

# Radiation-Induced Grafting of Pentamethyl Hindered Amine Light Stabilizer 1,2,2,6,6-Pentamethyl-4-piperidinyl Methacrylate onto Polypropylene

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**ABSTRACT:** The  $\gamma$ -radiation-induced grafting of 1,2,2,6,6-pentamethyl-4-piperidinyl methacrylate (PMPM) onto polypropylene (PP) was investigated with a simultaneous irradiation technique. The effects of the solvent, dose, monomer concentration, and photoinitiator on the grafting were investigated. The grafting was easier in a benzene solution than in chloroform and acetone solutions. The grafting percentage first increased almost linearly with the irradiation dose until 20 kGy and then increased slowly or remained constant. The grafting percentage increased with the monomer concentration until 1.1 mol/L. The grafting percentage was higher when the proper amount of benzophenone was added. The

grafted samples were characterized with Fourier transform infrared spectroscopy and thermogravimetric analysis. Carbonyl groups were found on grafted PP samples, and the carbonyl index increased with the grafting percentage. Thermogravimetric analyses proved the existence of grafted materials on PP, and grafted PMPM thermally decomposed at a lower temperature than PP. The radiation resistance of PP with grafted PMPM was better than that of pristine PP. © 2005 Wiley Periodicals, Inc. *J Appl Polym Sci* 98: 2157–2164, 2005

**Key words:** graft copolymers; HALS; poly(propylene) (PP); radiation

## INTRODUCTION

Polypropylene (PP) has been widely used to produce medical devices, such as disposable syringes. However, PP is particularly sensitive to high-energy radiation during  $\gamma$ -ray or electron-beam radiation sterilization, which is becoming more popular. Therefore, it needs to be stabilized before use.<sup>1–3</sup>

Hindered amine light stabilizers (HALSs) are the most effective existing light stabilizers protecting polyolefins and other polymers from light-induced degradation,<sup>4–6</sup> and they are also very effective in protecting PP from degradation induced by high-energy irradiation.<sup>7,8</sup> The stabilizing effectiveness of HALSs is strongly affected by its physical properties, such as its thermal stability in thermal processing, solvent extraction resistance, and compatibility with the polymer to be protected. A polymeric HALS usually has better stabilizing effectiveness than a low-molecular-weight (LMW) HALS<sup>9,10</sup> because the former has much better thermal stability and solvent extraction resistance than the latter. However, the stabilizing effectiveness of a polymeric HALS is restricted by its poor compatibility with the polymer to be protected. An alternative approach to using a poly-

meric additive is to graft a stabilizer onto the polymer substrate.<sup>11</sup> This method can improve the compatibility of a stabilizer with polymers and overcome the volatility problems. Allmer et al.<sup>12</sup> photografted glycidyl acrylate onto a polymer and then made it react with a hindered amine with a primary amine group, thus attaching the HALS onto the polymer. Ekman et al.<sup>13</sup> first grafted *m*-isopropenyl- $\alpha,\alpha$ -dimethyl benzyl isocyanate and styrene onto PP, and then the isocyanate moiety of the graft copolymer was allowed to react with the HALS 4-amino-2,2,6,6-tetramethyl piperidine. Minto et al.<sup>14</sup> grafted succinic anhydride groups onto selected polyphosphazenes, and this was followed by the reaction of the functionalized phosphazene substrates with amino-terminated HALS groups.

Radiation grafting is a powerful method for modifying more profoundly the properties of a polymer and for creating numerous, entirely new materials. The chemical modification can be applied to the bulk of the material or limited to a surface zone of any desired depth.<sup>15,16</sup> A great number of vinyl monomers have been grafted onto PP by  $\gamma$  radiation.<sup>17–22</sup> The author reported the grafting of HALS monomer 2,2,6,6-tetramethyl-4-piperidinyl methacrylate (TMPM) directly onto PP by  $\gamma$  irradiation, and it was found that the grafted HALS had higher stabilizing efficiency than LMW HALS.<sup>23</sup> Pentamethyl HALS was more effective in protecting the polymer from photodegra-

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dation and radiation-induced degradation.<sup>24</sup> This article presents the radiation-induced grafting of penta-methyl HALS 1,2,2,6,6-pentamethyl-4-piperidiny methacrylate (PMPM) onto powdered PP by simultaneous irradiation techniques with  $\gamma$  rays. The grafted samples were characterized with Fourier transform infrared (FTIR) and thermogravimetry (TG). In addition, the stabilizing effectiveness of grafted PMPM in the radiation-induced degradation of PP was measured.

## EXPERIMENTAL

### Materials

Powdered PP was supplied by Anqing Petrochemical Factory (Anhui, China); its melt flow index was 1.8 g/10 min. It was Soxhlet-extracted with chloroform for 48 h to remove impurities and additives before use. PMPM and the homopolymer of PMPM [poly(1,2,2,6,6-pentamethyl-4-piperidiny methacrylate) (PPMPM)] were synthesized by the authors.<sup>24</sup> All the reagents were analytical-reagent-grade.

### Radiation source

The irradiation of the samples was carried out in a  $^{60}\text{Co}$  ( $3.7 \times 10^{14}$  Bq)  $\gamma$  chamber at room temperature. All the samples were irradiated with different doses at a dose rate of 12 kGy/h; the dose rates were determined with a Fricke dosimeter.

### Grafting procedure

Grafting was carried out in a test tube in air. Weighed amounts of powdered PP and the monomer(s) were put into the test tube, and then the solvent was added; the mixture was left for 24 h to attain the equilibrium swelling of the powder. The tube was placed in the radiation chamber at a suitable distance and height for a desired period. Then, the polymerization was terminated by the addition of a large volume of acetone to the reaction mixture. The whole mass was filtered and washed with acetone. The residual monomer and homopolymer were removed by Soxhlet extraction with chloroform for 24 h. The graft copolymer was dried to a constant weight *in vacuo* at 50°C.

The grafting percentage was calculated as follows:

$$\text{Grafting (\%)} = \frac{W_g - W_0}{W_0} \times 100$$

where  $W_g$  and  $W_0$  are the weights of powdered PP after and before grafting, respectively.

### FTIR characterization

The pristine and grafted PP samples for FTIR analysis were hot-pressed to thin films with a thickness of about 0.1 mm. FTIR spectra were obtained with an Avatar 360 spectrometer made by Nicolet Instruments Corp. (Madison, WI).

The carbonyl index (CI) was used to study the grafting semiquantitatively; it was calculated by the following equation:

$$\text{CI} = A_{\text{C=O}} / A_{\text{C-H}}$$

where  $A_{\text{C=O}}$  is the absorbance of the carbonyl C=O stretching vibration peak at about  $1723 \text{ cm}^{-1}$ , which is the characteristic peak of the carbonyl group in PMPM, and  $A_{\text{C-H}}$  is the absorbance of the C-H stretching of the  $-\text{CH}_3$  group in PP at  $2722 \text{ cm}^{-1}$ , which was used as the internal standard peak. These peaks were autobaselined before the absorbance was calculated.

### Thermogravimetric analyses

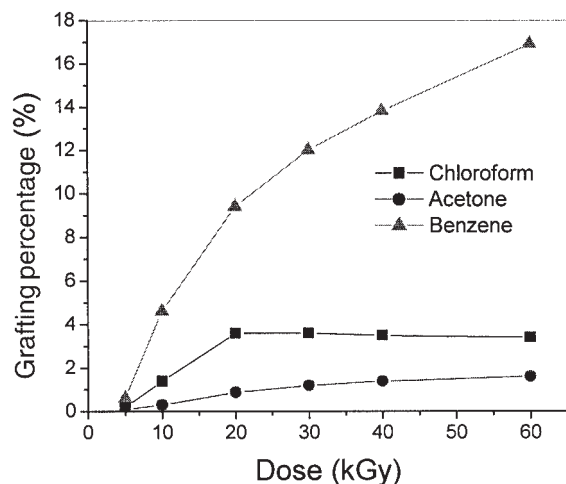
The samples for thermogravimetric analysis were dried before use. Thermogravimetric analyses were carried out in a TG 50 apparatus of a TA-3000 thermoanalysis system (Mettler, Zürich, Switzerland). The purge gas was  $\text{N}_2$ , the flow rate was 10 mL/min, and the heating rate was 20°C/min. The TG and differential thermogravimetry (DTG) curves of the samples were obtained. The relative thermal stability of the pristine and grafted PP samples was evaluated by a comparison of decomposition temperatures  $T_s$ ,  $T_p$ , and  $T_e$ , where  $T_s$ ,  $T_p$ , and  $T_e$  are the temperatures at which the samples start to decompose, the samples decompose at the fastest rate, and the decomposition ends, respectively.

### Preparation of the samples for the test of the elongation at break (Eb)

The graft copolymer and other additives were mixed with powdered PP, extruded at  $200 \pm 5^\circ\text{C}$ , heated at  $190 \pm 5^\circ\text{C}$  for 6 min, molded under a pressure of  $1.47 \times 10^7$  Pa for 4 min, and quenched immediately in tap water. The samples were punched into dumbbell shapes with a neck of 1 mm (thickness)  $\times$  3 mm (width). All the PP samples were irradiated with different doses at a dose rate of 12 kGy/h in air at room temperature.

### Test of Eb

The radiation resistance of the tested samples after irradiation was evaluated by the Eb value. The higher Eb value of the PP sample at a given dose shows the



**Figure 1** Grafting percentage as a function of the irradiation dose for the grafting carried out in acetone, chloroform, and benzene.

higher radiation resistance of PP. The stress-strain measurements of the dumbbell samples, before and after different doses of irradiation, were performed at a crosshead speed of 50 mm/min. The average Eb value of five samples was taken as the resultant value.

## RESULTS AND DISCUSSION

### Grafting of PMPM onto PP

Effect of the solvent and dose on grafting

About 0.5 g of PP, 0.2 mL of PMPM, and 1 mL of the solvent were used in each experiment.

Figure 1 shows that the grafting of PMPM onto PP carried out in benzene, chloroform, and acetone. Similar to the grafting of TPM on PP,<sup>23</sup> the radiation grafting of PMPM onto PP was highly dependent on the nature of the solvent. The grafting was much easier in benzene than in chloroform and acetone. At the same irradiation dose, the grafting percentage was highest when the grafting was carried out in benzene, whereas the grafting percentage was very low when acetone was used as the solvent.

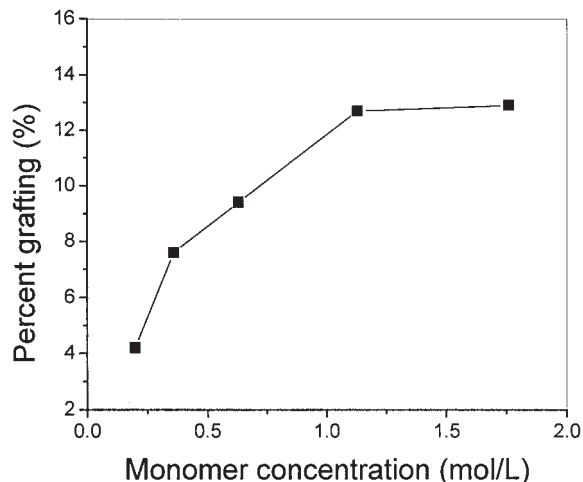
The solvent may play a more important role in radiation-induced grafting than in photografting. Because of the high energy of <sup>60</sup>Co  $\gamma$  rays (1.25 MeV), no solvent is stable under them. Therefore, the stability of a solvent under  $\gamma$  irradiation becomes an important factor affecting the radiation grafting. Benzene is a very stable reagent because of its  $\pi$ -bond structure, which can disperse radiation energy. Therefore, the free-radical yield of benzene is quite low and leads to the low degree of homopolymerization of PMPM. The stability of chloroform under  $\gamma$  irradiation is between that of benzene and that of acetone. Acetone is very unstable under  $\gamma$  irradiation; it can split directly and

form acetyl, methyl, and some other free radicals, and it can also be excited by absorbing irradiation energy to a excited state with enough energy to split and form free radicals or abstract a hydrogen atom from a nearby monomer or polymer molecule. These free radicals can recombine to form inactive products, initiate the homopolymerization of the monomer, or terminate the growing grafting or homopolymerizing chains. Commonly, more homopolymers can be formed if there are more free radicals in the solution. However, this is not true for grafting in acetone, for which the conversion of the PMPM monomer to the grafted polymer or homopolymer was very low (<5%) even after 60 kGy of irradiation. This occurred because that there were too many free radicals formed, and the growing grafting or homopolymerizing chains were terminated by small free radicals quickly after they were formed.

The swelling ability of a solvent for PP may be the other important factor affecting grafting. PP is a non-porous material and swells to some extent in organic solvents. Many solvents were used in grafting experiments to enhance the accessibility of the monomer to grafting sites within the polymer. A period of 24 h was used in our experiments to ensure equilibrium swelling. White, powdered PP became semitransparent when benzene and chloroform were used as solvents, but this phenomenon was not observed in acetone. This showed that the degree of the swelling of PP was much higher in benzene and chloroform in comparison with acetone.

As shown in Figure 1, for all the grafting copolymerizations carried out in the three solvents, the grafting percentage first increased quickly and almost linearly with the irradiation dose until 20 kGy and then increased slowly or even remained constant. For the grafting carried out in benzene, the grafting percentage increased quickly from 0.6% at 5 kGy to 9.4% at 20 kGy; it reached 16.9% after 60 kGy of irradiation. For grafting carried out in chloroform, the grafting percentage reached 3.6% at 20 kGy and remained constant. For grafting carried out in acetone, the grafting percentage increased quickly from 0.1% at 5 kGy to 0.9% at 20 kGy and then increased slowly to 1.6% at 60 kGy.

In the initial stage of polymerization, the monomer can diffuse easily to the active sites on powdered PP, and the grafting copolymerization can take place smoothly. However, with an increase in the irradiation, more homopolymers are formed, the viscosity of the reaction solution becomes higher, and the homopolymer acts as a barrier against the monomer reaching the grafting sites on PP. This can result in a decrease in grafting and an increase in homopolymerization.



**Figure 2** Grafting percentage as a function of the monomer concentration (irradiation dose = 20 kGy).

#### Effect of the monomer concentration on grafting

The effect of the monomer concentration on the grafting percentage of PMPM onto PP was studied with about 0.5 g of PP, 0.05–0.8 mL of PMPM, and 1 mL of benzene at an irradiation dose of 20 kGy, as shown in Figure 2.

According to Figure 2, the grafting percentage increased quickly with the monomer concentration up to 1.1 mol/L and then remained almost constant.

As a general rule, the grafting reaction rate increases with an increase in the monomer concentration. From the point of view of the kinetics of free-radical polymerization, the propagation rate of grafting chains ( $R_p$ ) can be expressed as follows:

$$R_p = k_p[M\cdot][M]$$

where  $k_p$  is the rate constant of propagation,  $[M]$  is the monomer molar concentration, and  $[M\cdot]$  is the concentration of primary free radicals formed on the PP surface.

The concentration of macromolecular free radicals formed on the PP surface, which can initiate grafting, is dominated by the radiation dose rate.  $[M\cdot]$  should be the same in all the experiments. Then,  $R_p$  is decided by  $[M]$  and  $k_p$ . When the reaction temperature is the same,  $k_p$  is a constant, and then  $R_p$  is proportional to  $[M]$ . So when  $[M]$  is higher, then  $R_p$  is higher too:

$$R_p \propto [M]$$

The grafting percentage should be proportional to  $R_p$  and the reaction time  $t$ . Therefore, at the same irradiation time, the grafting percentage should be proportional to  $[M]$ . When  $[M]$  was less than 0.36 mol/L, the grafting percentage increased linearly with the mono-

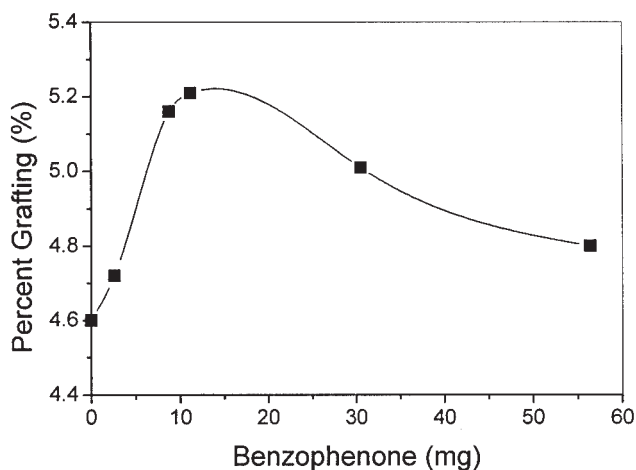
mer concentration. This result confirmed the previous deduction.

However, with an increase in the monomer concentration, the grafting percentage did not increase linearly with the monomer concentration anymore. When the monomer concentration was more than 1.1 mol/L, the grafting percentage did not increase any further. The obtained grafting percentage was much lower than that extrapolated from the grafting percentages obtained when the monomer concentration was less than 0.36 mol/L. The low grafting percentage was caused by the homopolymerization of the monomer. PMPM is unstable under  $\gamma$  irradiation, and several kinds of free radicals can be produced. These free radicals can terminate the propagation of grafting chains, and it leads to a low grafting percentage; in addition, they can initiate the homopolymerization of PMPM. More free radicals are formed with an increase in the monomer concentration, and hence more homopolymers are produced. Because of the consumption of the monomer for homopolymerization and the increase in the viscosity of the solution, the monomer that can be used for grafting becomes less and less. The actual monomer concentration for grafting is much lower than the initial concentration. This is possibly the reason for the grafting percentages being lower than expected when the monomer concentration was higher.

#### Effect of the photoinitiator on grafting

About 0.5 g of PP, 0.2 mL of PMPM, and 1 mL of benzene were used in each experiment. The irradiation dose was 10 kGy.

Figure 3 shows the effect of benzophenone (BP) on the radiation grafting of PMPM onto PP. BP had little effect on the radiation grafting of PMPM onto PP. At



**Figure 3** Grafting percentage as a function of the amount of photoinitiator BP added.

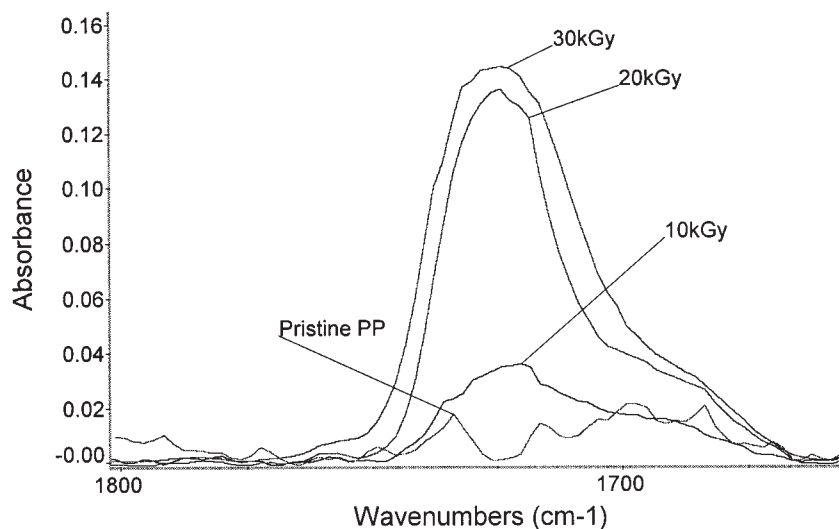


Figure 4 FTIR spectra of pristine PP film and PP film irradiated with different doses.

the same irradiation dose, the grafting percentage first increased and then decreased with the amount of BP added to the grafting system. The grafting percentage was highest when about 15 mg of BP was added.

A photoinitiator is usually not required in radiation-induced grafting; high-energy irradiation acts as a photoinitiator itself. BP is a photoinitiator commonly used in photografting. It absorbs UV light in the range of 200–360 nm. When BP absorbs a UV photon, it is excited to a short-lifetime singlet state and then relaxes to a more stable triplet state. BP in the triplet state can abstract a hydrogen atom from a polymer substrate (PH) and create an active site for surface graft polymerization. In this work, however, it cannot function as that under UV light. As is well known, excited state(s) or superexcited state(s) of molecules can be formed under high-energy irradiation. Possibly, the energy of the excited state(s) of the monomer or solvent molecules can be transferred to BP, and then BP is excited to a singlet state and relaxes to a triplet state. BP in a triplet state abstracts hydrogen from the PP surface and forms a macromolecular free radical that can initiate the grafting of PMPM onto PP. Therefore, more grafting occurs on the PP surface. However, the excited BP can also abstract hydrogen even from the monomer molecule and lead to the homopolymerization of PMPM. In addition, the hydrogen free radicals that form and the growing homopolymer free radicals can terminate the propagation of grafting chains. These factors have a negative effect on grafting. Therefore, a proper BP concentration is very important to balance the positive and negative effects.

#### FTIR characterization

The grafting of PMPM onto PP was confirmed by FTIR spectroscopy, as illustrated in Figure 4. Because of the

oxidation of PP in thermal processing and storage, the FTIR spectrum of pristine PP has a very weak absorption band near  $1733\text{ cm}^{-1}$ , which is the characteristic absorption band of the carbonyl group ( $\text{C}=\text{O}$ ). In the FTIR spectra of the grafted samples, a strong absorption band at about  $1723\text{ cm}^{-1}$  appears, which is similar to the absorption band at  $1715\text{ cm}^{-1}$  of the carbonyl group in PMPM. The absorbance of the absorption band increased with the irradiation dose. The results demonstrate that PMPM was successfully grafted onto PP.

The calculated CIs of the PP samples irradiated with different doses are shown in Figure 5.

The tendency of the increase in CI with the irradiation dose is very similar to that of the increase in the grafting percentage with the dose, as shown in Figure 1. CI of the grafted PP samples increased with the

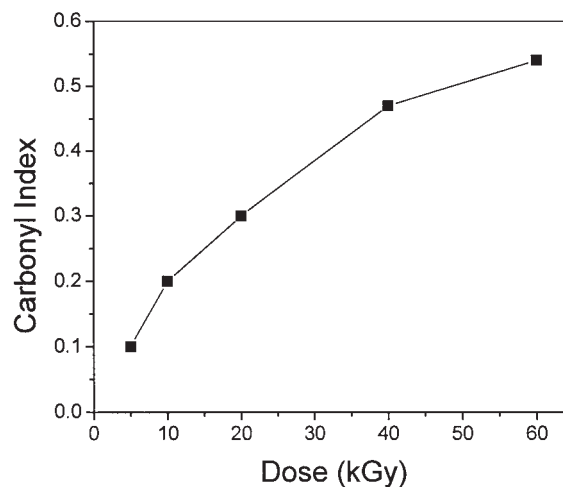


Figure 5 CI of the grafted samples as a function of the irradiation dose.

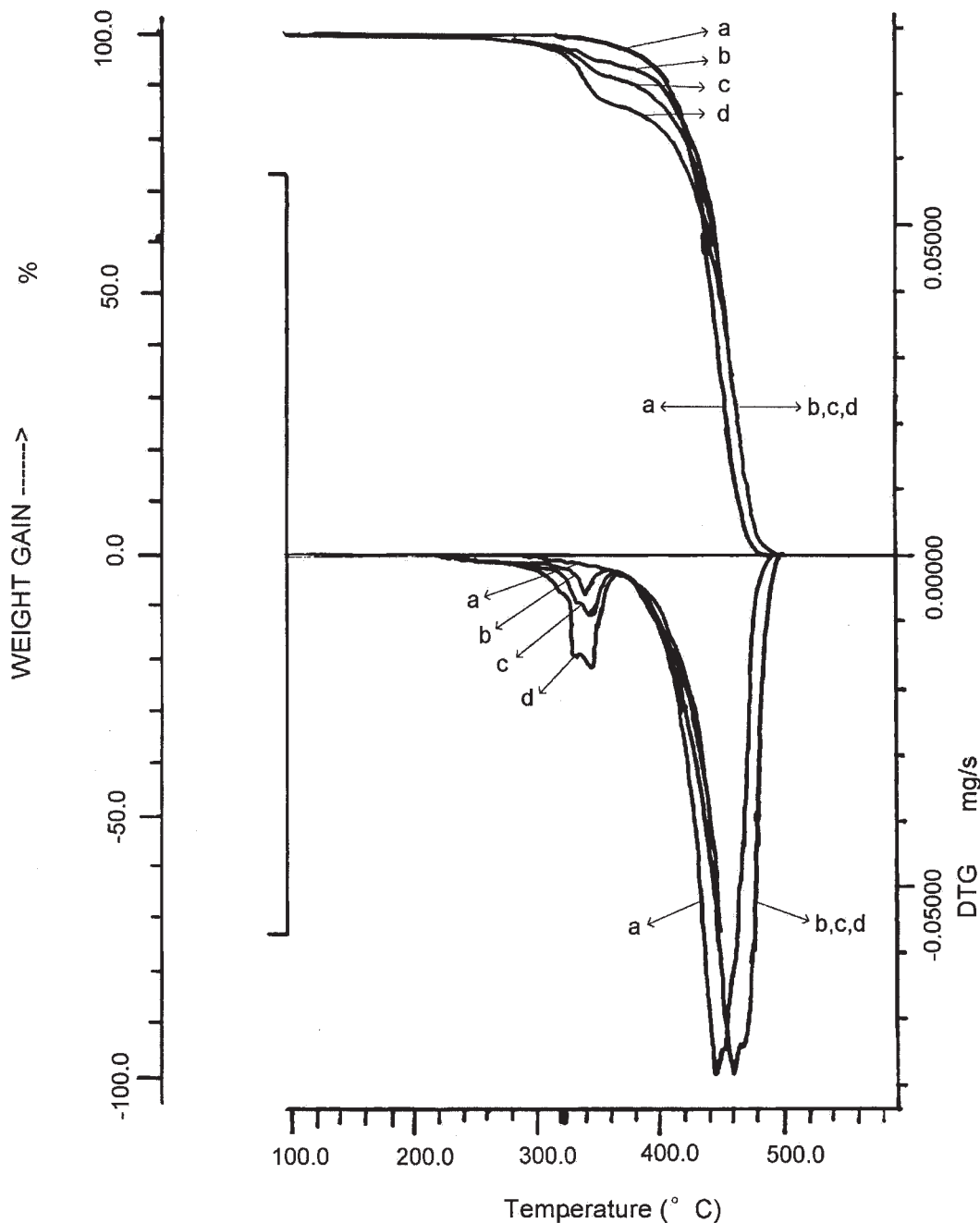


Figure 6 TG and DTG curves of (a) pristine PP and (b–d) PP samples grafted with 5.4, 9.4, and 16.9% PMPM, respectively.

irradiation dose until 60 kGy. The increase in CI was faster at lower irradiation doses.

#### Thermogravimetric analysis of grafted PMPM

The TG and DTG curves of pristine PP and PP grafted with PMPM are shown in Figure 6. The thermogravimetric analysis results of pristine PP and three PP samples grafted with PMPM are listed in Table I.

There is only one decomposition peak in the DTG curve of pristine PP;  $T_s$  is 304°C,  $T_p$  is 460°C, and  $T_e$  is

TABLE I  
 $T_s$ ,  $T_p$ , and  $T_e$  of the Pristine and Grafted PP Samples

Sample	Peak 1			Peak 2		
	$T_s$	$T_p$	$T_e$	$T_s$	$T_p$	$T_e$
Pristine PP				304	460	500
PPMPM	159	336	485			
5.4%	213	342	360	360	464	502
9.4%	222	345	364	364	461	501
16.9%	225	345	367	367	459	502

500°C. The TG and DTG curves of PPMPM were obtained previously. There is only one decomposition peak in the DTG curve of PPMPM too;  $T_s$  is 159°C,  $T_p$  is 336°C, and  $T_e$  is 485°C. However, there are two decomposition peaks in the DTG curves of the PP samples grafted with PMPM. For the sample grafted with 5.4% PMPM, in the first decomposition peak,  $T_s$  is 213°C,  $T_p$  is 342°C, and  $T_e$  is 360°C; in the second decomposition peak,  $T_s$  is 360°C,  $T_p$  is 464°C, and  $T_e$  is 502°C.  $T_p$  and  $T_e$  in the second decomposition peak are almost the same as those of pristine PP. Therefore, the second decomposition peak can be attributed to the decomposition of PP.  $T_p$  in the first decomposition peak is very similar to that of PPMPM. Therefore, the first decomposition peak should be attributed to the decomposition of grafted PMPM. The material loss of the first decomposition peak obtained from step analysis is 4.9%, which is a little lower than the grafting percentage (5.4%) obtained by the weighing of this sample. This further proves that the first decomposition peak can be attributed to the decomposition of grafted PMPM. Similarly, for other grafted samples tested, the first decomposition peak can be attributed to the decomposition of grafted PMPM, and the second one can be attributed to the decomposition of PP.

There is an increase in  $T_p$  and  $T_e$  of the thermal decomposition of grafted PMPM with an increase in the grafting percentage. The  $T_p$  values of the samples grafted with 5.4, 9.4, and 16.9% PMPM are 342, 345, and 345°C, respectively, and the  $T_e$  values of these samples are 360, 364, and 367°C, respectively. Therefore, the thermal stability of grafted PMPM increases with the grafting percentage. The reason is still unknown. It is possibly caused by the grafting occurring in the inner part of the powdered PP.

PMPM is a liquid at room temperature, and its boiling temperature is 181°C. The thermal processing temperature for PP usually is around 200°C, so PMPM can easily evaporate during thermal processing when it is added to PP as a light stabilizer. As shown in Table I, the thermal stability of PPMPM is much better than that of PMPM. The thermal decomposition of grafted PMPM is very similar to that of PPMPM. However, the  $T_p$  values of grafted PMPM are 6–9°C higher than those of PPMPM, so the thermal stability of grafted PMPM is a little better than that of PPMPM. Grafted PMPM does not decompose during the thermal processing because its decomposition temperature is much higher than the processing temperature. The grafting of HALS onto the polymer is an effective way to improve its thermal stability.

#### Radiation-resistance test of PP with grafted PMPM

PP grafted with PMPM (PP-g-PMPM) was added to powdered PP as a light stabilizer. The content of grafted PMPM in the graft copolymer was calculated

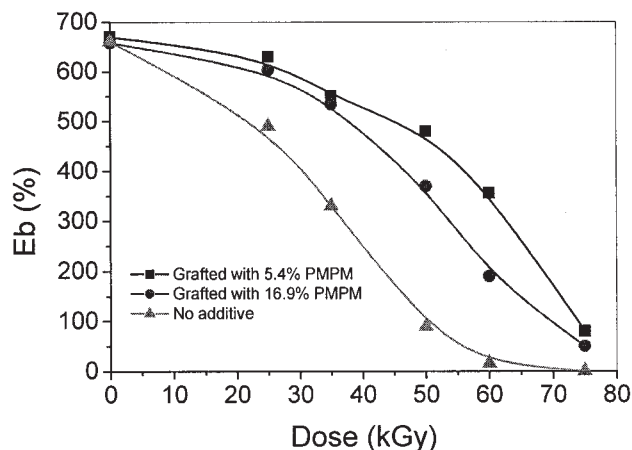


Figure 7 Eb as a function of the irradiation dose for PP samples with or without grafted PMPM.

according to the grafting percentage. Two kinds of graft copolymers, that is, PP samples grafted with 5.4 and 16.9% PMPM, were used. The weight of grafted PMPM in the graft copolymer added to PP was 0.1% of the weight of PP. These PP samples were prepared, irradiated, and tested under same conditions.

Figure 7 shows that the PP sample with grafted PMPM has better radiation resistance than PP without the graft copolymer. The Eb values of all the PP samples before irradiation (0 kGy) were almost the same, that is, about 660%. The Eb value of the PP samples without grafted PMPM decreased to 500% after just 25 kGy, less than 100% after 50 kGy, and close to 0% after 60 kGy. However, the Eb values of the PP samples with the graft copolymer were much higher than those of the PP samples without the grafted copolymer when the irradiation dose was less than 60 kGy. The Eb value of the PP sample with the graft copolymer (PP grafted with 5.4% PMPM) was still as high as 480% after 50 kGy and about 350% even after 60 kGy.

Figure 7 also shows that the stabilizing effectiveness of the graft copolymer with a higher grafting percentage was lower than that with a lower grafting percentage. At the same irradiation dose, the Eb value of the PP samples with the graft copolymer with a higher grafting percentage (16.9%) was a little lower than that of the samples with the graft copolymer with a lower grafting percentage (5.4%). This is possibly caused by the distribution of grafted PMPM in PP. Because the weight of grafted PMPM in the graft copolymer added to PP was the same, 0.1% of the weight of PP, more powdered PP-g-PMPM was required to be added to PP when the grafting percentage of the graft copolymer was lower. Because the size of the powdered PP-g-PMPM with a lower grafting percentage was smaller than that with a higher grafting percentage, this led to a more homogeneous distribution of the graft copolymer with a lower grafting percentage in

PP, and it protected PP more effectively from the damage of  $\gamma$  irradiation.

As discussed previously, the grafting of PMPM onto PP increases its thermal stability, solvent extraction resistance, and compatibility with the polymer; in turn, its stabilizing effectiveness increases. However, because the grafted chains are chemically attached to PP chains, the movements of grafted PMPM chains are strongly restricted. In other words, the grafted PMPM has one drawback: low mobility. This drawback can affect its stabilizing effectiveness. Very possibly, this is the essential reason for the lower stabilizing effectiveness of the graft copolymer with a higher grafting percentage. To overcome this drawback, it is better to add more graft copolymers with a low grafting percentage to PP.

In comparison with grafted TPM, <sup>23</sup> grafted PMPM is more effective in preventing PP from the damage of  $\gamma$  irradiation. A higher stabilizing effectiveness of pentamethyl HALS, compared with that of tetramethyl HALS, has been found and studied.<sup>25</sup> It is believed that pentamethyl HALS has more stabilizing reactions than tetramethyl HALS when pentamethyl HALS is converted to tetramethyl HALS by demethylation.

### CONCLUSIONS

PMPM was grafted onto PP by a simultaneous irradiation technique. The effects of various reaction conditions such as the solvent and monomer concentration on the grafting were studied. The grafting was easier in benzene than in chloroform or acetone, and the grafting was faster in a higher monomer concentration solution. BP accelerated grafting when used at a proper concentration. The FTIR and TG analyses proved that PMPM had been successfully grafted onto PP. The PP samples with grafted PMPM had better

radiation resistance than PP without the graft copolymer. The stabilizing effectiveness of the graft copolymer with a higher grafting percentage was lower than that of the graft polymer with a lower grafting percentage.

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