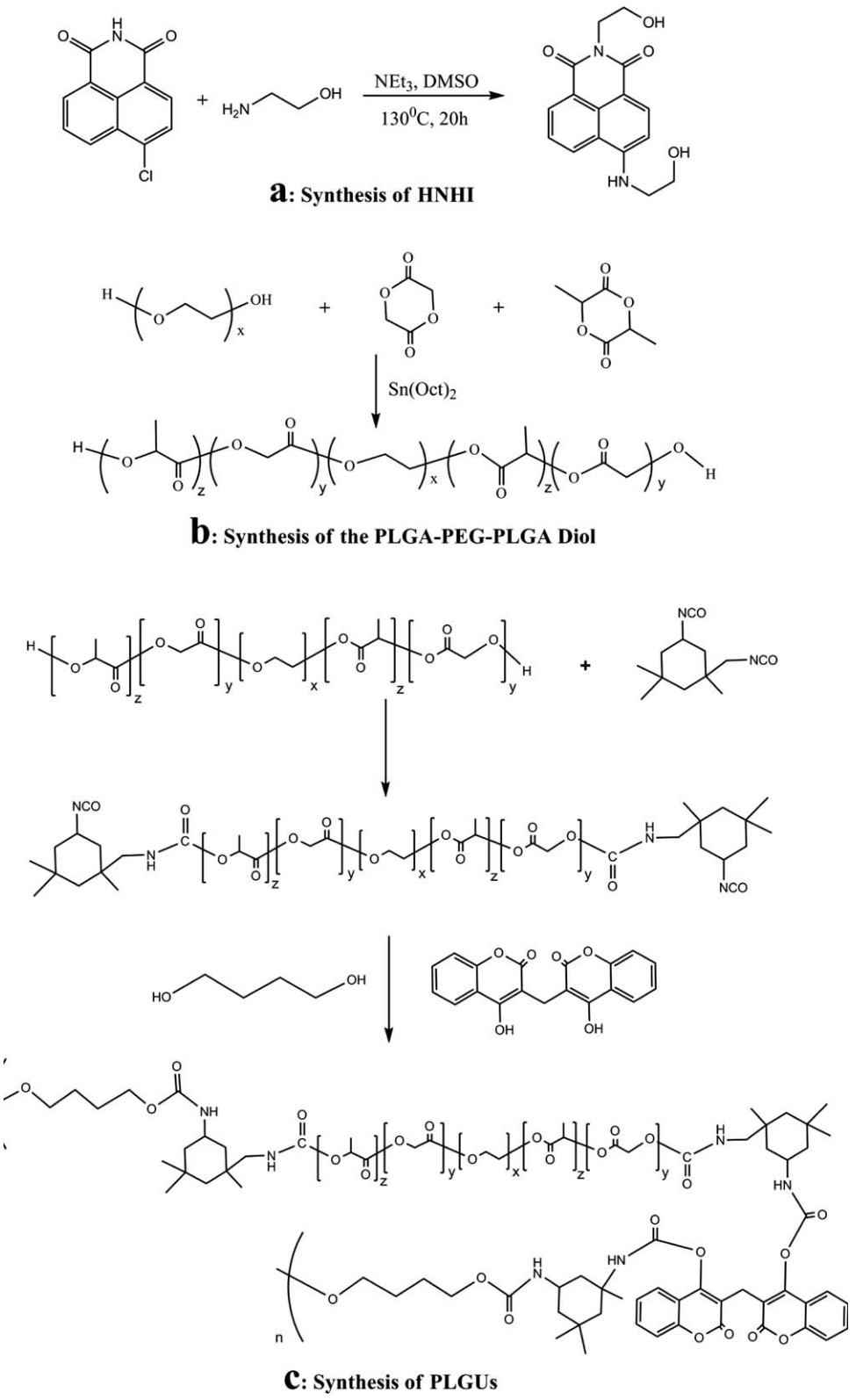
Received 5 May 2014; accepted 19 May 2015
DOI: 10.1002/app.42519

INTRODUCTION

Because of low toxicity, biodegradability, and a wide range of physical and mechanical properties, biodegradable thermoplastic polyurethane elastomers (TPUs) were widely used in biomedical field,[1–10] such as tissue engineering scaffolds,[11] drug release carriers,[12,13] medical adhesives and surgical sutures,[14] and so on.

Degradation behavior research is valuable in evaluation of applicative performance of polyurethane elastomer.[15] A lot of efforts have been focused on monitoring degradable PU degradation behaviors by measuring changes in weight loss,[16–18] mechanical properties,[19–21] molecular weight,[22] morphology,[18] and viscosity.[23] However, there is no literature about real-time observation of degradation behavior; that is, degradation process cannot be directly observed in situ by these common methods. While fluorescence characterization with high selectivity and sensitivity is more intuitional and convenient to monitor the degradation process with fluorescence image changes.[24] And the key problem for fluorescent characterization is to tag the materials with fluorescent dye in the first place. Fluorescent dyes are considered to be important chemicals which are widely used in both civil and military applications,[25–29] such as synthesis of polymers,[30–32] danger zone, airplane, ship, ambulance, safty cloths, and transportation.[33] Real-time optical fluorescence imaging techniques have been applied for in situ monitoring the degradation behavior of implant biometarials.[34,35] But there is no literature about real-time observation of material degradation process directly. Here the most important question is how the fluorescent dye evenly dispersed in its tagged material. In this work, we selected reactive HNHI, DHN, and DIC as the fluorescent probe compounds, which all have two active hydroxyl groups in their structures. Then we introduced them to elastomer material system using physical blend and chemical reaction methods respectively. The key objective of this work is to investigate the effects of different introducing ways for fluorescent compounds to the TPUs on degradation behavior by using fluorescence microscopy, except effects on the comprehensive properties of TPUs.

Fluorescently labeled degradable TPUs were synthesized with isophorone diisocyanate (IPDI), poly-lactic-co-glycolic acid (PLGA-PEG-PLGA) diol, and 1,4-butanediol (BDO). During the process of chain extension, three kinds of fluorescent monomers—(4-(2-hydroxyethylamino)-1,8-naphthoyl-(2-hydroxyethyl)imide



Scheme 1. Synthesis of (a) HNHI; (b) PLGA-PEG-PLGA; and (c) PLGA-PEG-PLGA-based PLGU.

(HNHI), 1,5-dihydroxy naphthalene (DHN), and dicoumarin (DIC))—were added. The structure and properties of TPUs were characterized by IR, NMR, GPC, DSC, and extension test. Then the degradation behaviors of the fluorescent-tagged degradable TPUs were observed by fluorescence microscope.

Table I. PLGUs with Varying Hard Segment Content or Fluorescence Monomers

Samples	HSC (%)	Fluorescence (wt %)
PLGU30	30	0
PLGU50	50	0
PLGU70	70	0
PLGU30-D01	30	DIC, 0.001
PLGU50-D01	50	DIC, 0.001
PLGU30-N01	30	HNHI, 0.001
PLGU50-N01	50	HNHI, 0.001
PLGU30-E01	30	DHN, 0.001
PLGU50-E01	50	DHN, 0.001

EXPERIMENTAL

Materials

L-Lactide (LA) and glycolide (GA) were purchased from Daigang Biomaterial Co. Ltd. (Jinan, China) and used as received. Isophorone diisocyanate (IPDI, Degussa Co. LTD. German) was used as received. 1,4-Butanediol (BDO) and stannous octoate ($Sn(Oct)_2$, 98%) were purchased from Aldrich. 4-Chloro-1,8-naphthalic anhydride(DHN) and dicoumarin (DIC) were purchased from Tianjin Heowns Biochemical Technology Co. Ltd. and used as received. Dimethyl formamide (DMF), analytical grade, and BDO were soaked with $CaCl_2$ overnight, refluxed with CaH_2, and then distilled under vacuum. All other chemicals or solvents were analytical grade and, if necessary, were dried according to the established procedures prior to use.

Synthesis of Fluorescent Compound HNHI

4-(2-Hydroxyethylamino)-1,8-naphthoyl-(2-hydroxyethyl)imide (HNHI) was synthesized following the method described by Patrick and Whiting.[36] The synthesis route is shown in Scheme 1(a). 4-chloro-1,8-naphthalic anhydride, hydroxyethylamine, triethylamine, and dimethylsulfoxide (DMSO) were placed in a 250 mL, three-necked, round-bottomed flask and heated to 130°C for 20 h. The solution was then allowed to cool, and water was added to the solution, and then a brown solid was precipitated. The solid was recrystallized from ethanol/dichloromethane (1/1, v/v) to yield the compound as a yellow solid. ν_{max}/cm^{-1} 3340 cm^{-1} (O—H/N—H), 1680 cm^{-1}, 1630 cm^{-1} (C═O); δ_H (400 MHz, $[CD_3]_2SO$), 3.36 (4H, 2 X CH_2OH), 3.47 (2H, t, $NHCH_2$), 3.70 (2H, t, $[CO]_2NCH_2$), 4.11 (2H, t, CH_2OH), 6.81 (1H, d, 3-H), 7.66 (1H, T, 6-H), 8.23 (1H, d, 2-H), 8.41 (1H, d, 7-H), 8.66 (1H, d, 5-H).

Synthesis of the PLGA-PEG-PLGA Diol

The following is a representative procedure for the synthesis of a PLGA-PEG-PLGA polyol. PEG1000 was charged into a three-necked 250 mL round-bottom flask equipped with a magnetic stirring bar, stirring at 120°C under vacuum for 2 h to eliminate a little of water. Then after cooling to room temperature, L-Lactide, glycolide, and $Sn(Oct)_2$ were added, respectively, and the reaction mixture was kept at 150°C for 8 h. The product PLGA-PEG-PLGA was dissolved in dichloromethane and precipitated into diethyl ether and dried in vacuum at 40°C for 48 h. The hydroxyl number of the obtained PLGA-PEG-PLGA is 58 mg KOH/g. The synthesis route is shown in Scheme 1(b).

Synthesis of PLGA-PEG-PLGA-Based TPUs (PLGUs)

The general synthesis procedure for PLGA-PEG-PLGA-based TPUs was as follows. A certain amount of PLGA-PEG-PLGA diol was dissolved in double volumes of DMF and heated at 65°C for 20 min. $Sn(Oct)_2$ (1.0% mole with respect to the PLGA-PEG-PLGA diol) in dried DMF and a given amount of IPDI were added to the solution. After 30 min of stirring at 65°C, BDO and fluorescent monomer were added. And the reaction mixture was stirred for another 6 h. The synthesis route is shown in Scheme 1(c). The synthesis product was isolated by the dissolution of the reaction mixture in chloroform, followed by precipitation in diethyl ether. Table I shows the formula of polyurethanes with different hard segment content or fluorescent monomers.

Degradation Test

The TPU films were prepared by solution casting. A 10% DMF solution of TPU was cast onto a polytetrafluoroethylene mold, kept at 60°C in oven for 24 h, and dried under vacuum at 40°C for 48 h. Hydrolytic degradation of the TPU films was carried out in PBS (pH = 7.4) at 37°C. The film samples (10 × 10 mm) were put into 50 mL conical flasks to which 10 mL PBS was added and then incubated with shaking for certain time at 37°C. After incubation, the films were taken out at predetermined time, rinsed thoroughly with distilled water, and dried in vacuum oven at room temperature to a constant weight. The degree of degradation was calculated by weight loss as follows: weight loss $(\%) = ((m_0 - m_t)/m_0) \times 100\%$, where m_0 and m_t represent the weight of film before and after degradation, respectively. Triplicate tests for each PLGU films were carried out to obtain the mean weight loss.

Water Uptake

The film samples (10 × 10 mm) were put into 50 mL conical flasks to which 10 mL PBS was added and then incubated with shaking for certain time at 37°C. After incubation, the films were taken out at predetermined time, surface water was wiped by filter paper. The water absorption amount was calculated as follows: water absorption $(\%) = ((m_2 - m_1)/m_1) \times 100\%$, where m_1 and m_2 represent the weight of film before and after immersed in water, respectively. Triplicate tests for each PLGU films were carried out to obtain the mean water absorption.

Measurements

FT-IR spectra were measured in the range from 4000 to 450 cm^{-1} with a Bio-Rad FTS-6000 (American) FT-IR spectrometer using KBr pellets.

Structures of the copolymers were determined by nuclear magnetic resonance (^1H NMR) spectra on a Varian UNITY-plus 400 spectrometer operated at 400 MHz with $CDCl_3$ as a solvent.

Molecular weights of the copolymers were measured on a gel permeation chromatograph (GPC) instrument (Equipped with Waters 2414 refractive index detector and Waters 1525 Binary HPLC Pump, using Waters styragel HT2, HT3, HT4 THF 7.8 × 300 mm^2 columns). Tetrahydrofuran (THF) was used as an

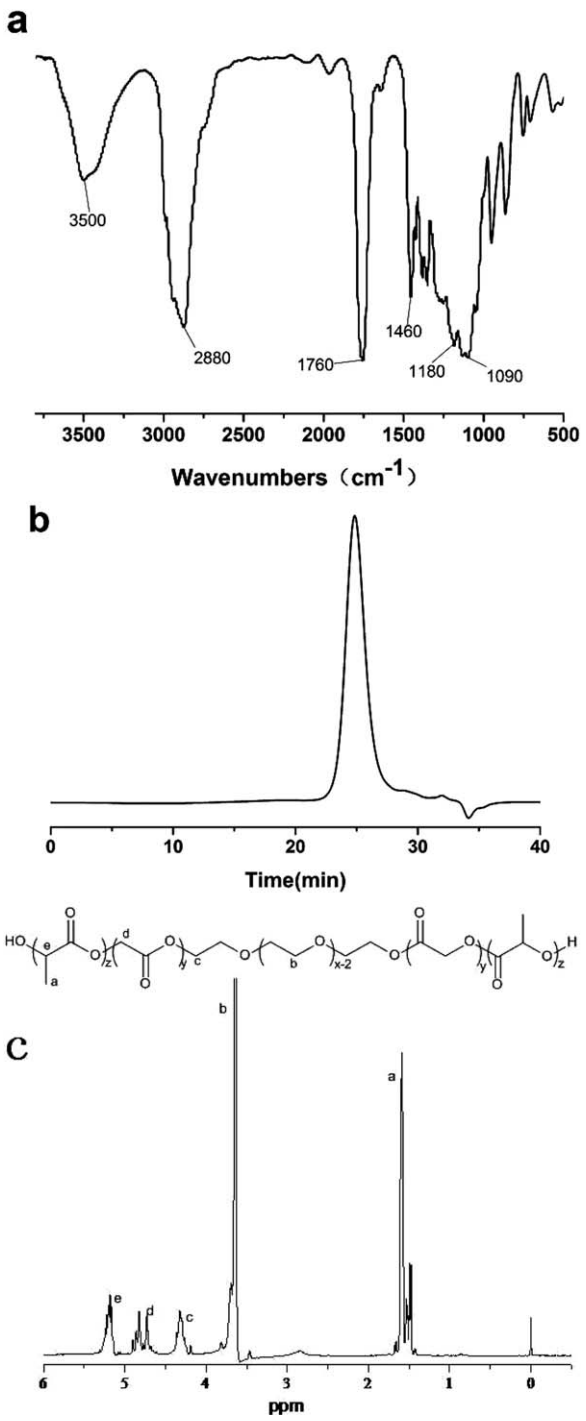


Figure 1. (a) FTIR, (b) GPC, and (c) ^{1}HNMR spectra of PLGA-PEG-PLGA.

eluent solvent and polystyrene standard samples were used to calibrate the results.

Differential scanning calorimetry (DSC) was carried out over a temperature range of −100 to 100°C with a NETZSCH DSC purged with nitrogen. The heating or cooling rate was 10°C/min. The T_g values were taken as the midpoints of the transition zones.

Table II. Molecular Weights, Compositions, and Dispersity Indices of the Copolymer

Triblock copolymer	^{1}HNMR		GPC		
	Mn	LA/GA	Mn	Mw	D
PLGA-PEG-PLGA	1900	3.0	2040	2238	1.097

The mechanical properties and the elasticity were determined with a Testometric tester (UK) at a draw rate of 100 mm/min at 23°C. Three dumb-bell-shaped specimens (effective dimensions: 12 mm long × 2 mm wide) of the same kind were tested to get mean values.

Fluorescence microscopy was carried out on OLYMPUS FV1000S - IX81 (Japan).

RESULTS AND DISCUSSION

Synthesis of PLGUs

At first, PLGA-PEG-PLGA triblock copolymer was synthesized via ring-opening polymerization of LA and GA (LA/GA = 3/1, mole/mole) in the presence of PEG1000 using $Sn(Oct)_2$ as a catalyst. We can see from IR spectrum of PLGA-PEG-PLGA in Figure 1(a) that the peaks at 3500 cm^{-1} (OH stretching) and 1760 cm^{-1} (C═O stretching) were observed. The peaks 2880, 1460, 1180, and 1090 cm^{-1} were corresponding to stretching vibrate of CH_2, C—C, C—O—C of PEG1000. The GPC profile and ^{1}H-NMR spectrum of PLGA-PEG-PLGA are shown in Figure 1(b,c). The ^{1}H-NMR peaks at δ_H = 1.5, 3.6, 4.8, and 5.2 ppm are assigned to the methyl hydrogen of the LA, methylene hydrogen of the PEG1000, methylene hydrogen of the glycolide units, and methine hydrogen of the LA units. This demonstrates that the terminal hydroxy polyester PLGA-PEG-PLGA was synthesized through a hydroxyl-bearing species initiating the lactone polymerization.[37] The number average molecule weight

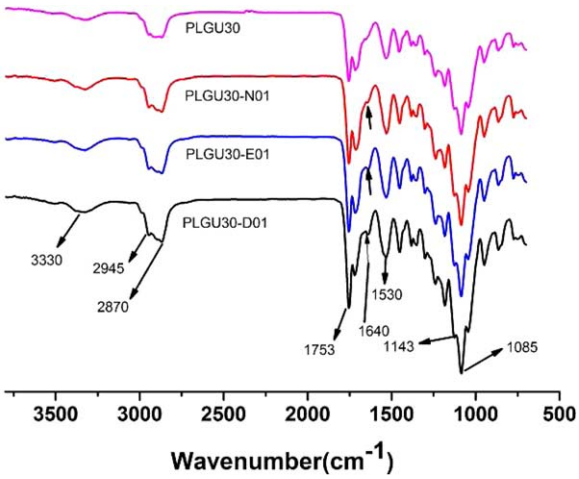


Figure 2. FTIR spectra of PLGU30, PLGU30-N01, PLGU30-E01, and PLGU30-D01. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

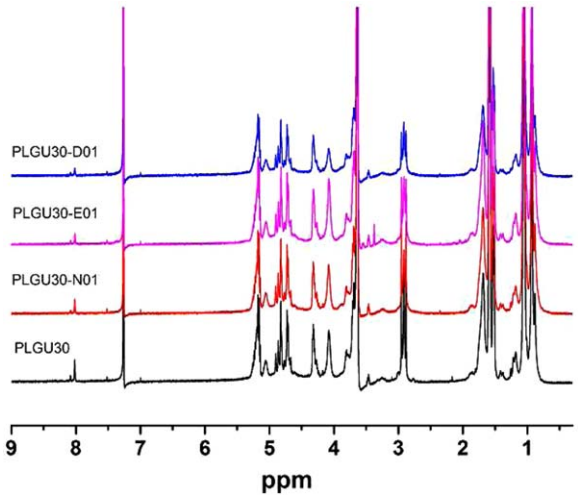


Figure 3. ^{1}H-NMR spectra of PLGU30, PLGU30-N01, PLGU30-E01, and PLGU30-D01. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

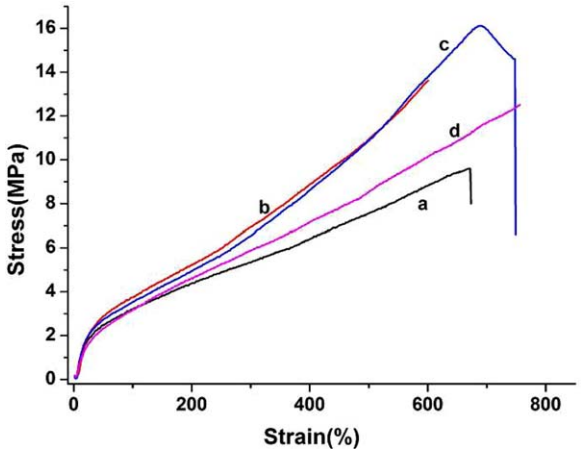


Figure 4. Tensile curves of TPUs: (a) PLGU30, (b) PLGU30-D01, (c) PLGU30-N01, and (d) PLGU30-E01. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

(Mn) of PLGA-PEG-PLGA triblock copolymer determined by the peaks of $\delta_H = 1.5$, 3.6, and 4.8 ppm is 1900. And the Mn and dispersity index measured by GPC are 2040 and 1.097 (as seen in Table II).

The polyurethane elastomers were synthesized with PLGA-PEG-PLGA as soft segments, IPDI as hard segment, and BDO as extension agent. The hard segment content was set as 30, 50, and 70, respectively, and the —NCO/—OH (mole/mole) value was set as 1.05 in this work. Three different fluorescent monomers—HNH1, DIC, and DHN—were introduced in the chain extension reaction stage for the elastomer systems with the 30% hard segment content. The FTIR spectra of the PLGU30, PLGU30-N01, PLGU30-E01, and PLGU30-D01 were shown in Figure 2. Compared with the IR spectrum (Figure 1a) of PLGA-PEG-PLGA, the peaks at 3500 cm^{-1} (OH stretching) disappeared, but a new band at 3330 cm^{-1} (NH stretching) can be observed. In the C═O stretching region, the 1760 cm^{-1} band for the PLGA-PEG-PLGA shifts to 1753 cm^{-1} as the hard segment content increases. A new band appears at 1640 cm^{-1} corresponds to PLGU30-N01, PLGU30-E01, PLGU30-D01 while it was not found in the IR spectrum of PLGU30, this is because of the addition of aromatic fluorescent monomers. The absence of an NCO peak at 2285–2250 cm^{-1} implies that the reaction has gone to completion. All these spectral changes provide convincing evidence for the formation of fluorescently labeled polyurethane.[38–40] Figure 3 shows the ^{1}H-NMR spectra of PLGU30, PLGU30-N01, PLGU30-E01, and PLGU30-D01. $\Delta = 8.0$ ppm was assigned to amino protons of NHCOO. The signals at 5.10, 4.80, 3.65, and 1.60 ppm were attributed to various protons belonging to PLGA-PEG-PLGA. The differences between polyurethanes with fluorescence monomers or not are very small because of very small content (0.001% wt) of fluorescent monomers in PLGU30-N01, PLGU30-E01, and PLGU30-D01. We can see from GPC results (Table III) that all polyurethanes have the similar number-average molecular weight around 10,000, and there is no significant effect in molecular weight with addition of small amount of fluorescent monomers. The molecular weight dispersity index of PLGUs range from 1.3 to 1.7 (Table III).[41,42]

Mechanical Properties and Thermal Properties

From the point of view of mechanical properties, the breaking strength and Youngs modulus of the TPU materials after introduction of fluorescent probe compounds have different degrees of improvement, and the elongation at break also have significant improvement except sample PLGU30-E01 (as seen in Figure 4 and Table IV), which shows that the mechanical performance of the material after introduction of fluorescent probe is slightly improved.

DSC curves of PLGU30, PLGU50, PLGU70, andPLGU50-D01 were collected in Figure 5. All these four species have obvious glass transition temperature at −2, 1.9, 28.2, and 1.2°C, respectively. From T_g of PLGU50 and PLGU50-D01, we can found that the addition of 0.001 wt % of DIC has no significant effect

Table III. Changes of Mn of PLGU30, PLGU30-D01, PLGU30-N01, and PLGU30-E01 Before and After Degradation

		Before degradation			After degradation (96h)		
Samples	Fluorescence (wt %)	Mn	Mw	D	Mn	Mw	D
PLGU30	0	9680	15,580	1.61	5981	8532	1.43
PLGU30-D01	DIC, 0.001	10,231	15,714	1.54	6320	9501	1.50
PLGU30-N01	HNHI, 0.001	10,258	17,784	1.73	6400	10817	1.69
PLGU30-E01	DHN, 0.001	11,229	18,700	1.67	6700	11526	1.72

Table IV. Mechanical Properties of TPUs

Samples	Fluorescence (wt %)	Tensile strength, MPa	Elongation at break, %	Youngs modulus, MPa
PLGU30	0	8.3 ± 1.8	533 ± 10	2.3 ± 0.6
PLGU50	0	11.2 ± 1.1	474 ± 15	6.2 ± 1.2
PLGU70	0	14.5 ± 1.2	277 ± 20	34.3 ± 4.0
PLGU30-D01	DIC, 0.001	8.5 ± 1.6	594 ± 10	4.1 ± 0.9
PLGU30-N01	HNHI, 0.001	8.8 ± 1.6	1110 ± 25	8.7 ± 2.1
PLGU30-E01	DHN, 0.001	10.0 ± 1.7	517 ± 15	6.8 ± 2.0

on T_g value of TPU. PLGA-PEG-PLGA macromolecular polyol is the soft segment and isocyanate and BDO are hard segments in the TPU system. Hard segments as the physical cross-linking point will serve as the increases of T_gs of the TPUs, which make polyurethane elastomer much tougher and elastic.

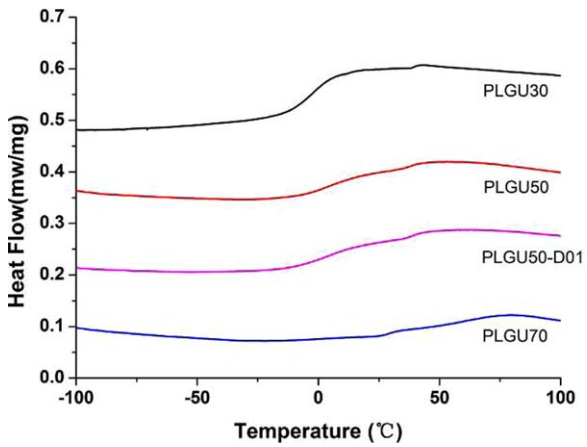


Figure 5. DSC curves of PLGU30, PLGU50, PLGU70, and PLGU50-D01. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Water Uptake and Hydrolytic Degradation Behavior

Degradability of polyurethane is dependent on the hydrolysis of ester bond in soft segment. As a result, water imbibition or water absorption ability of the material has a great influence on

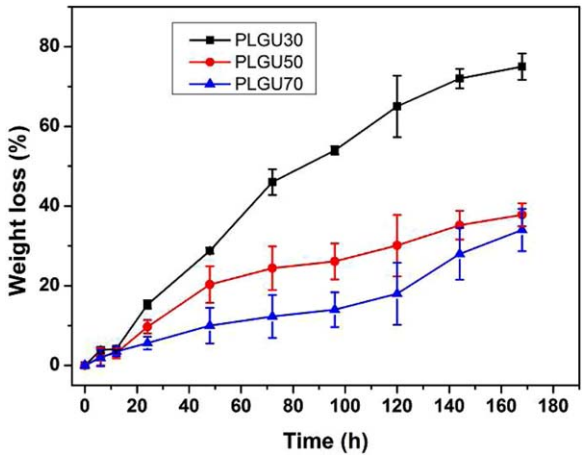


Figure 7. Weight losses of PLGU30, PLGU50, and PLGU70. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

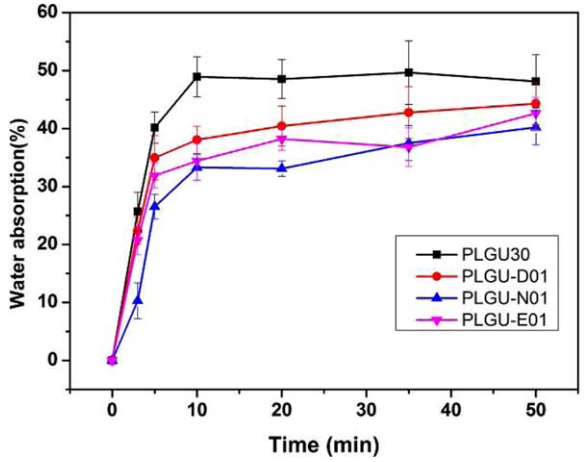


Figure 6. Water absorption over time curves of PLGU30, PLGU30-D01, PLGU30-N01, and PLGU30-E01. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

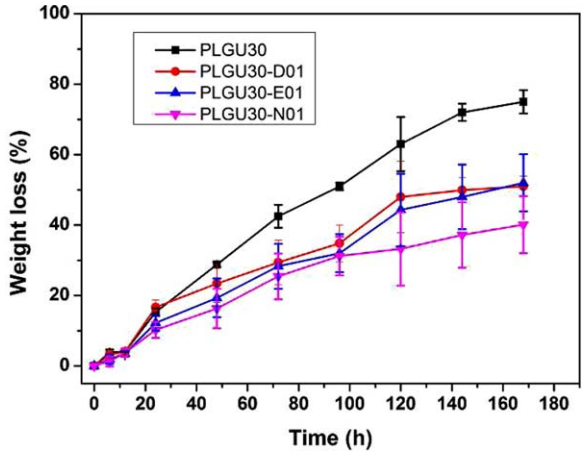


Figure 8. Weight losses of PLGU30, PLGU30-D01, PLGU30-E01, and PLGU30-N01. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

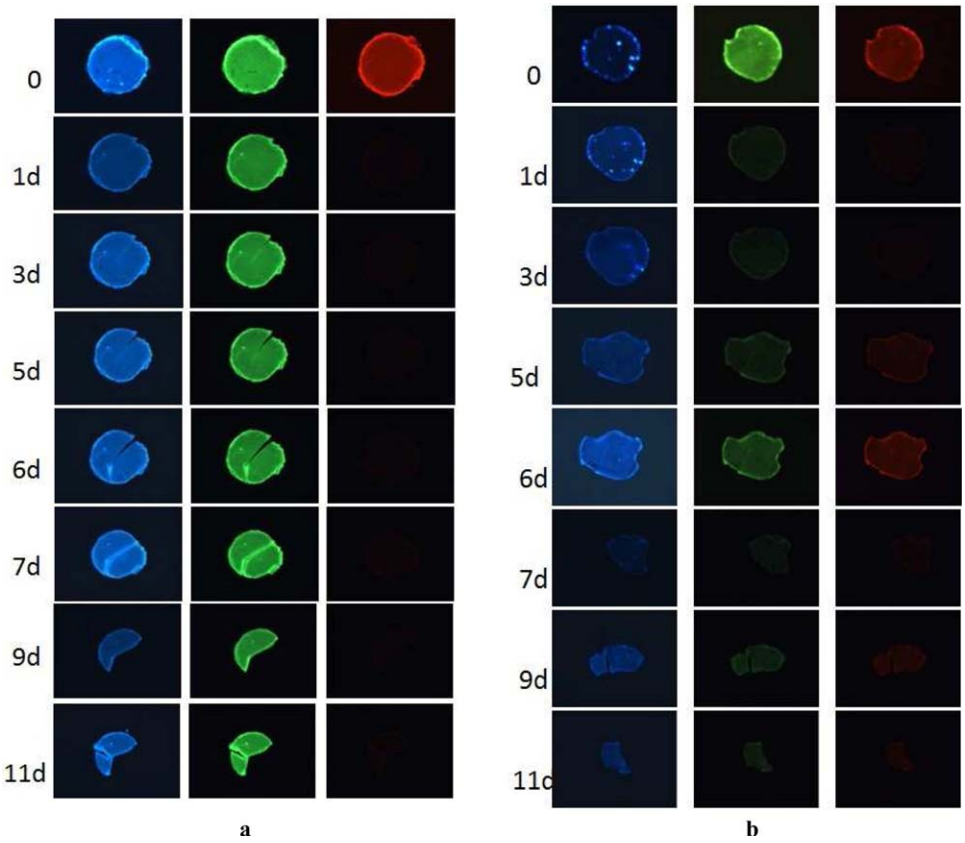


Figure 9. Fluorescence microscopy tracking in the process of degradation of (a) PLGU30-N01 and (b) PLGU30 blended with HNHI. Excitation light wavelengths of 395 nm (blue), 450 nm (green), and 525 nm (red). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the degradation performance. Water absorption test of the TPU films was carried out in PBS (pH = 7.4) at 37°C. As can be seen from Figure 6, water absorption initially increased rapidly in first 10 min, and then slowed down after 15 min, about 48, 44, 42, and 40% of water absorption were observed for PLGU30, PLGU30-D01, PLGU30-N01, and PLGU30-E01, respectively, finally. At the same time, water absorption of PLGU30 is larger than the other three samples introduced with fluorescent monomers. This is because the hydrophilicity of PLGU30-D01, PLGU30-N01, and PLGU30-E01 were reduced at some extent because of the addition of a small amount of hydrophobic fluorescent monomers. The thermoplastic elastomer prepared in this study contained PLGA fragments as the soft segment, which introduces the hydrolytic degradation ability to the system. The hydrolytic degradation rate under certain condition is related to the content of soft segment. Figure 7 illustrates the percent mass loss versus immersion time at 37°C of the TPUs with different soft and hard segment contents. We can see form Figure 7 that the weight losses within 12 h for three kinds of TPUs with different hard segment content were all less than 4%, and with extended time the weight loss increases. The weight loss increases fastest for PLGA30 sample, can reach 75.8% in 7 days, while only 37.7% for PLGU50, and the weight loss for PLGU70 is much lower. This demonstrates that the weight loss decreases with the increase of hard segment content of TPUs. This phenomenon indicates that the breakage of TPU chains starts from their soft segments. In addition, the hydrophilic PEG in the soft segments can uptake water, which makes the degradation fragments water soluble. And the higher the hard segment content, the slower the degradation rate, which is because of the weakened hydrophilicity.

As can be seen from Figure 8, PLGU30 demonstrated rapid degradation of 80% weight loss in 168 h, while PLGU30-N01, PLGU30-E01, and PLGU30-D01 with 0.001 wt % of HNHI, DHN, and DIC, respectively, have a smaller degradation rate, but did not differ much from each other. Compared with PLGA30, after the introduction of 0.001% fluorescent substance, the hydrolysis rate slowed significantly. And the impact on the degradation rate is not big between different kinds of fluorescent compounds. This indicates that fluorescent monomers are hydrophobic molecules, whose addition might weaken hydrophilic of polyurethane and make hydrolytic degradation rate decreased. The results showed that the addition of fluorescence monomers has a certain influence on the degradation rate of the polyurethane elastomers. But the fluorescent-labeled polyurethane elastomers still have a good degradability. As can be seen from Table III, before degradation, the number average molecular weight (Mn) of PLGU30, PLGU30-D01, PLGU30-N01, and PLGU30-E01 were 9680, 10,231, 10,258, and 11,229, respectively. After degradation for 96 h, Mn of PLGU30, PLGU30-

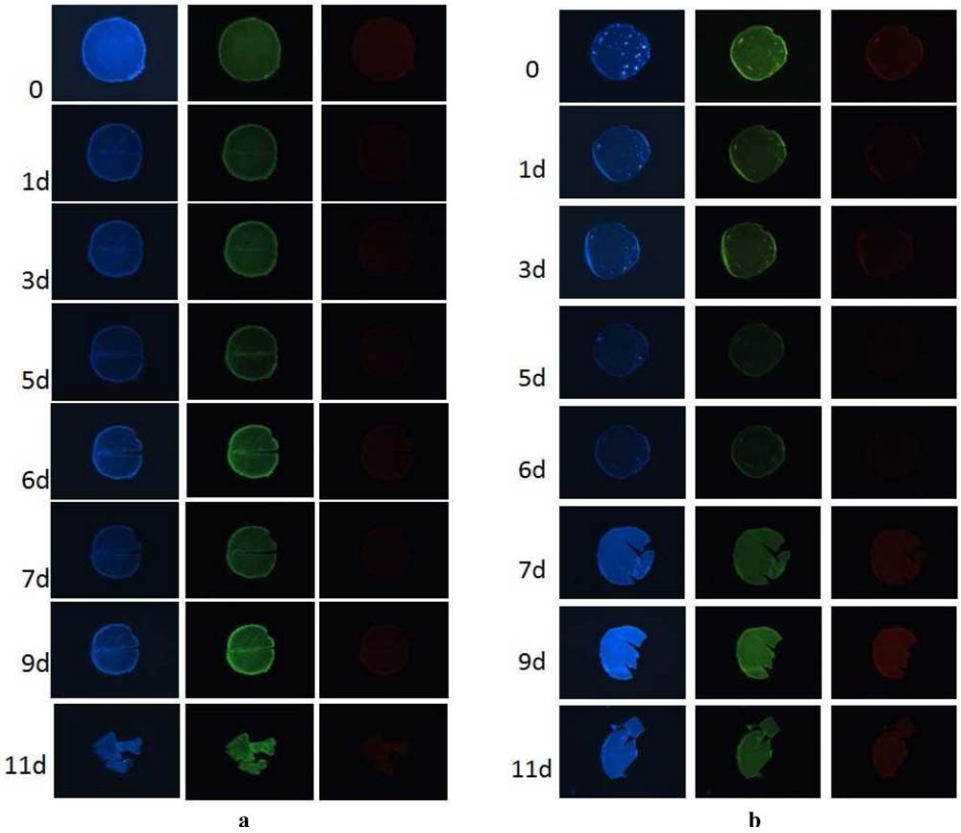


Figure 10. Fluorescence microscopy tracking in the process of degradation of (a) PLGU30-E01 and (b) PLGU30 blended with DHN. Excitation light wavelengths of 395 nm (blue), 450 nm (green), and 525 nm (red). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

D01, PLGU30-N01, and PLGU30-E01 were reduced to 5981, 6320, 6400, and 6700, respectively. As mentioned before, PLGU30, PLGU30-D01, PLGU30-N01, and PLGU30-E01 have good hydrophilicity because of a high content of PEG. When the samples were immersed in PBS, large amounts of water molecules diffused into the bulk of the materials that resulted in cleavage of the ester bond, and then the macromolecules were broken up into small molecules. In all cases, the incorporation of PLGA-PEG-PLGA into the TPU formulation will enhance the hydrolytic degradation. Fluorescent-labeled degradable TPU still has good hydrophilic degradability, which is the precondition for monitoring degradation process of degradable TPUs by fluorescence microscopy.

Degradation Behavior Tracking by Fluorescence Microscopic Image

Since when the hard segment content is 30%, the degradation performance of TPU sample is superior to that of 50% and 70%. Thus, in this work, we choose TPU samples with 30% of the hard segment content, the fluorescent tagged samples were coated to prepare the film samples. And at the same time, as a control in the preparation of different fluorescent monomer tagged films, the blend films were also prepared only through mix coating of fluorescent monomer and TPU with the same fluorescent monomer content. Their degradable behavior was observed by fluorescence microscopy. The obtained fluorescence imaging changes before and after degradation of the samples were shown in Figures 9–11.

As can be seen from Figure 9, blue, green, and red are the fluorescent images of the resulting samples under different excitation light wavelengths of 395, 450, and 525 nm. All the samples have relatively strong fluorescent intensity under 395 and 450 nm excitation light. Compared with the work of fluorescent compounds introduced in the process of synthesis of TPU, there is non-uniformity phenomena of the fluorescence intensity for the blend films prepared by solution blending of three kinds of fluorescent compounds with TPUs. This may be attributed to the crystallization aggregation of the fluorescent compounds because of thermodynamic incompatibility of polyurethane and fluorescent compounds in the film forming process, which makes the hydrophilic small fluorescent molecule crystallized from polyurethane macromolecular, and then aggregation occurs. Generally speaking, the fluorescent monomer chemically bonded into the polyurethane distribute uniformly in the film resulting in the well-distributed of the fluorescence intensity (as seen from Figures 9–11(a)). For fluorescent monomers HNHI and DHN, introduced to TPUs by chemical method, the fluorescence radiation uniformity is obviously better than that of the hybrid method. And for the fluorescent monomer DIC, though the fluorescent uniformity of TPU is still visible in combination with chemical method, it is introduced into slightly

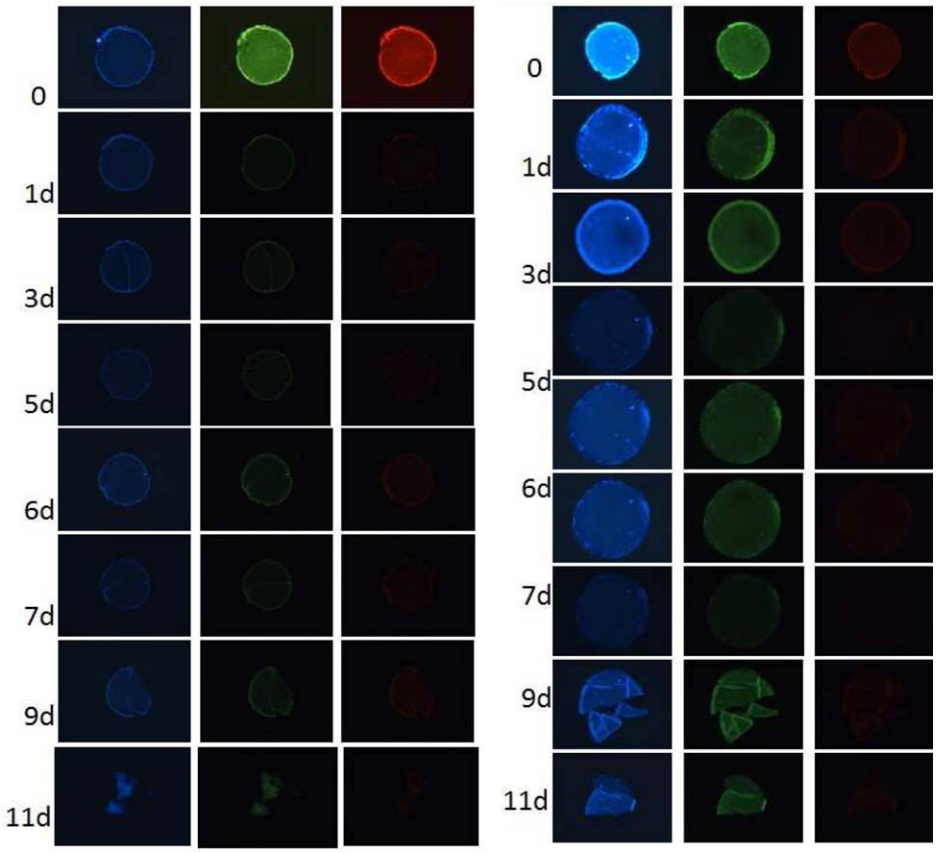


Figure 11. Fluorescence microscopy tracking in the process of degradation of (a) PLGU30-D01 and (b) PLGU30 blended with DIC. Excitation light wavelengths of 395 nm (blue), 450 nm (green), and 525 nm (red). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

better than blending method, but the difference is not obvious, which also illustrates that there are some difference around the fluorescent monomers used in this work on the compatibility with PU system, the compatibility between DIC and PU is better than the former two.

Before degradation, all the samples were relatively regular round and strong fluorescence intensity was obviously observed under excitation wavelength of 395 and 450 nm. After culturing at 37°C for 3 days, obvious cracks generated on the surface of the films, with around 5 days of incubation time, the cracks gradually expanded, the films were fragmented to two pieces, the sample was completely lost its shape, and broken up into small irregular pieces at last, and there are many smaller fragments of the material suspended in the degradation medium. During the degradation process of the samples, PLGU30-N01, PLGU30-E01, and PLGU30-D01 maintained relatively stable fluorescence intensity, while for the blending films of PLGU30 with fluorescent monomers, the uniformity of the fluorescence intensity seems to be worse (as seen from Figures 9–11(b)).

CONCLUSIONS

Degradable thermoplastic polyurethane elastomers were widely used in biomedical field, because of good biocompatibility, excellent mechanical properties, and molecular design flexibility. In this work, we synthesized degradable thermoplastic polyurethane elastomers with isophorone diisocyanate (IPDI), poly-lactic-co-glycolic acid (PLGA-PEG-PLGA) diol, and 1,4-butanediol(BDO). During the process of chain extension, 4-(2-hydroxyethylamino)-1,8-naphthoyl-(2-hydroxyethyl)imide (HNHI), 1,5-dihydroxy naphthalene, and dicoumarin were introduced respectively. There was no significant effect found in average molecular weight, glass transition temperature, and somewhat improvement for mechanical properties of polyurethane by introducing 0.001 wt % of fluorescent monomers. The materials were observed by fluorescence microscope under 395 nm light with stable blue fluorescence intensity. Fluorescence images change showed that degradable polyurethane in which fluorescence monomers, especially HNHI, were introduced by chemical reaction had more homogeneous and stable fluorescence intensity than polyurethane with fluorescence monomer blends. TPU is widely used on tissue engineering materials in the body, the degradation behavior of in-situ tracking in the body is of great significance. This work demonstrated a new characterization approach that can be more promising to monitor degradation behavior of degradable thermoplastic polyurethane elastomers used for soft tissue engineering or drug delivery system.

ACKNOWLEDGMENTS

The authors were grateful to Doctoral Fund of Ministry of Education of China (RFDP, Proj. No. 20130031110012), PCSIRT (IRT1257), and NFFTBS (No. J1103306) for financial support.

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