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Electrical Treeing Deterioration and Dielectric Breakdown Phenomena in Polymeric Insulator

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고분자 절연재료에서 전기트리 열화 및 절연파괴 현상

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초 록 폴리에틸렌과 에폭시 수지계 고분자 절연재료에서 발생하는 전기트리 열화 및 절연파괴 현상에 대해 연구하였다. 침-평판 전극구조를 갖는 블럭상 시편에 전기적 응력을 가하고 침 선단에서 발생하는 전기트리를 관찰하였다. 저밀도 폴리에틸렌에서 발생하는 전기트리 형상은 밀도가 매우 높은 부시상이었으며, 가교 폴리에틸렌에서는 가지형 전기트리가 관찰되었다. 에폭시 수지에서는 첨가제 SN의 함량과 온도가 증가함에 따라 절연파괴 강도는 감소하였으며 전기트리는 더욱 복잡해졌다. 가교밀도가 높아 딱딱한 DGEBA/MDA 에폭시 수지계에서는 전도성 트리 경로 주위에 일련의 부채꼴 크랙이 관찰되었다.

Abstract Studies on the electrical treeing deterioration and dielectric breakdown phenomena in the polymeric insulator of polyethylene and epoxy resin were carried out. Block type samples with needle-plane electrode geometry were electrically stressed and the tree pattern from the needle tip was observed. In LDPE the density of electrical tree was very high and its pattern was bush type. For the case of XLPE, branched tree was observed. As temperature and SN content increased, the dielectric breakdown voltage decreased and the treeing phenomena became more complicated. Fan type cracks were observed around the conducting tree path in the brittle DGEBA/MDA system.

Keywords: Dielectric, breakdown, electrical tree, deterioration, epoxy resin, LDPE, XLPE

1. Introduction

The consumption of electric power is expected to be doubled up in this coming early 21st century because of the continual development of advanced industries and increment of living standards. These trends require the credibility of electric power systems for supplying economical and stable electric power, safely. Many researchers have studied on the polymeric insulator to extend the life expectancy and to improve the insulating properties by adding new additives and fillers.[1,2]

Polyethylene has been used for the insulation of electric power distribution and transmission cable because of its good electrical property, simple structure and easy handling. But the demand for its modification is still increasing. The cross linking method and defects-free process are considered.[3]

Epoxy resin system has a good combination of electrical, mechanical and thermal properties and has been processed in various types for electric components. Dielectrics must frequently serve as a structural member as well as an insulating material. But the conventional epoxy resin was too brittle because of its high cross-link density.[4,5] The advanced and modified epoxies are developed for the high voltage electrical insulation.

The electrical tree starting from the stress concentrated regions such as impurities and defects has been reported as a main cause of dielectric failure in the polymeric insulator. To suppress the treeing phenomena, the initiation mechanism and propagation characteristics have been investigated, in detail.[6] The dielectric breakdown by treeing deterioration is governed by various factors such as electrode material, applied charge type, polymer structure, environmental condition, and so on. To design a good electrical insulator, all the factors should be considered.[7]

In this study, the electrical tree and the dielectric breakdown phenomena in the needle electrode embedded LDPE, XLPE and DGEBA/MDA/SN epoxy resin system under AC high electric field were observed at various test conditions and the dielectric breakdown mechanism is discussed.

2. Experimental

2-1. Materials

The pellet of LDPE was hot pressed and over-fold to 1 mm thickness. XLPE samples were cut out from the underground power distribution CN/CV 22.9 kV cable (60 mm^2) and degassed under vacuum for 24 hrs at 80 ℃.[8, 9] The epoxy resin used in this study was DGEBA (diglycidyl ether of bisphenol A, Epon 828 grade) with EEW, MW and viscosity of 188, 385 and 11,000-14,000 cps(25℃), respectively. 30 phr of MDA (4,4′-methylene dianiline) was mixed with epoxy resin as a curing agent. SN (succinonitrile) was added as a reactive additive. The needle electrodes of hard steel with diameter of 1 ㎜, tip curvature radius of 3.0 ㎛ and tip angle of 30° were used.

2-2. Specimen Preparation

Sheets of LDPE with needle electrode were hot pressed. Needle electrode was inserted into the block type XLPE sample with zig at 100℃. For the case of epoxy resin, the needle was located in the mold with electrode gap of 1 mm and the mixture of DGEBA, MDA and SN was cast into the mold at 80℃. The mixture was cured for 1.5 hr and then 2nd cured at 150℃ for 1 hr.[10] All the samples were cooled down slowly inside the oven. Specimen without defects such as voids and cracks around the needle tip was selected and electrically stressed.

2-3. Dielectric Breakdown and Treeing Deterioration Test

The specimen was immersed in the heated silicone oil to suppress the surface discharge. An AC voltage was supplied to the specimen until dielectric breakdown at the voltage rising rate of 500 V/sec. A specific voltage was applied at a temperature and the electrical tree at the tip of needle electrode was observed.

3. Results and Discussion

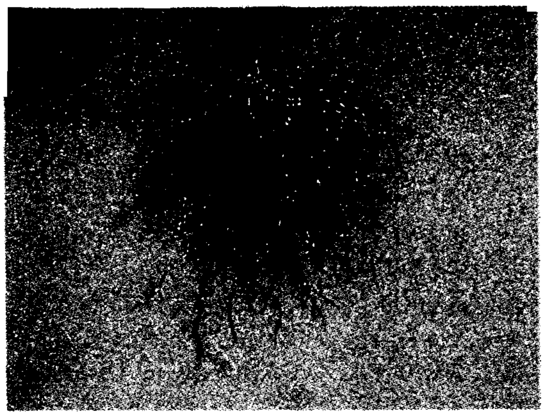

Fig. 1. Electrical treeing deterioration phenomena in LDPE.

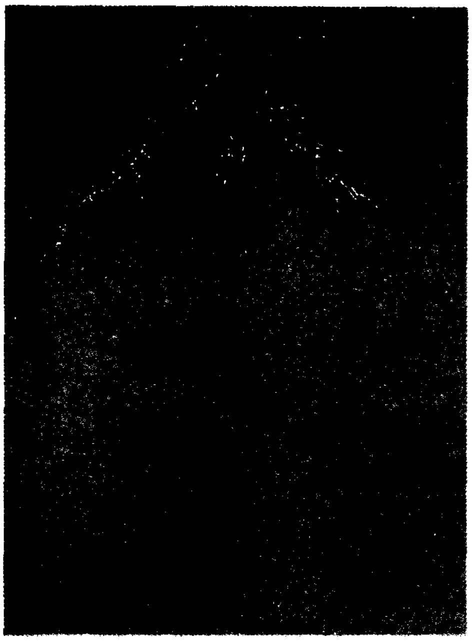

Fig. 2. Electrical treeing deterioration phenomena in XLPE.

Fig. 1 shows an electrical tree pattern in LDPE at 25 ℃. After the tree induction time, electrical tree initiated from the needle electrode. Needle electrode was inserted to simulate the defects and in which the electric field is concentrated and reinforced. The initiated tree propagated toward the counter electrode and showed bush type tree. The electrical properties of LDPE are excellent, though, the uses are restricted because of its low softening point. As the temperature increased, the material is melt and can't operate as an electrical insulator. At the high electric field, the electric power transmission and distribution systems are operated at the elevated temperature above 70℃ and the LDPE insulation on the cable is melt down. At high electric field which is higher than the tree resistance voltage, tree grows step by step from the weakest point. The electrical tree pattern depends on the structure of polymeric insulator.

Fig. 2 shows the electrical tree grown from the needle electrode in XLPE under the 7.5 kV for 210 secs at room temperature. The tree length and width are 660 ㎛ and 1,020 ㎛, respectively. The electrical tree pattern differed from that observed in LDPE. Branch type dominated the electrical tree in XLPE. The electrical tree density is lower than that of LDPE. The complexity of treeing deterioration phenomena in polymeric insulator can be analyzed, quantitatively, by using fractal

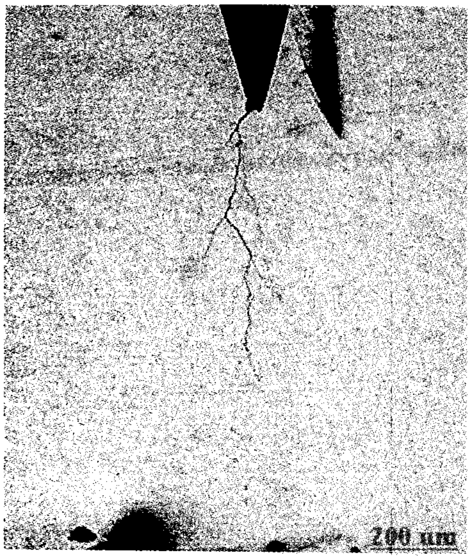

Fig. 3. Electrical treeing deterioration phenomena in the conventional epoxy resin system DGEBA/MDA.

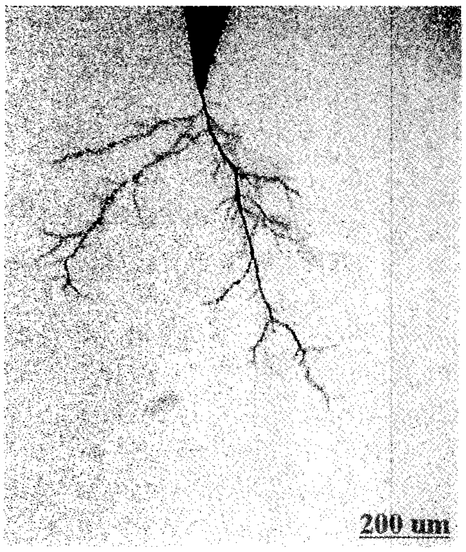

Fig. 4. Electrical treeing deterioration phenomena in the modified DGEBA/MDA/SN system.

concepts and this is far beyond from the scope of this study.[2,11] It is clear that the electrical tree pattern depends on the internal structure of insulator. To compare the electrical tree pattern in polymeric insulator, the epoxy resin system was electrically stressed.

Fig. 3 is the electrical tree in the conventional epoxy resin DGEBA/MDA system which is brittle and has high density of cross link. The tree propagated from the needle tip and is very thin. The treeing phenomenon is very differ from those observed in PE which is flexible. Electrical tree is a long deterioration phenomenon in the electrical insulating material which is subjected under several kinds of stresses such as electric field, high temperature, compression, vibration, and so on. Electrical tree is initiated from the most highly stressed local region. At the tip of protrusion, conducting inclusions, voids, cracks, etc., the combined stresses are concentrated and magnified. When the electric field goes over the maximum limit of the elastic breakdown, the material is distorted and physical crazes are generated and propagated. It is clear the treeing resistance of DGEBA/MDA system is very high.

The conventional epoxy resin system DGEBA/MDA was too brittle because of its high cross-link density. Though it has a good thermal and chemical resistance it is vulnerable to the impact and vibrational stress. The electric power generating motor and converter with high capacity are subjected under the said stresses. We reported the modified epoxy resin system by adding new reactive additive of nitriles showed high impact stress resistance. As the chain extender SN added the cured polymeric material was flexiblized and absorbed impact stress, effectively.[10] At the 20 phr of SN content, the impact strength was doubled up. Fig. 4 shows the electrical tree in DGEBA/MDA/SN(15 phr) system. The electrical tree is wider and thicker than that of DGEBA/MDA system. At higher temperature than T_g, the electrical tree of DGEBA/MDA is similar to the DGEBA/MDA/SN system. So that, the main factor of different electrical tree pattern is internal structure of the polymeric material.

Fig. 5 shows the dielectric breakdown phenomena started from the artificial needle electrode inserted inside LDPE block sample. A growing tree from the tip of needle electrode bridged to the counter electrode. As a tree branch reached the counter electrode, the LDPE sample was melt and thermally deformed.[8] As shown in this test result, the treeing deterioration takes a main role of dielectric breakdown in thick polymeric insulator. When the 2 electrodes bridged by electrical tree, the electric field at the LDPE is lowered and the work function of the electron decreases. So that, electrons and holes are easily emitted from the metal electrode and meet each other at the tree channel. The conducting path is formed and the flashover or electronic luminescence is occurred and generated heat around the main tree channel increased. The LDPE sample is melt and cannot operate as an electrical insulator at this high temperature. The dielectric breakdown phenomenon is similar to the XLPE sample. By the way, the melt was not observed at the XLPE case because of its

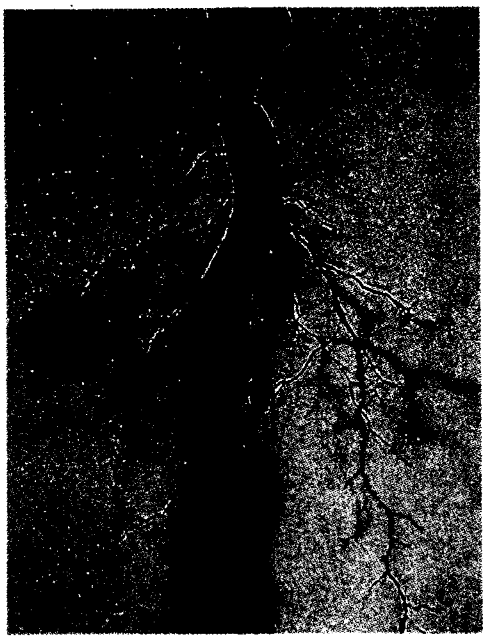

Fig. 5. Dielectric breakdown phenomena in LDPE.

Fig. 6. Dielectric breakdown phenomena in DGEBA/MDA system.

highly cross-linked structure and thermal resistance.

Fig. 6 shows the dielectric breakdown phenomena in the DGEBA/MDA system. There are many cracks around the puncture by tree and they look like a serial fan attached, linearly. High energy gas is generated when the insulator birdged and the gas inside the channel expands, abruptly. The cracks induced from the pressive shock by the hot gas inside the tree channel occur like the lightning from cloud to land. The crack size is very big and it reflects the system is very brittle and broken down at the high electrical stress.[1]

Fig. 7. Dielectric breakdown phenomena in DGEBA/MDA/SN system.

The dielectric breakdown phenomena in the modified system showed small cracks and it indicates the system is very flexible and broken down at lower electrical stress. The flexiblized system could efficiently absorb the impact shock and showed a little crack around the channel. The surface of tree channel was rapidly carbonated at the both systems. At higher temperature than T_g the dielectric breakdown pattern of DGEBA/MDA system was similar to DGEBA/MDA/SN system. At the elevated temperature the polymer chain segment moves freely by the thermal stress and free volume is arranged along the direction of electric field. The electrons can fly into the deep inside and form the space charge. Also the electrons are accelerated under high electric field, and crashe against the polymer chain. As the flight distance of the carriers increases the impact stress by the accelerated hot electrons increases and the polymeric chain is cut under the stress. By this way, pits are formed at the tip of needle electrode and propagated. When the tree reached the counter electrode the electron could emitted more easily and conduction current increased and the insulator was broken down, finally. The flexibilized epoxy resin system could absorb the impact shock and one or two fan type cracks were observed around the bridged channel.

Voltage applying time dependence of electrical tree propagation from the tip of needle electrode is described in Fig. 8. The propagation of electrical tree grown in DGEBA/MDA/SN at 25℃ under the applied voltage of 15 kV was detected. Continual application of the tree inception voltage causes the tree to propagate further into the dielectrics, while application of a higher voltage accelerates the tree growth. At the tip of the

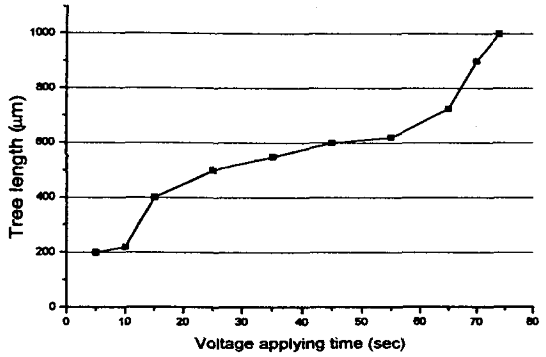

Fig. 8. Tree length dependence on voltage(15 kV) applying time at 25℃.

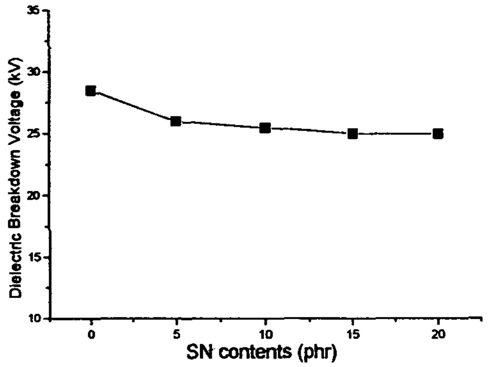

Fig. 9. Effect of SN content on dielectric breakdown voltage of DGEB/MDA system.

tree, the electric field is reinforced by the same mechanism at the needle tip. Therefore the tree can propagate toward the counter electrode, progressively.[12] After retardation time, pits grew and tree initiated from the needle tip. The tree grew rapidly during the first 10 to 30 secs. As the tree density increased, however, the growth rate decreased. The tree grew rapidly again near the counter electrode and dielectric failure occurred, abruptly. It took 74 secs for the system to breakdown.

Fig. 9 shows the effect of SN content on dielectric breakdown voltage (V_b) of the DGEBA/MDA system with needle-plane electrode geometry. As the content of reactive additive nitrile increased the dielectric breakdown strength (DBS) decreased at the initial content and then saturated to 24.0 kV/mm until the SN content of 20 phr. The dielectric breakdown mechanism can be described by electrical conduction mechanism. As the nitrile content increases the trap depth of carrier increases because the cured polymeric chain loosens.[10] Also the work function of electron decreases and electrons and holes are emitted easily from the metal electrode under the ac high electric field. The decrease of DBS relates with the decrease of thermal properties and space charge behaviour.[13]

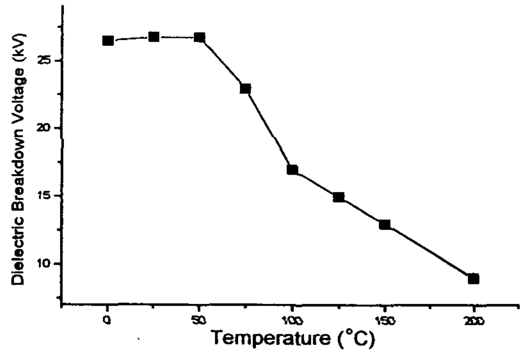

Fig. 10. Dielectric breakdown voltage dependence on the ambient temperature.

The temperature dependance of the dielectric breakdown voltage was studied and the result is shown in Fig. 10. Rapid decrement of V_b around T_g was found. With the increase of temperature, the movement of molecular chain became active and the electron diffusion region from needle electrode expanded.[14] To reinforce the polymeric electrical insulator, several factors should be considered at the same time and it is not easy to innovate a good insulator. We are trying to modify the conventional insulator by adding new reactive additive. The results of the concerned study will be presented next.

4. Conclusions

From the test results of electrical treeing deterioration and the dielectric breakdown characteristics in polymeric insulator of PE and epoxy resin system, the following conclusions were obtained. In LDPE the density of electrical tree was high and bush type but in XLPE branched tree was observed. As the temperature and SN content increased the dielectric breakdown voltage decreased and the treeing phenomena became more complicated. Fan type cracks were observed around the conducting tree path of brittle DGEBA/MDA system. To design a good insulator the dielectric breakdown and conduction mechanism should be considered at the same time.

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