Paper

Propagation of Electrical Tree in Extended Chain Crystal Polyethylene

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Extended chain crystal(ECC) polyethylene exhibits some unique properties. It is possible to make transparent highly crystallized polyethylene in the ECC phase. Electrical treeing discharges were investigated using a needle to plate electrode system under an application of lightning impulse voltage. The propagation of trees was observed using a high-speed image converter camera. The formation of tree channels was a very rapid phenomenon, 1 μs. The discharge current accompanying the trees consisted of two kinds: A large current pulse, occurring just after voltage application, appeared to be a combination of injection current and charging current. Immediately following this large pulse, small current pulses appeared intermittently in the wave tail of the applied voltage. It is thought that these small current pulses are attributable to the rearrangement of charges in the gas phase on the inside surfaces of tree channels.

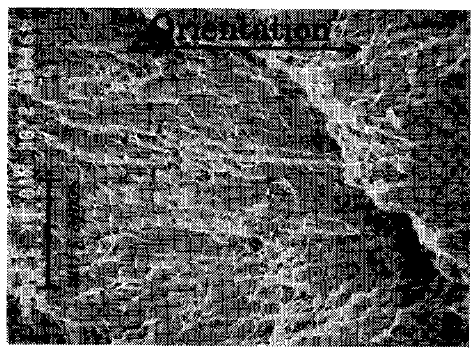
Keywords: electrical treeing, extended chain crystal, polyethylene,discharge current

1. Introduction

Treeing phenomena are important to the application of polymers in insulation materials. They have been mainly studied in the transparent state because of the ease of tree observation. Crystalline polymers, however, are opaque, and it is not easy to measure their tree growth. The mechanical properties of polymers depend largely on their morphology, and particularly on orientation and crystallinity (1). It is almost impossible to manufacture polyethylene products without any orientation and crystals because they always have some of both properties. It has been reported in some studies that tree propagations are influenced by the crystal morphology (2) or mechanical strain (3), but the influence of orientation on tree propagation in highly oriented and crystalized polyethylene remains largely unknown.

In extended chain crystal(ECC) polyethylene (4)(5), transparent high-orientation with crystallinity higher than 0.95 can be achieved in the manufacturing process. This means that it is easy to observe the tree growth, enableing us to get information on intrinsic qualities of the electrical treeing in insulating materials. This paper describes the properties of treeing in ECC polyethylene under a lightning impulse voltage application. The relations between the tree inception and the discharge current have been discussed on the basis of the results obtained by an image converter camera and a current measurement system with a light-emitting diode(LED).

(a)unoriented ECC polyethylene
Scale(3.0 μm) is shown on the left side of the photo



(b)oriented ECC polyethylene
Scale(3.0 μm) is shown on the left side of the photo

図 1 Criofractured surface of ECC-Polyethylene

2. Polyethylene test samples

Typical polyethylene crystals are referred to as folded chain crystals (FCC). In this type of polyethylene, molecules are folded and reinserted into a lamella crystal [6]. These lamellae then gather into spherulites and the molecules align to the thickness direction of lamellae. The thickness of lamellae is 10 to 20nm. On the other hand, the ECC consists of a linearly extended molecular structure. The thickness in the molecular axis direction exceeds approximately 1 μm.

The SEM image of the criofractured surface of unoriented ECC polyethylene is shown in Fig.1(a). The image clearly shows the domain structure and alignment of the crystals in the domain. Fig.1(b) shows a SEM image of oriented ECC polyethylene. The orientation direction is represented in this figure by an arrow. It is evident that the oriented ECC polyethylene does not have a domain structure; that is, a fibril structure is formed within oriented ECC polyethylene.

3. Experiments

To investigate the propagation of an electrical tree, oriented ECC polyethylene samples were prepared as follows. HDPE (high density polyethylene HJ560 Nihon Polychem) was hot pressed into plates and the plates were drawn by 600% at room temperature. After the plate was cut into test samples 10mm in width, a needle electrode (ϕ0.52, tip radius 5μm) was inserted in the center of the sample. The direction of the needle was set vertical to the orientation of the samples. These samples were crystallized under high pressure(500MPa) at 241°C for 10 minutes and were cooled to room temperature while maintaining high pressure. All samples were approximately 2.5mm in thickness. Orientation was evaluated using Herman's orientation function from the Raman spectra [7] [8]. The measured value of the orientation was approximately 0.5 which was sufficient for making transparent ECC polyethylene samples.

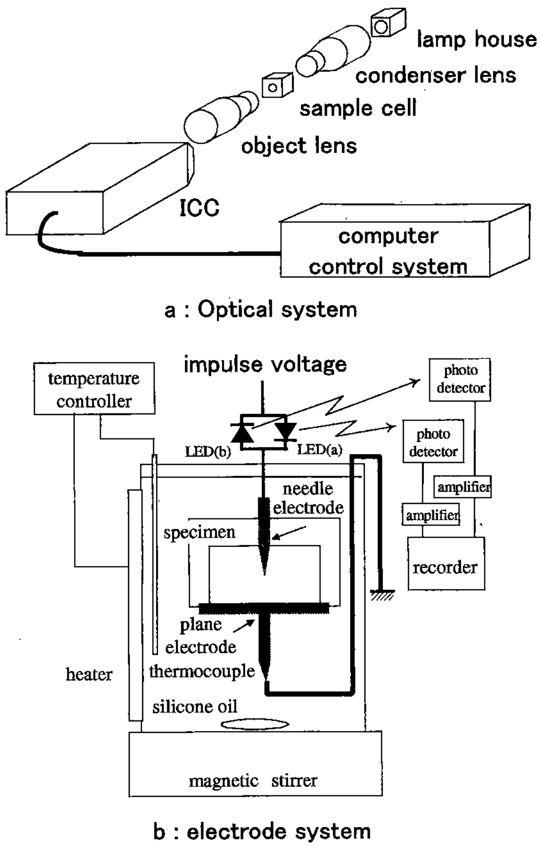


図 2 A schematic diagram of the experimental setup
LED(a): positive connection; LED(b): negative connection

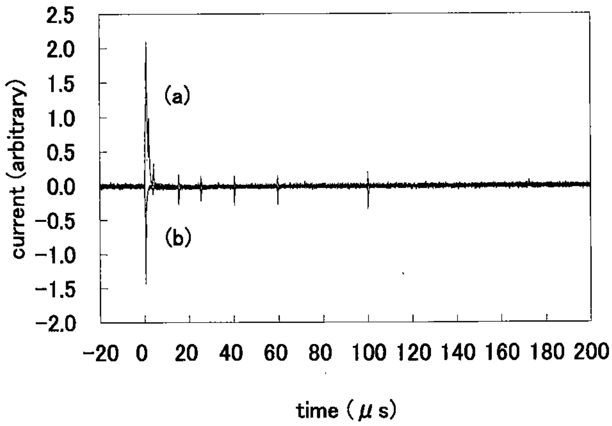


図 3 A typical example of current pulses
(a): positive connection, (b): negative connection

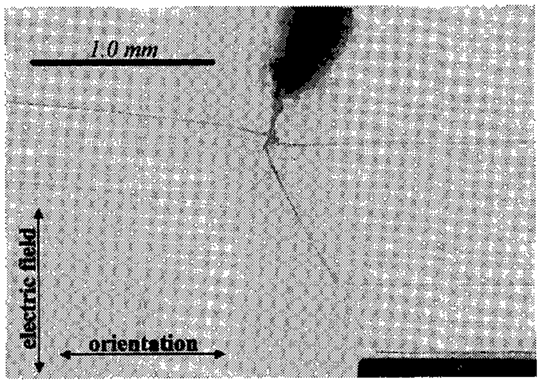


図 4 Tree propagation in oriented ECC polyethylene
Electric field and orientation are shown by arrows. A scale shown in the upper left side of the photo is 1.0 mm.

In order to prevent creepage discharges over the sample surface under applied high voltage, the samples were sandwiched between acrylic plates and were cemented with epoxy resin. A metallic plate (ground electrode) was installed on the sample as a counter electrode. Gap spacing between the needle tip and the plate was 5mm. After the test sample was immersed in insulating oil (silicone oil), the standard lightning impulse voltage (1.2/50μs) with a peak value V_m was applied to the needle electrode.

Treeing discharges in ECC polyethylene were measured using a high-speed image converter camera(ICC) (IMACON 468, nac) and a polarized microscope. A

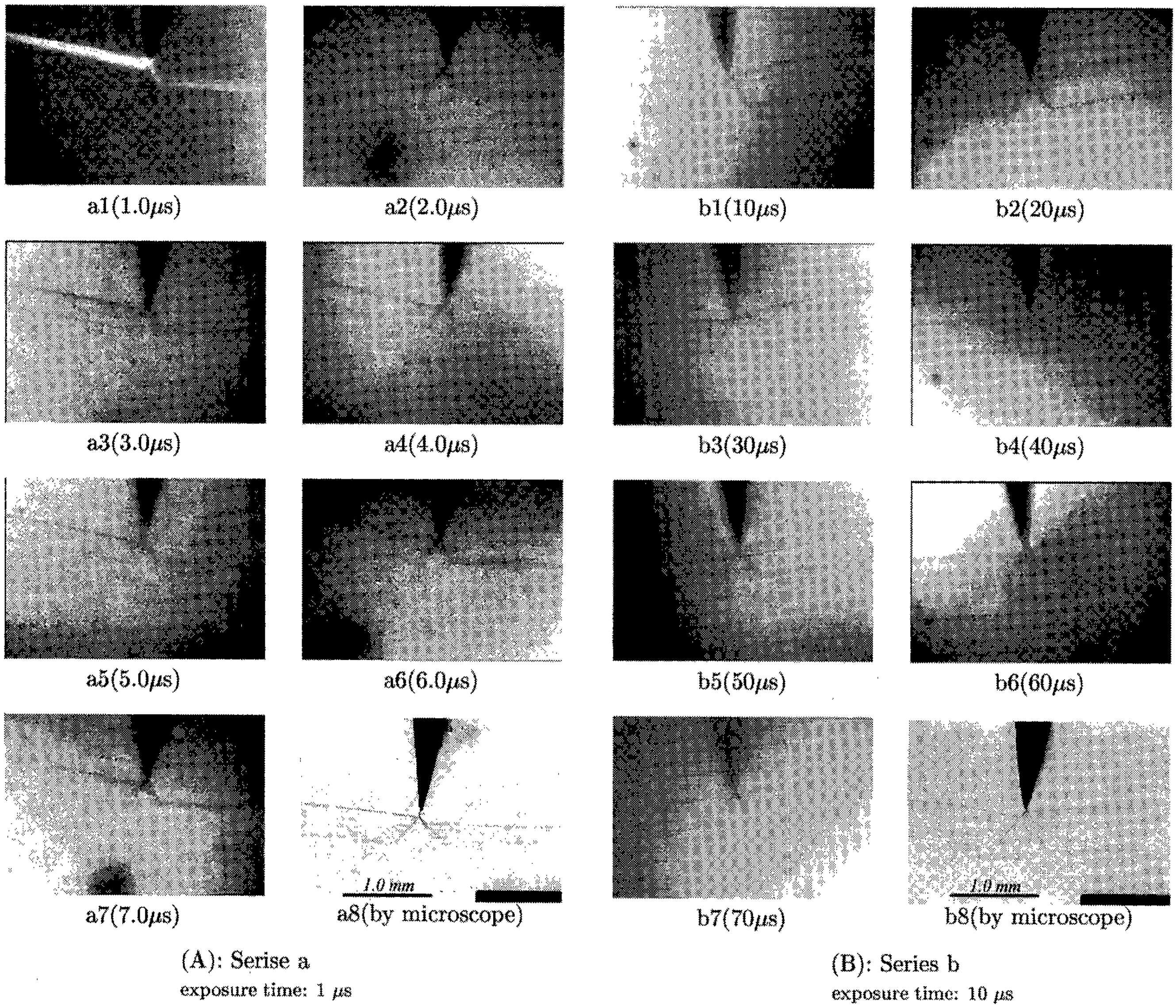


図 5 Framing photographs of treeing

Standard lightning impulse voltage (1.2/50μs) with a peak value 70kV was applied

high-speed ICC was used to examine the propagation steps of trees. The contrasts of the images were emphasized using a personal computer. The current pulses accompanying the treeing were recorded by means of light intensity measurement using an LED circuit which was connected to the high voltage side. The measurement system is shown in Fig.2.

The current pulses were detected by light emission from an LED. The light emitted by the LED was transmitted to a photo diode, and the current of the photo diode was recorded. A reversed parallel connection can detect the current in both directions. A typical example of current recorded through both diodes is shown in Fig.3. LED(a) and LED(b) in Fig.2 emitted light at the same time as shown in Fig.3. The reason for light emission by the reverse diode is thought to be the capacitance behavior of the LED.

The current from the impulse source to the needle is assumed to be positive. The first large current pulse is thought to be positive. The following small pulses are thought to be negative. For the study of the first large current pulse, data obtained through the LED(a) was used. For that of the following small pulses, data obtained through the LED(b) was used.

4. Result and discussion

A typical example of treeing in an oriented ECC polyethylene which was observed through the polarized microscope is shown in Fig.4. The directions of electric field and orientation are shown in the figure by arrows. The trees in ECC polyethylene take a very simple shape, and it is easy to identify each treeing channel. This figure shows that the trees in an oriented ECC polyethylene sample never propagate along the direction of the electric field, but rather along the direction of the orientation. The trees also propagated in a straight line without branching [9].

Close-up images of the tree propagations taken by the

ICC are shown in Fig.5. Each frame is a shadow image of tree channels which appear as a black lines, because the ICC detects the light passed through the sample as shown in Fig. 2(a). The serise (a) and (b) were different experiments under the same condition except for the exposure timing. The images of Fig.5 were taken as aseries in time intervals of 1 μs and10μs, respectively, (the shutter of ICC was opened for 1μs in Fig.5(A) and for 10μs in Fig.5(B)). The frame a1 in Fig.5(A) shows the image immediately after an impulse voltage application (in the period 0 to 1μs corresponding to the wave front of the applied voltage). Two bright lines in this frame indicate that the trees propagated along the orientation axis, which is the characteristic feature of oriented ECC polyethylene samples as mentioned previously.

The bright lines of the trees suggest that they propagate in the plasma state resulting from the ionization phenomenon. In Fig.5(A) we see that the shape of the trees in the first frame is almost the same as the shape in the final frame (a8) which was measured through a polarized microscope after the voltage application. That is, frames a1 and a8 reveal almost the same shape trees. This means that the formation of trees is completed in the very short period (within 1μs) after applying the impulse voltage (V_m=70kV) to the needle electrode. The resolution of the ICC used here was not high enough to resolve the tree shapes for exposure times less than 1μs. Figure5(B) illustrates the aspects of trees in the wave tail of applied voltage.

Figure 6 shows a typical example of the relationship between the impulse voltage and the current pulses accompanying the occurrences of trees. The currents were measured simultaneously with the exposure of images of the tree propagations shown in Fig.5. In Fig.6, exposure timings are shown as an example. Frames a1 to a7 and b1 to b7 represent the positions corresponding to the exposures of the ICC which were taken at 1 and 10μs intervals, respectively. After a large current pulse was recorded just after the voltage application (in frame a1), intermittent small current pulses were visible in the wave tail of the applied voltage. It is thought that these two kinds of current pulses (first large current pulse and intermittent small current pulses) relative to the treeing are different from the mechanism which created them.

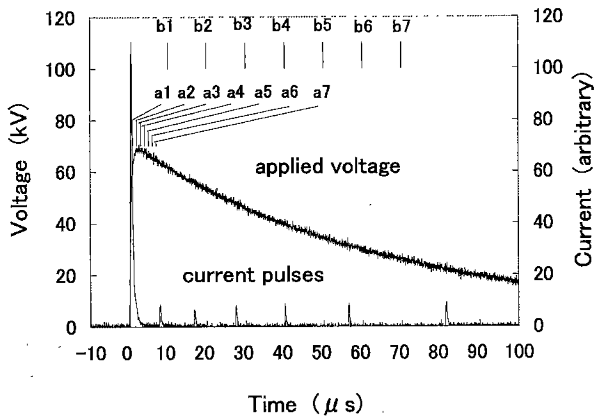


図 6 A typical example of current pulses due to treeing

Time interval in frame a1 to a7: 1.0μs
Time interval in frame b1 to b7: 10μs

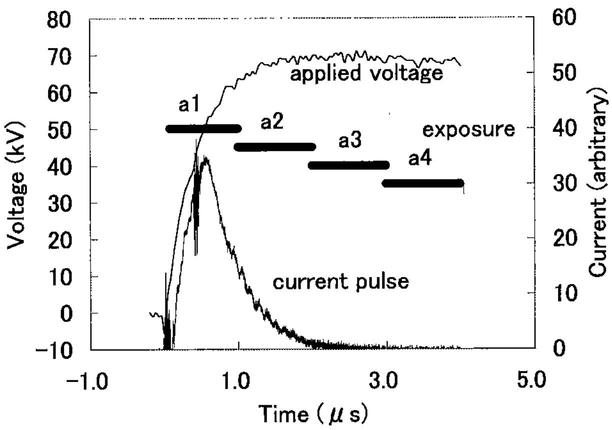


図 7 First large current pulse

V_m = 70kV
Exposure timeing is shown in a1 to a4

(A) Occurrence of first large current pulse

Figure 7 shows the first large current pulse which occurs in the wave front of the applied voltage. The exposure time of the ICC for the frames in Fig.5(A) is shown by bold lines. The image of frame a1 shows the wave peak of the first current pulse and the image of frame a2 shows the wave tail of the first current pulse. (The tree channels in frame a2 are the tracks of the tree propagation as shown in Fig.5[A].) The current pulse in Fig.7 also shows burst pulses before reaching the wave peak which is thought to be caused by the propagation of trees.

On the other hand, these current pulses appeared differently when the applied voltage V_m was lower than 70kV; that is, for lower applied voltage, the current pulse was separated from the charging current. Figure 8 shows the changes in the current pulses at lower voltages. In these cases, the current pulse had a single peak, and the height and width of the pulse were larger than intermittent small current pulses in the wave tails of the applied voltages. The time of occurrence of a peak current decreased when the applied voltage was increased, and this current pulse could not be separated from the charging current when the applied voltage exceeded V_m=65kV. These large current pulses could not be observed within 5μs at less than V_m=25kV, but some samples showed the small current pulse at around 50μs for V_m=25kV. The current pulses for V_m=30 and 35kV occurred in 2.6 and 1.3μs respectively after exceeding the peak value of the applied voltage.

The treeing seems to begin when an applied voltage exceeds a threshold value, since the occurrence of the first large peak current is thought to be concurrent with the begining of the treeing. The time when treeing begins depends on the applied voltage and it decreases when the applied voltage is increased. The amplitude of the current pulses also depends on the applied voltage as shown in Fig.8; the amplitude of pulses becomes

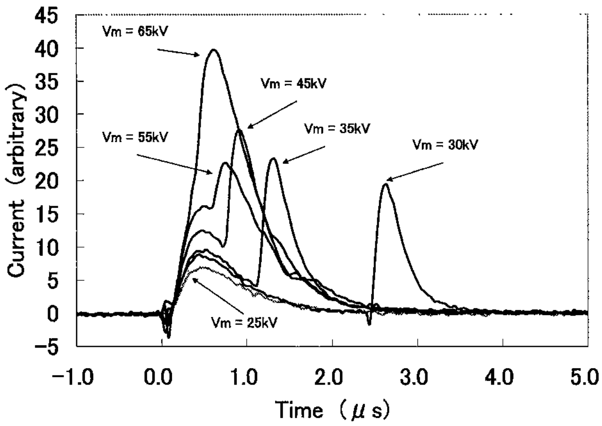


図 8 V_m dependence of first large pulse
Temperature is 20 °C

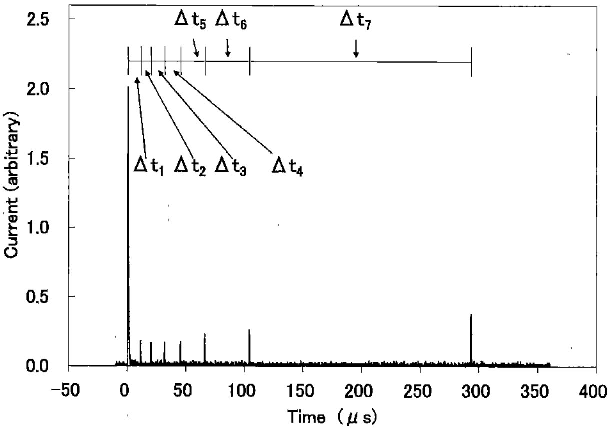


図 9 Time interval between current pulses
V_m = 60kV(1.2/50μs),Temperature: 20 °C

larger when the applied voltage is increased.

(B) Occurrence of intermittent small current pulses

As mentioned previously (Fig.6), when a large current pulse occurred immediately after voltage application, intermittent small current pulses generated in the wave tail of the applied voltage. In general, it has been reported that the current pulses accompanying the impulse creepage discharges in gases or liquids correspond to the individual branches of the streamers [(10)~(12)]. Concerning the treeing in solid insulating materials, current pulses were generated as small pulses even when the voltage decayed to a lower value (approximately 20kV) in the wave tail of the applied voltage as shown in Fig.6. These small pulses, however, never appeared when applied voltage was V_m=20kV, which means that these pulses appeared only after the formation of tree channels. We have reported previously [(13)] that the tree inception voltage is related to the number of current pulses in a wave tail of applied voltage. There was a linear relation between the applied voltage and the number of current pulses, and the inception voltage was determined by an extrapolation of this linear relation. Microscopic observation showed that this

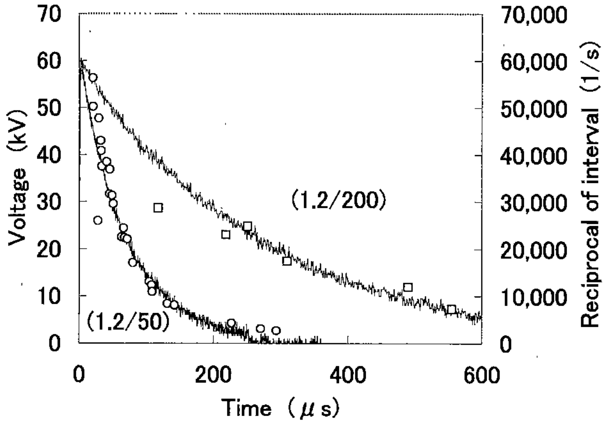


図 10 Relationship between applied voltage wave form and reciprocal of Δt
V_m=60kV (1.2/50μs), temperature: 20°C
○: 1.2/50μs impulse voltage, □: 1.2/200μs impulse voltage.

extrapolation was consistent with the morphologies of tree inception. In the present study, furthermore, we noticed the relationship between the time intervals and the current pulses.

Figure 9 shows the time intervals Δt between intermittent current pulses which occurred after the treeing. The time intervals were represented as time differences between two current pulses. The Δt increased with the lapse of time, and there was no change in the V_m value of applied voltage. This suggests that the occurrence of the current pulses depends on the attenuating degree of voltage in the wave tail. This can be illustrated by the statistical relationship between the reciprocal of Δt and the applied voltage as shown in Fig.10. We see that the reciprocals of Δt being multiplied by scaling factors 0.5 and 3.23 correlate to the applied voltage wave forms with two wave tails, 1.2/50μs and 1.2/200μs, respectively. It is evident that if the wave tails of the applied voltages are different, the intermittent current pulses occur at different time intervals depending on the attenuating degree of voltage.

We might also expect to find criteria between the attenuated voltage (ΔV) and the time (Δt) in the interval between the current pulses. Figure 11 shows the relationship between ΔV and Δt which were measured in a range of V_m=30 to 80kV for the impulse voltage with two wave tails. In all data, the standard deviation of ΔV was distributed in a range of approximately 5 to 20kV: the ΔV was in a range of 5 to 17kV for the impulse voltage of 1.2/50μs and of 10 to 20kV for that of 1.2/200μs.

Furthermore, we can calculate the probability P to find a current pulse for any ΔV value on the basis of the data in Fig.11 using the following steps. All data(Σn_i) were sorted over ΔV. The number of ΔV within 1 kV range (n_i) was counted. The probability P is defined as $n_i/\Sigma n_i$. The voltage difference between ΔV_{i-1} and ΔV_i is 1kV. n_i represents the number of current pulses in which ΔV is between ΔV_{i-1} and ΔV_i . Figure 12 shows the relationships between P and ΔV, which are roughly fitted to a Gaussian distribution. This means

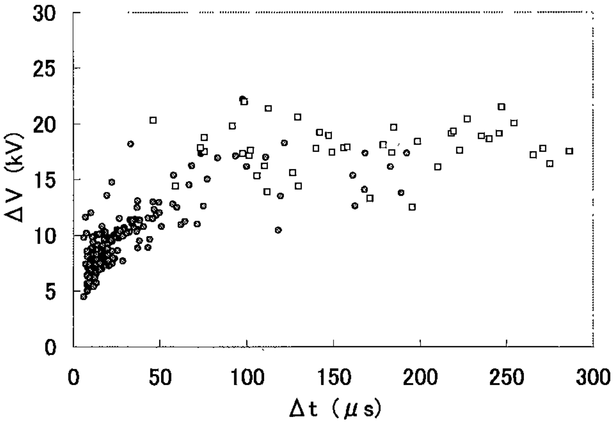


図 11 Relationship between (ΔV) and (Δt)
•: 1.2/50μs, □: 1.2/200μs
ΔV and Δt were measured in a range of V_m = 30kV to 80kV

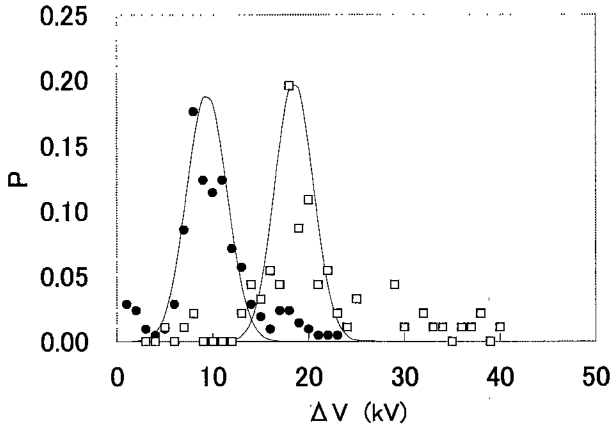
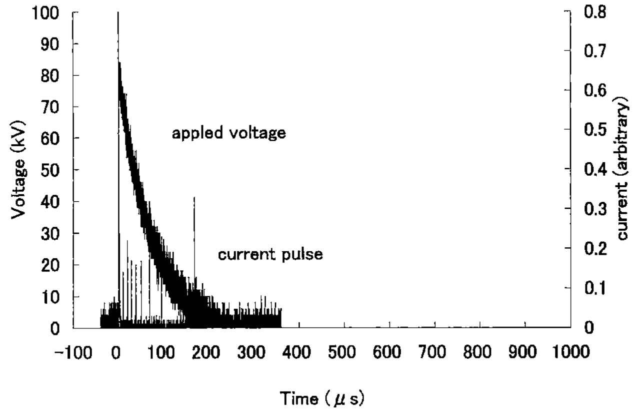
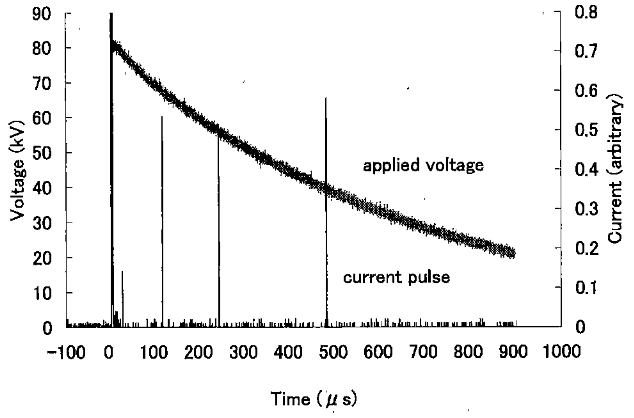


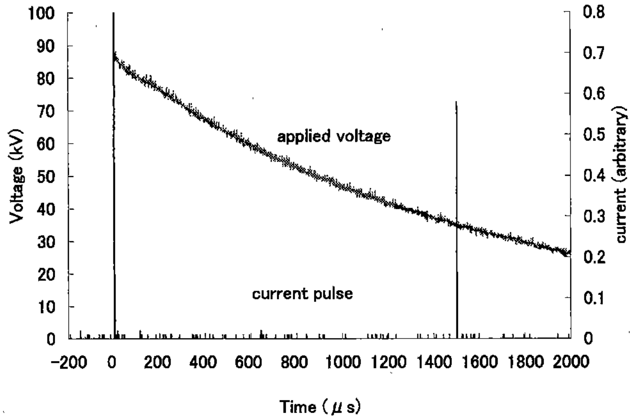
図 12 Relationship between P and ΔV
•: 1.2/50μs, □: 1.2/200μs.
Two solid lines represent Gaussian distribution.



(a) 1.2/50μs



(b) 1.2/400μs



(c) 1.2/1000μs

図 13 Difference in wave tails

that the intermittent current pulses are readily occur when the ΔV reaches the corresponding critical value for each applied voltage with the different wave tails. In this experiment, the critical ΔV values were 9.4kV for the impulse voltage of 1.2/50μs and 18.5kV for that of 1.2/200μs.

According to these results, it is thought that the occurrence of intermittent current pulses in the wave tail of the applied voltage is due to the movement of electric charges accumulated on the inside of tree channels. When an impulse voltage is applied to the sample polyethylene, electric charges are injected simultaneously with the treeing, and charges will accumulate in the tree channels. These charges create an electric potential (V_c) between the electrodes. The V_c remains constant unless the charge moves. The impulse voltage (V) which is applied to the needle electrode decays gradually in the wave tail. As the voltage decays a potential difference between V and V_c will occur in the tree channels. It is thought that when this potential difference becomes apparently greater than the critical value ΔV, a current pulse will occur due to the movement of electric charges based on the Coulomb force.

The amplitude of the current pulses and ΔV increase with the lengthening of the wave tail of the applied voltage, but the number of pulses decreases in a measured time scale as shown in Fig.12. It seems that this is related to the migration process of the charges in the tree channels. The migration of charges is a somewhat slower process than the decaying of the voltage at the needle electrode. The charges are redistributed around the needle electrode creating a space charge by migration for the longer time interval, Δt. The attenuated voltage ΔV during Δt is thought to be the equal to the potential difference needed for the charge to migrate. The occurrence of current pulses for the applied voltage with a longer wave tail require a longer time and a greater amplitude (increase by a larger ΔV).

5. Conclusions

The treeing phenomena in ECC polyethylene were investigated using a high-speed ICC and a polarized microscope through the application of a lightning impulse voltage with differing wave tails. The current pulses accompanying the treeing were also measured using a current measurement system with an LED, and the property of the current pulses was discussed on the basis of the experimental data. The results can be summarized as follows.

(1) The trees in ECC polyethylene revealed a very simple shape which propagated along the orientation direction of the sample polyethylene. The tree channels were formed in a plasma state during a very short time (within 1μs). The current pulses accompanying the treeing could be devided into the two kinds distinctive. They differed according to the mechanism which created them - the first large current pulse and subsequent intermittent small current pulses. The first large pulse, which appeared as a single pulse with a relatively large width was generated along with the formation of tree channels. The intermittent small current pulses were observed to be sharp over the long period in the wave tail of the applied voltage after the formation of tree channels.

(2) The occurrence of intermittent current pulses depended on the attenuating degree of voltage in the wave tail. As a result of these current pulses, there was a criteria between the attenuated voltage (ΔV) and the time intervals (Δt) between the pulses. The critical ΔV values were 9.4kV for the impulse voltage of 1.2/50μs and 18.5kV for that of 1.2/200μs.

It was thought that the intermittent current pulses were caused by the rearrangement of electric charges accumulated in the inside of tree channels. The critical ΔV plays an important role in the migration of electric charges insides of the tree channels. Thus, the amplitude and the number of current pulses were also changed by the applying voltage with different wave tails.

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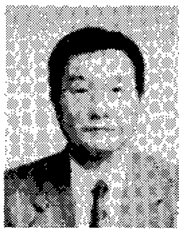

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