

# Effects of Electron Beam Irradiation on PP Film

**Chen Guangyu**

(Shanghai World Foreign Language Academy, Xuhui District, Shanghai)

## Abstract:

This study investigated the physicochemical changes of polypropylene (PP) film exposed to electron beam irradiation in the atmospheric environment at varying absorbed doses. Moreover, the structural evolution and macroscopic properties of the irradiated film were systematically characterized using methods such as Fourier transform infrared spectroscopy (FTIR), stress-strain mechanical testing, and differential scanning calorimetry (DSC). It was found that at an absorbed dose of 100 kGy, the mechanical properties of the PP film declined significantly due to oxidative degradation induced by irradiation. Moreover, the emergence of functional groups with oxidation characteristics was clearly observed in the FTIR spectra.

**Keywords:** PP Film;  $\beta$  Irradiation; FTIR; DSC; Oxidative Degradation; Stability; Electron Beam Irradiation

## 1. Introduction

Polymer materials are often exposed to high-energy rays in nuclear power and aerospace applications, making the study of irradiation effects and their stability highly significant<sup>[1]</sup>. The massive production and use of plastics brings convenience to people. However, these highly chemically stable materials also lead to severe global environmental pollution<sup>[2]</sup>. Among these materials, polypropylene (PP) film is widely used in fields like food packaging, adhesive tapes, textile packaging and capacitors, owing to its excellent moisture barrier properties, chemical inertness and low cost. It has become one of the most common plastic products in our daily life<sup>[3]</sup>. However, plastic wastes, especially disposable PP products, are difficult to degrade effectively in the natural environment and may be broken down into microplastics (<5mm) through physical and chemical processes,

which can then migrate to every corner of the world. These microplastics not only pose a direct threat to wildlife but may also accumulate through the food chain, ultimately potentially endangering the health of the ecosystem and human safety<sup>[4]</sup>. Therefore, a thorough understanding of the degradation behavior of these plastics is essential for assessing their recyclability.

The study systematically investigated the impact of electron beam irradiation on polypropylene (PP) film and assessed the potential recyclability of the material. Specifically, it systematically analyzed the changes in physicochemical properties of the PP film that had been exposed to electron beam irradiation in the atmospheric environment at varying absorbed doses. Moreover, several analytical techniques were employed to explore the property changes of PP film in depth. For example, the Fourier transform infra-

red spectroscopy (FTIR) was used to detect the chemical structure changes, stress-strain tests were carried out to evaluate mechanical properties, and differential scanning calorimetry (DSC) was applied to study the thermal behavior. The results indicated that the PP film underwent significant oxidative degradation with increasing absorbed dose, accompanied by a notable decline in mechanical properties, particularly at the absorbed dose of 100 kGy. The formation of oxygen-containing functional groups, such as carbonyl and hydroxyl groups, was observed in the FTIR spectra, corroborating the occurrence of oxidation reactions. These findings give comprehensive insights into the aging mechanism of PP film induced by electron

beam irradiation at both molecular and material levels, providing an experimental basis for subsequent recycling and resource recovery.

## 2. Experimental Process

### 2.1 Sample Materials

Commercial-grade double-layer polypropylene (PP) film with a thickness of 0.16 mm.

### 2.2 Sample Treatment

**Table 1 Details of Electron Beam Irradiation Dose and Duration.**

Sample No.	1	2	3	4	5	6	7	8	9	10
Irradiation Dose (kGy)	10	20	30	50	100	150	200	300	400	500
Irradiation Duration (s)	16	32	48	80	160	240	320	480	640	800

First, the PP film from the same roll was cut into 11 sample sets, each measuring 20 cm in size while retaining the double-layer structure. These samples were designated for different target absorbed doses: 0 kGy (serving as the blank control), 10 kGy, 20 kGy, 30 kGy, 50 kGy, 100 kGy, 150 kGy, 200 kGy, 300 kGy, 400 kGy, and 500 kGy (see Table 1 for details), respectively. To minimize potential impact of contaminants (particularly organic residues) introduced during industrial production and transportation on the irradiation effects and test results, all samples underwent a unified cleaning process before irradiation. Specifically, all samples were placed in a bag, to which ethanol (approximately one-quarter of the bag's volume) was added; the samples were then immersed and shaken for 10 minutes to thoroughly remove surface impurities. Subsequently, any adhered samples were carefully separated individually. Filter paper was inserted into the inter-layer of each double-layer PP film to prevent re-adhesion. All samples were then clamped and then dried in an oven for approximately 2 hours. After complete drying, the samples were placed according to their preset doses in 11 pre-labeled sealable plastic bags for subsequent irradiation. (See Table 1)

### 2.3 Experimental Steps

Each set of samples was sealed in a polyethylene (PE) sealable plastic bag and then irradiated using a high-energy electron beam generated by an electron accelerator. Following that, the irradiated samples were further cut into specific shapes for different characterization tests:

(1) Fourier transform infrared spectroscopy (FTIR) test-

ing: The samples were cut into single-layer sheets sized to completely cover the detection aperture of the instrument, with a size approximately the size of a fingernail; (2) Tensile property testing: Samples were cut into dumb-bell-shaped strips featuring a narrowed central region to ensure that fracture occurs within the effective test zone; (3) Differential scanning calorimetry (DSC) analysis: Samples were cut into small sheets weighing no more than 5 mg, such that they could be tightly placed in the sample crucible to ensure consistent thermal conduction.

## 3. Results and Discussion

### 3.1 Electron Beam Irradiation Test

Figure 1 shows the changes in the apparent color and macroscopic mechanical behavior of the PP film after electron beam irradiation at varying doses. Visually, no significant irradiation-induced color change was observed in the samples even at high doses, suggesting that no severe chromogenic degradation occurred within the tested dose range.

However, a qualitative manual stretching assessment revealed a significant increase in material brittleness with rising irradiation dose. At the dose range of 0-300 kGy, all samples exhibited good ductility and could not be easily torn by hand; at 400 kGy, they might fracture under substantial force; at 500 kGy, samples became highly brittle, breaking even with minimal force. These observations provide visual evidence of the severe mechanical degradation of PP film induced by high-dose electron beam irradiation.

ation<sup>[5]</sup>.

While no obvious color variation was observed, the significant change in macroscopic mechanical properties revealed that the molecular structure of the PP film had undergone profound physicochemical changes.



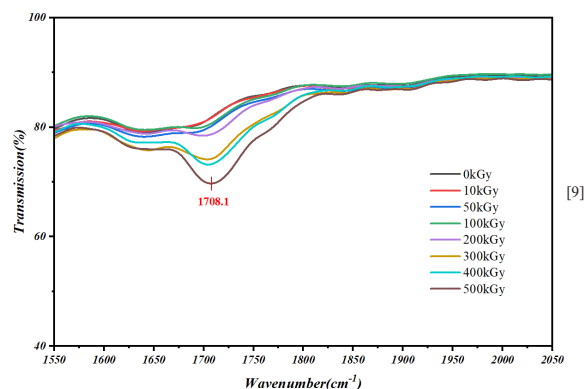
**Fig. 1. Photos of PP Film Before and After Electron Beam Irradiation with Different Doses**

### 3.2 Fourier Transform Infrared Spectroscopy (FTIR) Test

Figure 2 displays the partial FTIR spectra (1600–2200  $\text{cm}^{-1}$ ) of PP film after electron beam irradiation at different doses. A distinct absorption peak could be observed at about 1708  $\text{cm}^{-1}$ , which was attributed to the stretching vibration of carbonyl (C=O). It is a characteristic signal of oxidative degradation of polypropylene. As the irradiation dose increased gradually from 0 kGy to 500 kGy, the transmittance of this absorption peak progressively decreased, indicating a continual rise in the content of C=O groups and thereby reflecting the intensification of oxidative degradation with increasing dose<sup>[6]</sup>.

During irradiation, the C–H bonds in the polymer chains underwent homolytic cleavage, generating alkyl radicals, which then reacted with atmospheric oxygen to form peroxy radicals, ultimately leading to the formation of carbonyl compounds. The increase in irradiation dose thus led to more extensive chain scission and a greater amount of carbonyl-containing small-molecule products, which was reflected by the increasing absorption intensity at 1708  $\text{cm}^{-1}$  in the FTIR spectra<sup>[7,8]</sup>.

Notably, the difference in carbonyl peak intensity between 200 kGy and 100 kGy was substantially greater than between 100 kGy and 0 kGy, suggesting a non-linear, exponential increase in oxidative degradation, reflecting a pronounced dose accumulation effect in the electron beam-induced degradation<sup>[9]</sup>.



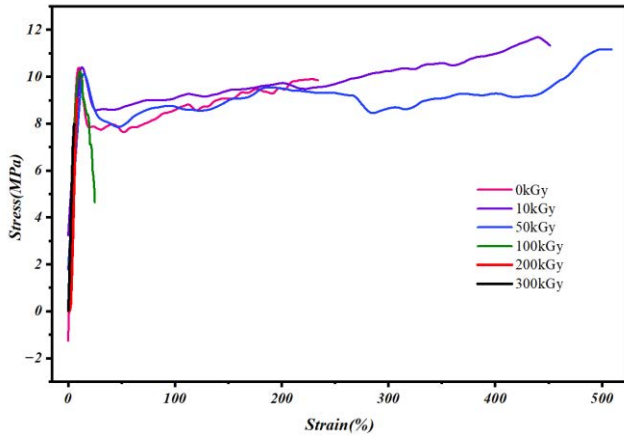
**Fig. 2. The Relationship between Transmittance and Wavenumber for PP Film Samples Irradiated at 0-500 kGy in FTIR Testing**

### 3.3 Stress-Strain Test

Figure 3 shows the stress-strain curves of PP film after electron beam irradiation at different doses, revealing a non-monotonic trend in mechanical properties, characterized by an initial increase followed by a decrease. The data for each dose is the average value of two parallel tests.

The results show that highest strength was not found in the unirradiated sample (0 kGy). Instead, PP film displayed enhanced fracture strength and elongation at break when irradiated at doses of 10 kGy and 50 kGy. Notably, the samples irradiated at 50 kGy exhibited a significantly greater elongation at break than those irradiated at 10 kGy, indicating its greater resistance to fracture during stretching. These observations reveal that moderate irradiation can have a certain enhancement effect on PP film<sup>[10,11]</sup>.

However, the mechanical properties of the material deteriorated significantly when the irradiation dose exceeded 100 kGy. For samples irradiated at 100 kGy, 200 kGy, and 300 kGy, the elongation at break decreased to approximately 170%, 19%, and 10%, respectively, corresponding to the fracture strengths of about 8.8 MPa, 9 MPa, and 8 MPa. Notably, the decrease in elongation at break was far greater than in fracture strength. Moreover, the samples irradiated at 100 kGy exhibited slightly lower fracture strength than those irradiated at 200 kGy. This suggests that irradiation damage at high doses primarily manifests as an increase in material brittleness and a more pronounced loss of ductility<sup>[12,13]</sup>.



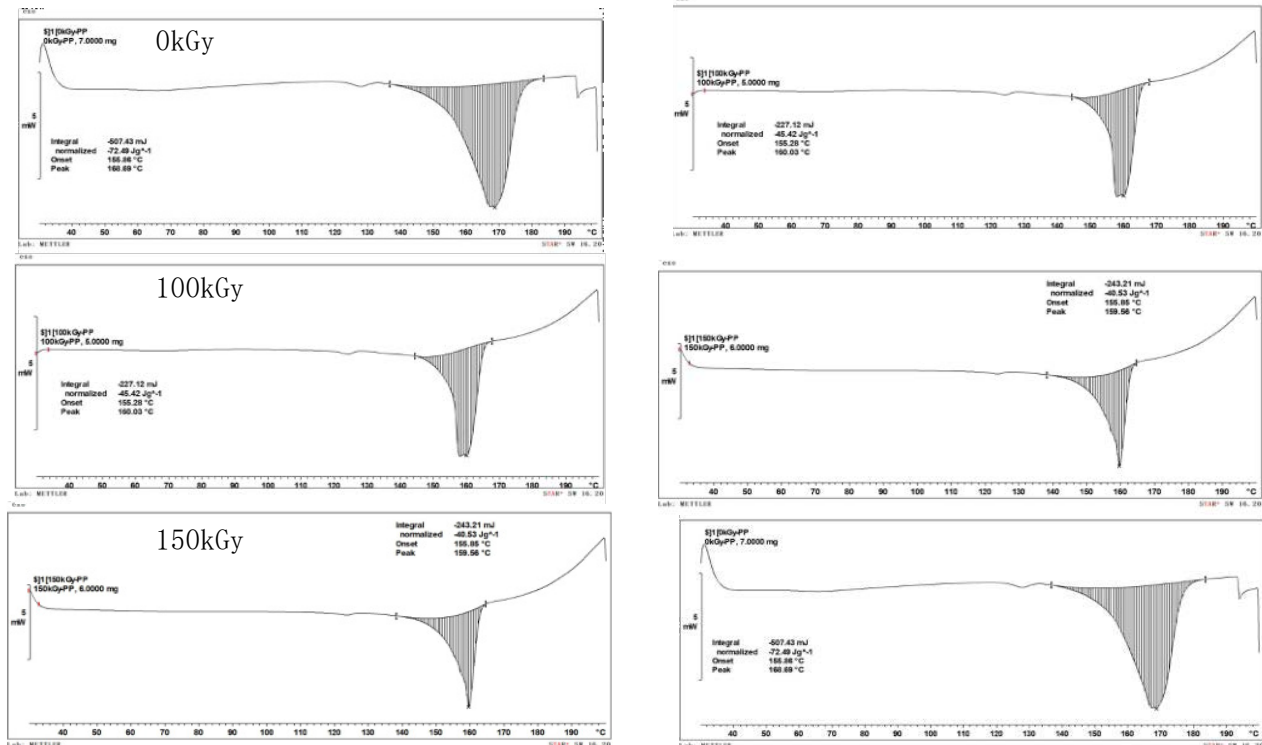
**Fig. 3. The Relationship between the Applied Tension and the Elongation of PP Film Samples Irradiated at 0-300 kGy in Stress-Strain Test**

### 3.4 Differential Scanning Calorimetry (DSC)

Figure 4 presents the results of thermal analysis for PP film before and after irradiation via differential scanning

calorimetry (DSC), with a focus on the melting behavior and changes in melting enthalpy. As can be seen from the figure, for all samples, an endothermic peak began to emerge at 140–145°C, and the melting process ended near 170°C. This endothermic peak corresponds to the crystallization and melting behavior of polypropylene.

With increasing electron beam irradiation dose (0 kGy, 10 kGy, 100 kGy, 150 kGy), the initial melting temperature of the PP film progressively dropped, indicating that melting point of the material decreases with increasing irradiation dose<sup>[14]</sup>. This trend can be explained by radiation-induced chain scission and destruction of crystalline structure, which reduces crystalline perfection and consequently enables melting to occur at lower temperatures<sup>[15]</sup>. Furthermore, the integral area of the melting peak in the DSC curves, aka melting enthalpy ( $\Delta H_m$ ), also exhibited a distinct declining trend with increasing irradiation dose. This decline directly indicates a reduced crystallinity of PP, resulting from the disruption of molecular regularity due to electron beam-induced chain scission, cross-linking, or oxidation, which consequently compromises the crystallization capacity of the material<sup>[16]</sup>.



**Fig. 4. Melting Enthalpies of Samples Irradiated at 0, 100, and 150 kGy in DSC Test**

In summary, DSC results demonstrate that electron beam irradiation significantly affected the thermal stability and crystallization behavior of PP. Specifically, both the melting point and melting enthalpy decreased with increasing irradiation dose. This indicates that irradiation process

aggravated the degradation of molecular chains, disrupted the crystalline structure, thereby compromising the overall thermal performance and mechanical stability of the material. These findings align with the conclusions from FTIR and stress-strain tests, validating that irradiation-induced

oxidative degradation is the primary cause of the deterioration in PP properties.

## 4. Conclusion

This study explored and revealed the evolution patterns of structure and properties of polypropylene (PP) materials irradiated at different doses through comprehensive analysis. FTIR results demonstrated that the extent of oxidative degradation in PP molecular chains intensified with increasing irradiation dose, which was primarily evidenced by the notable enhancement of the carbonyl absorption peak intensity at  $1700\text{ cm}^{-1}$ . In terms of thermal properties, DSC tests revealed a progressively lowering melting point and significant decline in melting enthalpy with increasing irradiation dose. These observations confirmed damage to the crystalline structure and a decrease in crystalline perfection, leading to a lower heat required for phase transition. At a macro level, tensile testing data revealed a non-linear rise-fall trend in the mechanical properties of polypropylene with increasing irradiation dose. When irradiated at around 50 kGy, the material exhibited a property enhancement due to the dominance of cross-linking. However, at doses exceeding 100 kGy, molecular chain degradation became pronounced, ultimately leading to a rapid decline in properties. In conclusion, irradiation dose has a significant impact on the structure, thermal stability, and mechanical properties of polypropylene materials. The evolution of their properties results from the synergy between cross-linking and degradation mechanisms.

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