

Article

Enhanced Electrical Tree Resistance of Polypropylene Cable Insulation by Introducing β -Crystals

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Abstract: Polypropylene (PP) is regarded as a recyclable material for high-voltage direct current (HVDC) cable insulation due to its high melting point and electrical resistivity. This work focuses on the effect of the β -nucleating agent content on the electrical tree growth characteristics in isotactic PP (iPP) insulation. The results demonstrate that adding β -nucleating agents promotes the growth of β -crystals while limiting the α -crystal content. The crystallinity improves with the reduction in the average size of spherulites due to the addition of a β -nucleating agent with 0.1 wt% content. Electrical tree experiments show that the electrical tree growth rate declines as the nucleating agent content rises from 0 to 0.1 wt%. Meanwhile, the expansion coefficient increases with higher nucleating agent content. Continuous increases in the nucleate agent content result in the upward growth rate of electrical trees. When the nucleating agent content is below 0.1 wt%, the α - β -crystal interface introduced by the agent suppresses carrier migration and limits impact ionization, leading to the slower growth rate of the electrical tree. Further addition of the nucleate agent induces a β - β -crystal interface with weak coupling in carriers. It is concluded that β -nucleating agent-modified PP with 0.1 wt% content has potential application in HVDC cable insulation.

Keywords: polypropylene; β -crystals; power cable insulation; electrical tree; DC superimposed impulse voltage; crystallization



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1. Introduction

An extruded insulated HVDC cable is the key piece of power equipment to realize the flexible interconnection of a large power grid, long-distance large-capacity transmission and the large-scale utilization of renewable energy [1]. At present, cross-linked polyethylene (XLPE) is widely used as the main insulation material in HVDC power cables. Polypropylene (PP) insulation is a type of thermoplastic cable insulation with great application potential. Compared with XLPE insulation, PP insulation presents better insulation performance, higher thermal resistance, a simplified production process and recycling advantages, which represent the development directions of HVDC cable insulation in the future [2–4].

However, due to the electrical, thermal and mechanical requirements of cable insulation regarding the material properties, polypropylene insulation materials cannot be directly used as the main insulation materials of power cables. Significant work remains to be performed to enhance polypropylene's performance and promote its extensive use in HVDC cables. Blending, a straightforward and effective modification method, has garnered scholars' attention in initial studies of polypropylene. Studies on the electrical and mechanical characteristics of blends of PP and elastomers have shown that a specific level of elastomer content can fulfil the majority of the performance criteria for the primary insulation used in environmentally friendly HVDC cables. However, space charge accumulation arises, which leads to the lower breakdown strength of blending insulation [5,6]. Owing to the quantum confinement effect and extensive specific surface area, inorganic nanoparticles excel in enhancing the insulation strength of polymer materials [7]. The effects of MgO,

ZnO and Al₂O₃ on the electrical characteristics of isotactic polypropylene (iPP) insulation were investigated. The dielectric constant of the insulation increased with the rise in the nanoparticle mass fraction. In comparison to the dielectric loss of pure PP, the dielectric loss of MgO and ZnO nanocomposites is lower, whereas that of Al₂O₃ nanocomposites is similar. In actual cable insulation production, the aggregation of nanoparticles requires careful attention [8]. Adding nanoparticles with poor dispersibility can cause local electric field distortion, leading to reduced insulation performance.

As a method to enhance the characteristics of PP, the regulation of the aggregate configuration is attracting more and more attention among scholars. Polypropylene exhibits various crystal forms, such as α , β and γ , which significantly influence its macroscopic properties. Under typical cooling conditions, polypropylene crystallizes into the α -form [9,10]. The α -spherulite crystal consists of radial and tangential lamellae growing around a core, contributing to its higher strength and rigidity. β -spherulites can form through the addition of nucleating agents or by controlling the temperature. Unlike the growth mechanism of α -spherulites, β -spherulites nucleate around a crystal nucleus, with the lamellae assembling into parallel bundles [11,12]. The termini of the structure of the bundle continue to extend, with the lamellae bending until they come into contact, forming complete spherulites. Observations reveal that the β -crystal affinity for electrons can impede the passage of a space charge through the amorphous region of isotactic polypropylene (iPP). Simultaneously, β -crystals exhibit a wide band gap, restricting charge transmission, thereby enhancing the breakdown strength and reducing the electrical conductivity [6,13–16]. Nevertheless, there has been no comprehensive research on the electrical tree propagation characteristics in PP insulation modified with a β -nucleating agent, which is crucial in advancing its application.

In this study, the influence of crystallization on the charge-blocking effect and electrical tree growth characteristics is investigated by using iPP insulation combined with a β -nucleating agent. The aggregation structure is analyzed by enthalpy variation, X-ray diffraction (XRD) and polarizing microscopy (POM). An analysis based on the migration of electrons is provided to aid in understanding how microscopic crystallization influences macroscopic degradation.

2. Experimental Arrangement

2.1. Sample Preparation and Mechanical Properties

Isotactic polypropylene (T30s, Zhongtian Hechuang Energy Co., Ltd., Ordos, China) is employed to produce the test samples. In the experiment, the β -nucleating agent (WBG-II) added to the iPP insulation is manufactured by Weilinna Material Co., Ltd., Guangzhou, China. WBG-II is classified as a lanthanide rare earth nucleating agent with a general formula of Ca_xLa_{1-x}(LIG1)_m(LIG2)_n, in which LIG1 and LIG2 are dicarboxylic acid and amide-type ligands. The content of the nucleating agent and the sample labels are shown in Table 1.

Table 1. Composition of the PP insulation samples.

Sample	WBG-II (wt%)
WBG-0	0
WBG-0.05	0.05
WBG-0.1	0.10
WBG-0.15	0.15
WBG-0.3	0.30
WBG-0.5	0.50

PP insulation particles are melted in a Banbury mixer with a temperature of 240 °C for 20 min, and powdered WBG-II is added to the molten PP as a β -nucleating agent. The β -modified PP insulation is removed from the Banbury mixer and is molded at a temperature of 240 °C and pressure of 15 MPa. The prepared insulation enters a molten state, and a steel needle-shaped electrode is inserted to maintain a tip-to-bottom plate distance of 2 mm.

At a rate of 12 K/min, the samples are cooled to 126 °C. Following 15 min of isothermal crystallization, the samples are cooled to room temperature at a rate of 12 K/min. The needle body has a diameter of 300 μm and a radius of curvature of 3 μm .

The dumbbell-shaped PP insulation used for the tensile test measures 20 mm in length, 4 mm in width and 0.3 mm in thickness. The tensile tests are conducted using an electronic universal testing machine (WD-D3), manufactured by Zhuoji Instrument Equipment Co., Ltd. (Shanghai, China). The samples are stretched at a speed of 30 mm/min at 25 °C until failure occurs. Figure 1 illustrates the stress–strain characteristics of the β -nucleating agent-modified PP insulation, where the end of each curve indicates the elongation at break. WBG-0.15 exhibits the most significant elongation at break, indicating excellent tensile resistance. With further increases in the nucleating agent content, the elongation at break decreases. The β -crystal has the unique shape of parallel wafers. The bonding force between the crystalline phase and amorphous phase in the β -crystal is less than that in the α -crystal. The microcrystals in the β -crystal can move along the sliding direction and then deform or tilt and slide the wafer, so it has better toughness. The introduction of a β -crystal can improve the elongation at break. When the content of WBG is higher than 0.15 wt%, due to the limitation of the solubility of WBG, the excess WBG is concentrated in the grain boundary of iPP, forming a stress concentration point, which reduces the elongation at break. On the other hand, excessive nucleating agent content forms a large number of imperfect microcrystals, which place greater constraints on the pulling of the amorphous region than larger microcrystals, thus presenting greater rigidity.

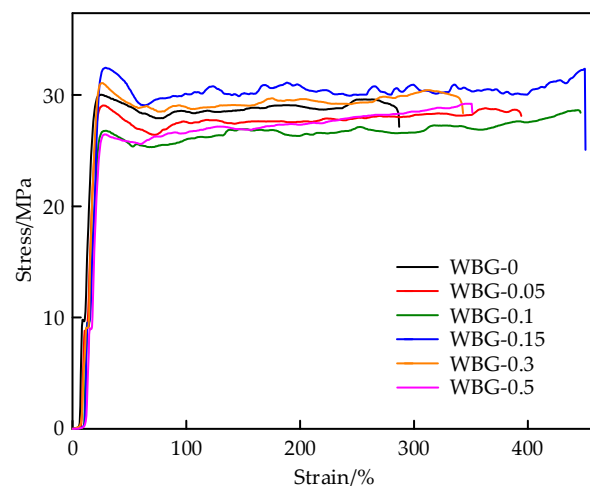


Figure 1. Stress–strain curves of β -nucleated iPP with different content of WBG-II.

2.2. Experimental Setup

The electrical tree experiment and observation platform consist of a DC superimposed pulse composite power supply, the needle plate electrode sample (immersed in silicone oil to prevent flashover), a digital image acquisition system (comprising a microscope unit, computer and cold light source) and a heating console (including a temperature sensor, heating plate and control unit). The DC superimposed pulse composite power supply is composed of a high-voltage DC power supply and pulse voltage generator. The DC high-voltage power supply is connected with the output high-voltage terminal through a current-limiting resistor and filter capacitor. The electrical tree experiments on the samples are conducted using a needle-plate electrode system under a pulse voltage (the amplitude and frequency are 17.6 kV and 200 Hz, respectively) superimposed DC voltage (−8 kV) at the temperatures of 60, 90 and 110 °C. PP insulation samples are stressed with a DC superimposed pulse voltage for 40 min. Electrical tree photos of the samples are captured using a charge-coupled device (CCD) lens and stored on a computer for subsequent analyses. Every experiment is repeated six times to generate a boxplot graph.

In this paper, the electrical tree length and expansion coefficient are used to describe the degradation level of the insulation. The expansion coefficient of the electrical tree is related to the width and length of the electrical tree (length/width).

The isothermal discharging current (IDC) method is used to discuss the trap level distributions of the β -nucleated iPP samples. At a temperature of 50 °C, a DC electric field of 30 kV/mm is applied on the tested insulation samples for 45 min. After this, the isothermal discharge current (I) is measured during depolarized progress for 40 min. The Keithley 6514 (Cleveland, OH, USA) is used to measure the current values. The trap density $N_t(E)$, varying with the trap level E_t , can be calculated by the equation below [17]:

$$\frac{N_t(E)}{E_t} = \frac{It}{\frac{ekTl^2}{2d} f_0(E) kT \ln(vt)} \quad (1)$$

where E is the trap energy level; $N_t(E)$ is the trap density as a function of E ; I is the discharging current; t is the depolarization time; l indicates the depth of the injected charge; T is the absolute temperature; k denotes the Boltzmann constant; e is the charge of electrons; d represents the thickness of the tested sample; in this paper, $f_0(E)$ is 1, denoting that the traps are fully occupied; v is 10^{12} s^{-1} , describing the escape frequency of trapped charges.

3. Experimental Results

3.1. Effect of Nucleating Agent Content on Aggregate Structure

Differential scanning calorimetry (DSC, Mettler Toledo DSC1 STARe, Chicago, IL, USA) is employed to study the crystallization properties. The temperature is increased to 240 °C in a nitrogen atmosphere at a rate of 20 °C/min and held for 5 min; it then decreases to 80 °C at 20 °C/min to eliminate the thermal history. This process is repeated under the same conditions to obtain DSC curves for the melting and crystallization processes. The crystallinity of the modified PP insulation material is reflected in the melting enthalpy. According to the different crystal forms and its melting temperatures, the melting temperature associated with the peak in the DSC curve results can show the crystal form. The crystallinity of various PP insulation samples is shown in Figure 2. The total crystallinity of the samples encompasses the crystallinity of various crystal forms. As shown in Figure 2, the β -crystal form is introduced by the addition of WBG-II. The $X_{m\beta}$ rises with increasing nucleating agent content. For content below 0.15 wt%, an increase in crystallinity is promoted by the addition of the nucleating agent. If the addition of the nucleating agent is excessive, the crystallinity of the modified samples may be reduced.

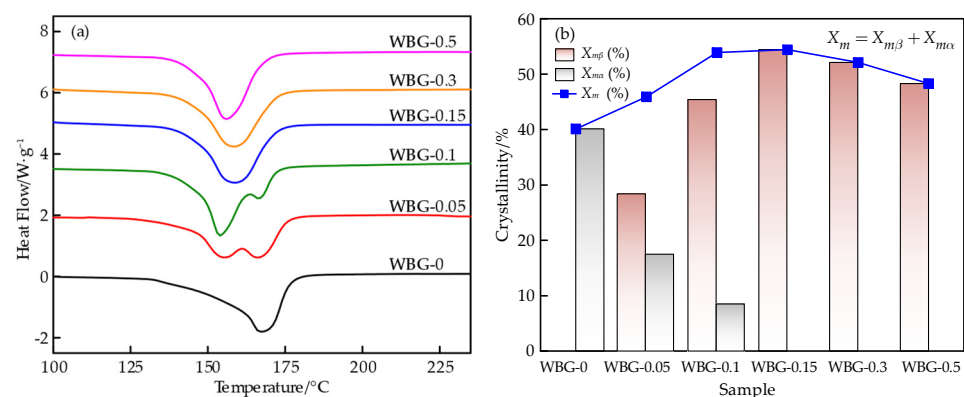


Figure 2. Crystallinity of β -nucleating agent-modified iPP. (a) DSC curve of melting process [18]. (b) Crystallinity of iPP insulation.

Figure 3 presents the XRD patterns (Rigaku Ultima IV XRD) of various insulation samples. The characteristic diffraction peaks of pure iPP are 14.2°, 17.1° and 18.6°, respectively, corresponding to α (110), α (040) and α (130), indicating that there is only the α -crystal

form in pure iPP. However, the diffraction peak of the samples containing different concentrations of WBG at 16.2° corresponds to $\beta(300)$, which indicates that a β -crystal pattern appears in β -nucleated iPP. With the increase in the WBG concentration, the intensity of the $\beta(300)$ diffraction peak increases, which indicates that the β -crystal form content increases. The intensities of $\alpha(110)$, $\alpha(040)$ and $\alpha(130)$ decrease with increasing nucleating agent content, indicating the inhibition of α -crystal growth. The ratio of β -crystals to the total crystal form (K_β) can be obtained according to the formula below [17]:

$$K_\beta = \frac{H_\beta(300)}{H_\alpha(110) + H_\alpha(040) + H_\alpha(130) + H_\beta(300)} \quad (2)$$

where K_β is the ratio of β -crystals of PP insulation; $H_\beta(300)$ denotes the intensity at 16.2° ; and $H_\alpha(110)$, $H_\alpha(040)$ and $H_\alpha(130)$ denote the diffraction intensity at 14.2° , 17.1° and 18.6° , respectively.

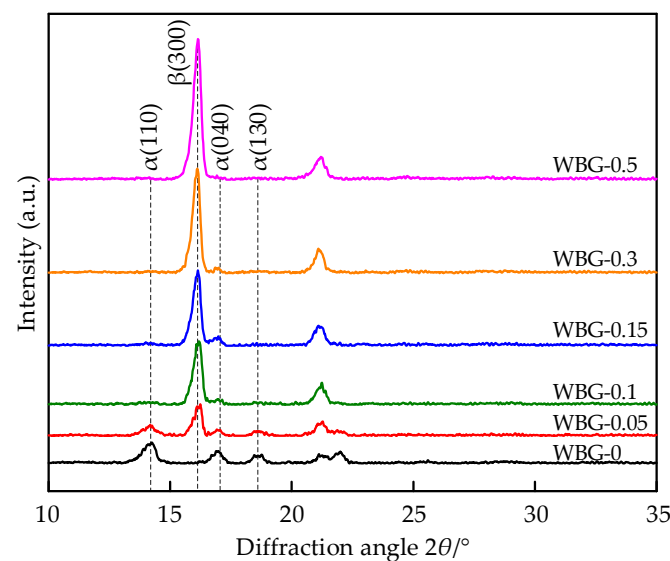


Figure 3. XRD spectra of β -nucleated iPP with different content.

The K_β values for WBG-0 to WBG-0.5 are 0, 0.59, 0.90, 0.95, 0.98 and 0.98, respectively, demonstrating that increasing nucleating agent content promotes β -crystal formation and inhibits α -crystal growth.

Figure 4 depicts the specific crystallization condition of the PP modified with WBG-II at 126°C . There are α -spherulites in the pure PP. When the concentration of the added WBG-II is 0.05 wt%, the size of the α -crystals declines significantly. At the same time, the β -crystal form appears. As the WBG-II content grows, the proportion of β -crystals rises while that of the α -crystal form declines. At 0.15 wt% nucleating agent content, the α -spherulites almost disappear, while the β -crystals aggregate so as to form clusters. Small spherulites are densely packed within the cluster, as evidenced. Upon adding 0.3 wt% nucleating agent, a large-scale self-assembly network structure around the β -spherulites is formed. Meanwhile, the edges of the clusters of the β -spherulites disappear. With the content of the nucleating agent increased to 0.5 wt%, the crystal nucleation density becomes too high. The crystals appear as flake-like structures, failing to form perfect spherulites.

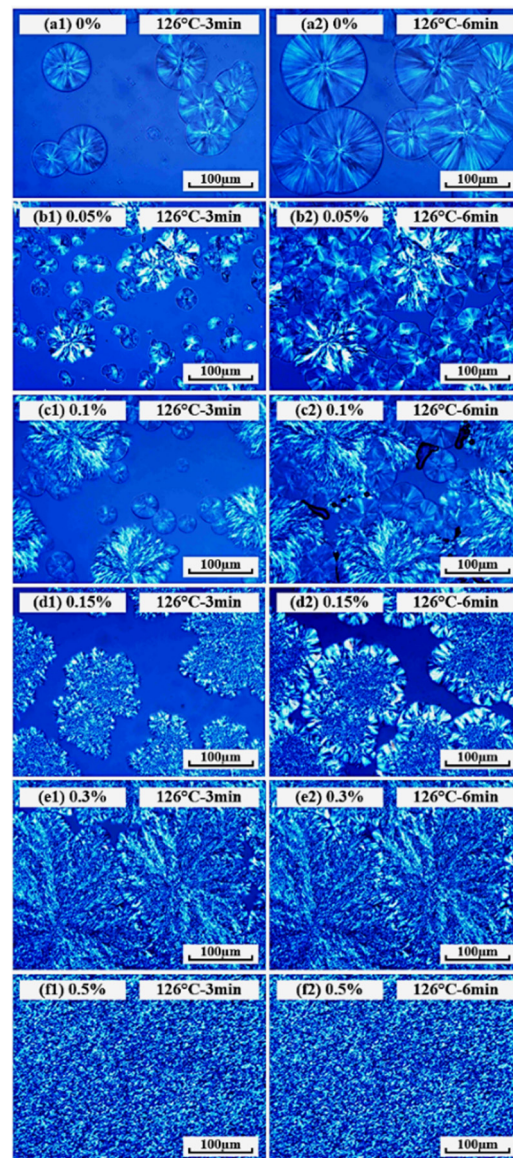


Figure 4. Crystal morphology of β -nucleated iPP with different content. (a1,a2) WBG-0 at 3 min and 6 min. (b1,b2) WBG-0.05 at 3 min and 6 min. (c1,c2) WBG-0.1 at 3 min and 6 min. (d1,d2) WBG-0.15 at 3 min and 6 min. (e1,e2) WBG-0.3 at 3 min and 6 min. (f1,f2) WBG-0.5 at 3 min and 6 min.

The enthalpy variation during isothermal crystallization is displayed in Figure 5. As the temperature decreases to 126 °C, increasing nucleating agent content advances the crystallization time of iPP and accelerates the crystallization rate, indicating that the nucleating agent promotes the crystallization of iPP. The isothermal crystallization process can be described quantitatively by the Avrami equation, and the growth dimension information and half-crystal time can be obtained as follows:

$$\ln[-\ln(1 - X_t)] = \ln Z_t + n \ln t \quad (3)$$

where t is the crystallization time, X_t is the relative crystallinity when the crystallization time is t , Z_t is the crystallization rate constant and n is the Avrami index, including the nucleation mode. Figure 6 shows the Avrami index and half-crystal time ($t_{1/2}$) obtained from the crystallization curve. From the figure, it is evident that the half-crystal time decreases monotonously with the addition of the nucleating agent, which indicates that the addition of the nucleating agent promotes the crystallization process and shortens the crystallization time. It can be seen from the change in the Avrami index that the addition

of WBG-II (0.05 wt%–0.1 wt%) can significantly improve the heterogeneous nucleation ability, promote the formation of nuclei and increase the crystallization rate. At nucleating agent content of 0.15 wt%, the Avrami index increases, and the crystal morphology exhibits flower-like clusters. With further increases in the nucleating agent content, the Avrami index decreases, and a large number of bright small crystals are formed.

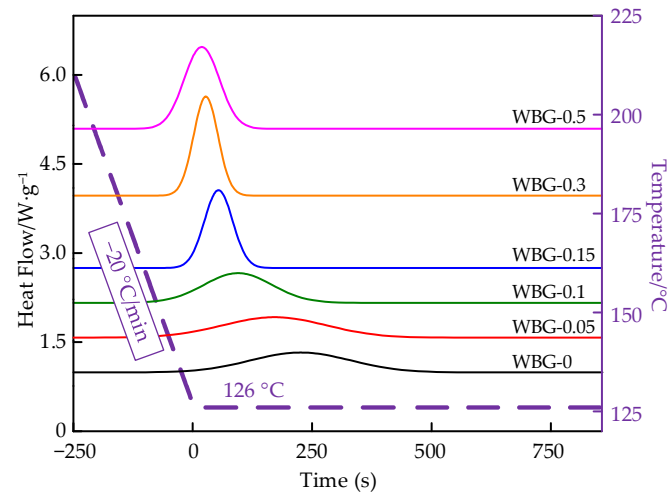


Figure 5. Isothermal crystallization curve of β -nucleated iPP with different content.

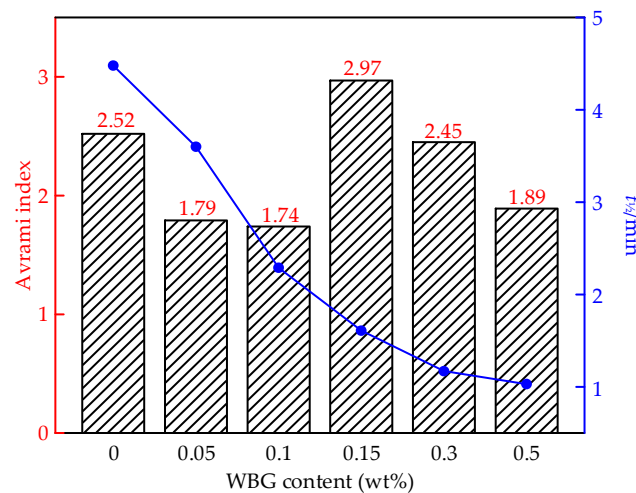


Figure 6. Avrami index and half-crystal time of β -nucleated iPP with different content.

3.2. Effect of Nucleating Agent Content on Electrical Tree

The electrical tree morphologies of the β -nucleated iPP samples are shown in Figure 7. The electrical tree of pure iPP presents a typical branch structure with obvious bifurcation between the vines. With the addition of WBG-II, the development of electrical trees is suppressed, decreasing the length of the electrical trees. With an increase in the WBG-II concentration (0–0.1 wt%), there is a decline in the length of the electrical trees and there is no significant increase in width. With further increases in the concentration of WBG-II, the morphology of the electrical dendrites transitions from branching to bush-like structures. Upon adding 0.5 wt% nucleating agent, the electrical structure exhibits a relatively dense, forest-like pattern. The electrical tree length in β -nucleated iPP increases with increasing nucleating agent content when the content of the β -nucleating agent exceeds 0.1 wt%.

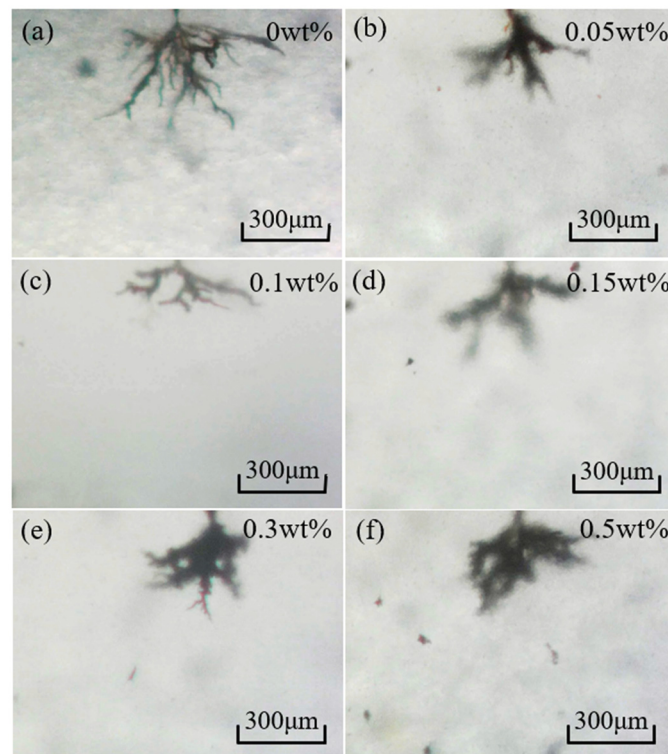


Figure 7. Electrical tree morphologies of β -nucleated iPP samples at 60 °C. (a) WBG-0. (b) WBG-0.05. (c) WBG-0.1. (d) WBG-0.15. (e) WBG-0.3. (f) WBG-0.5.

Figure 8 exhibits a quantitative description of the electrical tree length and the expansion coefficients of the electrical tree morphologies. From the figure, it is evident that with a rise in the nucleating agent concentration, the length of the electrical tree declines at first and then increases. At 0.1 wt% content of the nucleating agent, the electrical tree length is 69% of that observed in PP insulation. With further increases in the WBG-II concentration, the length grows. At 0.5 wt% nucleating agent content, it is slightly less than that observed in pure iPP. It can be deduced from the results that the expansion coefficient of electrical treeing with 0.05 wt% nucleating agent is close to that of pure iPP. At 0.1 wt% nucleating agent content, the expansion coefficient increases significantly, indicating a flat dendritic morphology. With the further addition of WBG-II, there is a decrease in the expansion coefficient of the electrical tree. The expansion coefficient in iPP with 0.5 wt% nucleating agent is slightly lower than that of pure iPP.

3.3. Effect of Temperature on Electrical Treeing

Based on the experimental results in the previous section, insulation with 0.1 wt% WBG-II content is selected for comparison with pure iPP for an electrical tree experiment at different temperatures. The electrical tree morphologies of WBG-0 and WBG-0.1 at 60, 90 and 110 °C are displayed in Figure 9. At a temperature of 60 °C, the electrical tree of pure iPP presents a branched structure. As the temperature reaches 90 °C, the electrical branches remain branch-like and become denser. As the temperature reaches 110 °C, the electrical tree length increases conspicuously. For WBG-0.1, there are electrical trees with branch-like structures at 60 °C. With the increase in the temperature, the electrical tree density grows. Compared with pure iPP, at various temperatures, the length of the electrical tree is significantly inhibited, and the inhibitory effect becomes more obvious with the rising temperature.

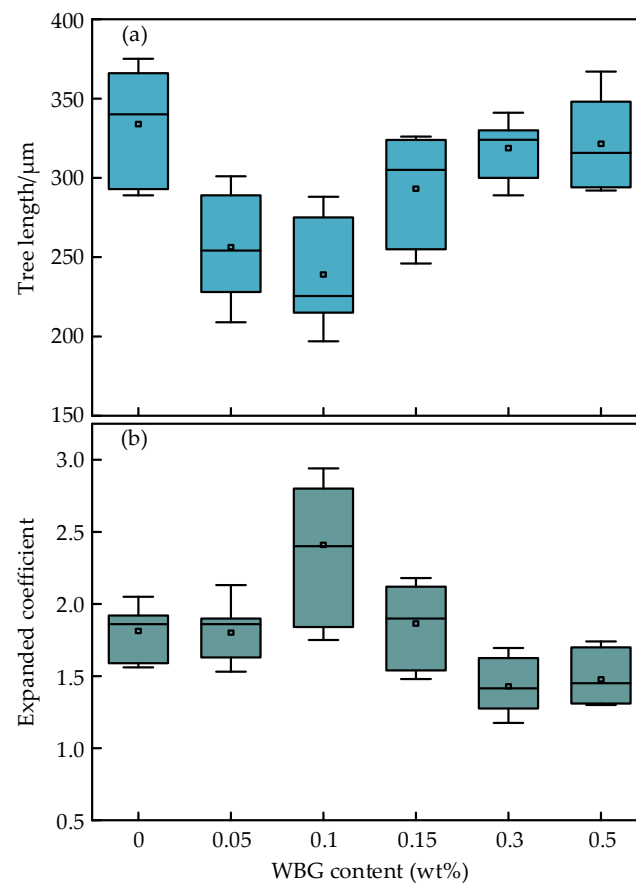


Figure 8. Comparison of electrical tree length and expansion coefficient of different β -nucleated iPP samples at 60 °C. (a) Tree length. (b) Expanded coefficient.

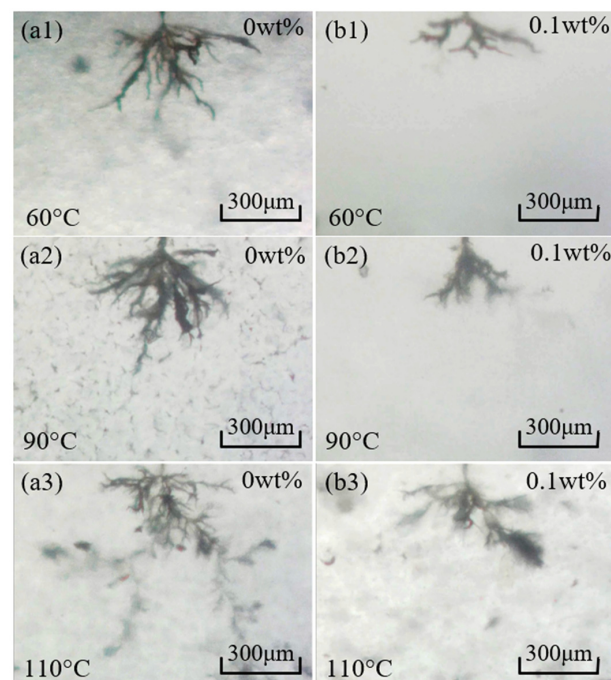


Figure 9. Electrical tree morphologies of WBG-0 and WBG-0.01 at 60, 90 and 110 °C. (a1–a3) WBG-0 at 60, 90, and 110 °C. (b1–b3) WBG-0.1 at 60, 90, and 110 °C.

Figure 10 shows the comparison of the length and expansion coefficient of the electrical trees between WBG-0 and WBG-0.1 at different temperatures. With the increasing temperature, an increasing trend is displayed in the lengths of the electrical trees of WBG-0 and WBG-0.1, and the randomness of the electrical tree lengths increases with the increase in temperature. With the increasing temperature, the difference in the tree length between WBG-0 and WBG-0.1 rises. At a temperature of 60 °C, the tree length of WBG-0.1 is 67% of that of WBG-0. As the temperature reaches 110 °C, the electrical treeing length of WBG-0.1 is 35% of that of WBG-0, which illustrates that the addition of WBG-II displays a better inhibitory effect on the electrical treeing growth of polypropylene at high temperatures. It can be deduced from the expansion coefficient that the electrical tree expansion coefficient of WBG-0.1 is higher than that of WBG-0 at different temperatures. With the temperature increasing, the difference in the expansion coefficient decreases.

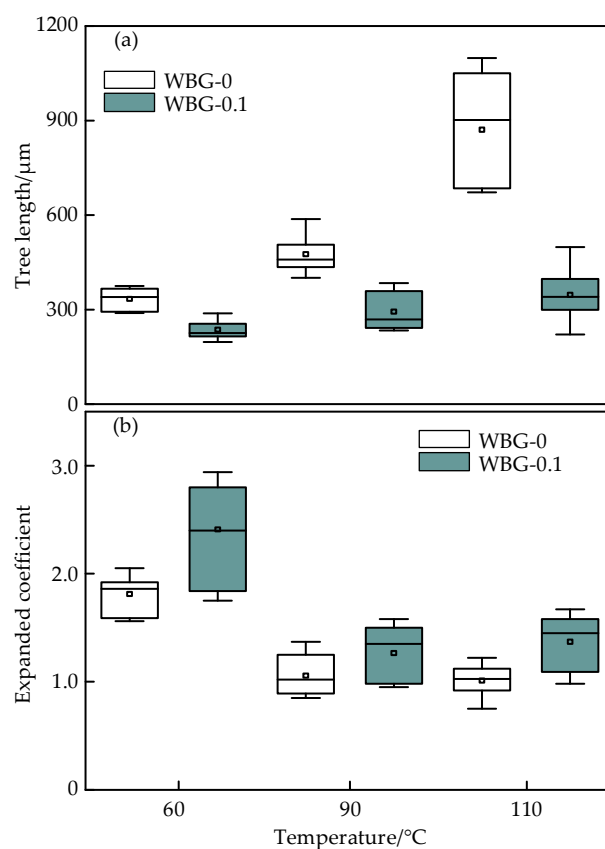


Figure 10. Comparison of electrical tree length and expansion coefficient of β -nucleated iPP samples at different temperature. (a) Tree length. (b) Expanded coefficient.

4. Discussion

The amount of nucleating agent is a significant factor influencing the β -crystal content in iPP. Due to the competition between α - and β -crystals, with the rise of the WBG-II concentration, the proportion of β -spherulites increases and the growth of α -crystals is inhibited. At the same time, the nucleating agent's addition accelerates the heterogeneous nucleation of polypropylene, which causes the number of spherulites to increase and the size of the spherulites decreases. The crystallinity and crystallization speed are increased due to the promotion of the nucleating agent. When the content of the nucleator is higher than 0.15 wt%, the β -spherulites form clusters due to the dense interleaving of the β -crystals, thus decreasing heterogeneous nucleation. With a further increase in the nucleator content, a large number of bright and incomplete β -crystals are formed.

Previous studies have shown that the molecular chain in the crystal region of a semi-crystalline polymer is relatively dense, and it is not easily affected by charge injection or

destroyed [19–21]. Therefore, the interface and amorphous region of the crystal region become the main factors affecting the electrical properties of PP insulation. When the concentration of the nucleator is low (<0.1 wt%), the trap density increases with increasing nucleator content, as shown in Figure 11. The addition of a nucleating agent leads to a decrease in the size of α -spherulites, which results in more α - α -crystal interfaces. The crossed chip structure formed by a radial crystal and attached tangential chip in an α -crystal has strong binding to the molecular chain of the interface area, and it is thus easier to form a capture trap of limiting carriers. The increase in the interface density promoted by heterogeneous nucleation leads to an increase in the trap density. On the other hand, a β -crystal is introduced by WBG-II, and the β -crystal is inlaid in the α -crystal matrix, thus introducing many interfaces between the α -crystal and β -crystal. The crossed chip structure of the α -crystal forms strong coupling at the interface, which forms traps that hinder charge transport. When the content of the nucleator is higher than 0.15 wt%, the flooding β -crystal inhibits the production of α -crystals and forms a large number of β - β -crystal interfaces. A β -crystal structure develops in space, mainly through the spiral winding of the molecular chain beam, and forms a spherical envelope with radial outward development. The β - β interface wafer is arranged in parallel and the molecular chain density is large among the chips, which results in weak coupling and a large amount of free volume that the wafer uncovers, which leads to a decrease in trap density.

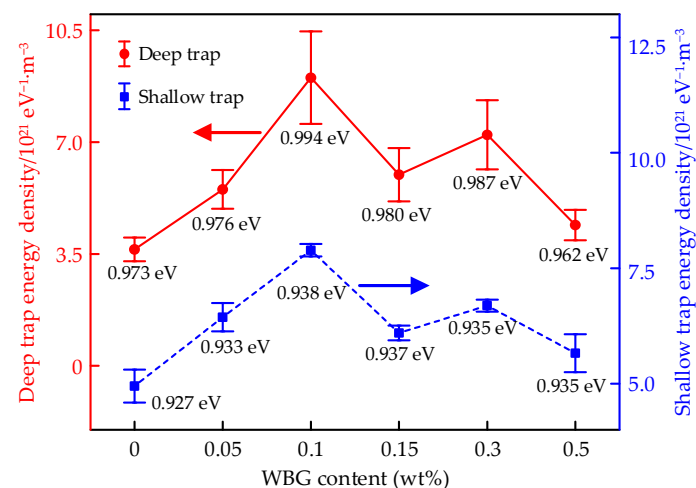


Figure 11. Trap characteristics of β -nucleated iPP with different content.

When the test samples are subjected to the DC superimposed impulse voltage, from the needle electrode, a unipolar charge is injected into the samples. These carriers become trapped in the insulation and tend to stabilize quickly. When an impulse voltage is applied, a substantial quantity of charge is injected from the needle tip in a short time due to the brief ascent period of the impulse voltage. These charges prompt existing trap charges to move away from the tip or the branch end. Excess energy is released in the process of charge subsidence and recombination. In the free volume, the hot electrons accelerate, accompanied by a gain in energy, impact and the breakage of the molecular chains, which speeds up the low-density region's formation. There are collisions and ionization among the charges in the region with a low density, resulting in the release of energy and the destruction of the molecular chain. The addition of WBG-II enhances the carrier-blocking effect within the sample, restrains the movement of activated carriers and then alleviates the degradation of the molecular chain of the polymer, thereby inhibiting and relaxing the electrical tree growth.

5. Conclusions

When the β -nucleating agent content rises from 0 to 0.1 wt%, the growth rate of the electrical tree decreases with an increasing expansion coefficient. As the concentration of

WBG-II grows further, the electrical tree lengthens, and its morphology tends to become more bush-like.

The introduction of α - β -crystal interfaces by 0.1 wt% WBG-II enhances the charge-blocking effect. Moreover, the enhanced effect helps to inhibit the movement of carriers and limit ionization, leading to the slower growth rate of the electrical tree.

Thanks to its resistance to electric treeing, the modified iPP insulation with 0.1 wt% WBG-II demonstrates potential for use in environmentally friendly HVDC cables.

Author Contributions: Conceptualization, Z.L.; methodology, Z.Y. and Z.L.; software, Z.Y. and Z.L.; validation, B.T. and H.W.; formal analysis, Z.Y. and Z.L.; investigation, Z.Y. and Z.L.; resources, B.T.; data curation, P.Z. and H.R.; writing—original draft preparation, Z.Y. and Z.L.; writing—review and editing, Z.Y. and Z.L.; visualization, Z.L.; supervision, Z.L.; project administration, Z.L.; funding acquisition, B.T. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Zhuoran Yang, Bin Tong, Han Wang, Peixuan Zhu, Huanyu Rao and Zhonglei Li were employed by the State Grid Nanjing Power Supply Company. They declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this study received funding from State Grid Jiangsu Electric Power Co., Ltd. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

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