Article

Interface Damages of Electrical Insulation in Factory Joints of High Voltage Submarine Cables

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Abstract: As a key accessory of high-voltage (HV) insulated submarine cable, the factory joints of the cross-linked polyethylene (XLPE) represent an unpredictable uncertainty in cable-connecting fabrications by means of the extruded molding joint (EMJ) technique. The electrical breakdown pathways formed at the interfaces between recovery insulation and cable body under alternative current 500 kV voltages are specifically investigated by microstructure characterizations in combination with the electric field and fractal simulations. Dielectric-defected cracks in tens of micrometers in insulation interfaces are identified as the strings of voids, which dominate insulation damages. The abnormal arrangements of XLPE lamellae from scanning electron microscopy (SEM) imply that the structural micro-cracks will be formed under interface stresses. Electrical-tree inception is expedited to a faster propagation due to the poor dielectric property of interface region, manifesting as 30% lower of tree inception voltage. The longer free-paths for accelerating charge carriers in the cracks of interface region will stimulate partial discharging from needle electrodes. The carbonized discharging micro-channels arising in interface region illustrate that the partial discharging will be triggered by the electrical-trees growing preferentially along the defect cracks and could finally develop into insulation damages. The mechanism of forming cracks in the fusion processes between the molten XLPE of cable body and the molten cross-linkable PE of recovery insulation is elucidated, according to which the crack-caused degradation of insulation performance is expected to be alleviated.

Keywords: cross-linked polyethylene; dielectric breakdown; electrical tree; factory joint; high voltage cable

1. Introduction

With the development of wind power generation in seashore and island power networks, great demand lies in the high-voltage submarine cable (HVSC) for electric power transmissions from wind power stations and island power systems to mainland power networks [1–3]. Recently, cross-linked polyethylene (XLPE) has been successfully applied as the essential insulating material for 500 kV HVSC with a single cable length approaching to 18.5 km in China. Furthermore, it is comprehensively required for long submarine cable due to the specific operation environments. However, the current extruding equipment of manufacturing XLPE high-voltage cable cannot achieve sufficient length of submarine cable for offshore power transmissions. Therefore, it is desired to connect...
and assemble submarine cables into a large-length power line by cable joints in a suitable way for remote-sea power transmission engineering. In spite of the significant developments in designing cable joint with the evidently improved thermal-stress distribution and dielectric breakdown strength, it is still acting as the most vulnerable part in HVSC system [4–6]. The traditional cable joint made up with silicone rubber in a complicated structure is incompetent for the relaying operations of HVSC system. As an essential accessory, the factory joint fabricated through the extrusion molding technology (extrusion molding joint, EMJ) is a key factor for the reliability of HVSC system [7]. Recovery insulation of this factory joint as a super-clean cross-linkable polyethylene compound material is extruded into joint mold with an almost identical diameter for cable connections to facilitate submarine cable laying. In coordination with the appropriate countermeasures taken for keeping defect-free in semiconductor-layers, identical material and extrusion process can prevent EMJ fabrications from being contaminated so as to acquire excellent electrical performances. It has been generally accepted that the dielectric performance of EMJ relies on the manufacturing technology of extruding and cross-linking processes [8,9]. It is also affirmed that the contaminants introduced in semiconductor-layer protrusions govern the insulation performances of EMJ. For the voltage grade rising to 500 kV, the high rejection rates of EMJ fabrication from statistical results indicate that weakness points occur not only at the interface between semiconducting and insulating layers but also arise at the interface between cable body and recovery insulation. The most recent report for factory joints of 500 kV submarine cable provided insights into the optimization of XLPE crystalline morphology for ameliorating dielectric performances by modifying the extrusion process of fabricating EMJ [10]. Whereas, the electrical damage occurring in insulation interface has been rarely reported, which motivates us to reveal its mechanism in essence.

The present study focuses on the interface region between cable body and recovery insulation rather than the individual semiconducting and insulating layers. The remarkably distinguished breakdown characteristics suggest that interface region is another dangerous weak point in EMJ in addition to the defects in semiconductor-layer. In order to emphasize on the investigating clue, both 500 kV EMJs with and without electrical breakdown points have been selected for comparison. Moreover, 500 kV EMJ samples without electrical breakdown point are cut into pieces along the interface for micro-structure characterizations by optical microscopy and SEM, in which large number of cracks and discharge channels are found to be a manifestation of abnormal arrangements of lamellae in XLPE crystalline domain. Electrical-tree inception and propagation experiments in combination with electric field and fractal simulations are performed to evaluate the dielectric performances of interface region. Meanwhile, 500 kV EMJ samples with electrical breakdown points are heated into transparency in an oil tank to reveal where the starting points of dielectric breakdown channels are located in interface region. The microstructures of EMJs are explored by analyzing the crystal morphology in interface region to elucidate the underlying mechanism of electrical insulation damages. The dielectric failure mechanism is consistently confirmed by initiation and propagation characteristics of electrical-trees in interface region.

2. Experimental

2.1. EMJ Fabrications

A typical commercial HVSC EMJ consists of inner and outer semiconductor shielding layers, cable body (XLPE) with a stress relief cone, recovery insulation (XLPE), and a copper wire core, as schematically shown in Figure 1. During EMJ fabrications, the copper cores of two cables are connected through the welding process, and the semi-conductive inner shielding layer is recovered through the wrapping heating process outside the copper wire core. Before outer semiconducting layer has been recovered, the cross-linkable polyethylene compound materials are extruded by a small plastic extruder into the chamber covered by a heating tubular mold which is constantly heated to melt the compound materials for cross-linking reactions under the pressure of 1.0 MPa until recovery XLPE
insulation has been formed. After preparation of recovery XLPE insulation, the outer semiconducting layer can also be recovered. The stress relief cone is capable of effectively attenuating the electrical field in the direction along the interface between the cable body and recovery insulation.

![Schematic factory joint of high voltage submarine cable](image1)

**Figure 1.** (a) Schematic factory joint of high voltage submarine cable from which the (b) slice samples of EMJ are produced.

During the preparation of recovery insulation, after the molten PE material has been extruded into the chamber with a temperature of 110–125 °C, the PE material still retains intermediate at a neither a cross-linked state nor a solidified state, by which the PE molecules will be penetrated to be entangled with XLPE molecules of cable body. After the temperature of cross-linking reactions has been raised up to 170 °C, the interface eventually acquires a sufficient mechanical strength for cable, as shown by the tensile fracture results that no broken point appears in interface region. In contrast, 20% breakdown in statistics occurring at the interface of EMJ means that it is a hard way to simultaneously achieve excellent mechanical and electrical strengths in EMJ [9].

### 2.2. Testing and Analysis Methods

The present study focus on analyzing the microstructure of interface region in correlation with the electrical-tree characteristics. Employing the optical microscope and scanning electron microscope (SEM), the microstructures of different insulation domains are observed in the electrical-tree inception and growth experiments to evaluate dielectric performances of EMJ. The mechanism of dielectric deterioration involved in EMJ fabrication is further investigated though finite element simulations of electrical field distribution under 50 Hz alternative voltage. The insulation damages of a typical commercial 500 kV submarine cable EMJ (provided by China State Grid Zhejiang Electric Power Co. Ltd., Hangzhou, China) are investigated at high temperatures in a transparent oil tank to observe the carbonized electrical breakdown channels occurring at the stress relief cone.

Cable samples including EMJ are made into slices in a thickness of 0.3 mm with the cutting surface along cable orientation to present a clear boundary area, which is referenced as interface region for microstructure characterizations, as shown in Figure 1b. The integral conical area is referenced as cable body, while the other XLPE regions are defined as the recovery insulation area. Surface contaminants introduced in sample cutting process are removed by ultrasonic cleaning in deionized water. Then, the topography of the interface region of the sliced sample is preliminarily observed by a polarizing fluorescence microscope (DM2500P, Leica Co., Berlin, Germany).

Slice samples are brittlely fractured in liquid nitrogen at low temperature, and then immersed in the solution for 7 h to observe the spherulitic structures of XLPE [11]. Permanganic acid is used to preferentially etch the amorphous part in spherulites so that the lamellae appear clearly. Subsequently, the fractured slice samples with etched surfaces are washed with a detergent consisting of concentrated sulfuric acid, deionized water and hydrogen peroxide in the volume ratio of 2:7:1 [12]. Finally, a thin gold layer is sputtered onto samples covering all the fractured surfaces to export any undesirable
Charges introduced during SEM characterizations using a field emission scanning electron microscope (SU8020, Hitachi Co., Tokyo, Japan).

For electrical-tree inception and propagation experiments as schematically shown in Figure 2, a special tungsten needle with a radius of curvature of 5 μm is inserted vertically into EMJ samples from the recovery insulation to interface region in an oven at 100 °C, with the needle tip being controlled at a distance of 3 mm from the bottom surface. A layer of thermosetting conductive adhesive has been uniformly coated on bottom surface in a vacuum oven at 80 °C for 48 h to solidify adhesive and eliminate the inside stresses caused by the needle insertion. After taking the HV needle electrode out of the tested sample, the generated electric-trees are observed by the polarizing fluorescence microscope.

![Figure 2. Schematic experimental system of electric tree inception and propagation.](image)

In electrical-tree experiments, the sample is immersed in silicone oil with the inserted needle electrode being connected to alternative current high-voltage power of 50 Hz frequency and the conductive glue electrode being grounded via a copper plate. The step-up mode of increasing voltage is adopted as, boosting up to 2.5 kV at a constant rate of 0.1 kV/s until electric tree inception appears. The optical system, including an in-situ optical microscope and a charge-coupled device (CCD) camera, which are accessed to the computer interface, is utilized to observe the inception and propagation characteristics of electric-trees for a time interval of 5 min. The tree length of 10μm is specified as the tree inception and 10 samples of each material are tested for statistical analyses being fitted with two parameters Weibull statistics. The fitted voltage value with a failure probability of 63.2% is considered as the characteristic voltage for electric-tree inceptions.

3. Results and Discussion

3.1. Characterization and Analysis of Interface Region

A large number of cracks are recognized being parallel to interface extension plane in interface region, as shown in Figure 3 of the morphology photos taken from transparent observations by the optical microscope. The background oblique traces in Figure 3 represent the knife marks (slants) remained after the cutting process, which extend along the vertical direction through the sample as illustrated by Figure 1b. Accordingly, the cracks indicated in Figure 3 just develop along the parabolic interface as referenced in Figure 1b. The cracks with a width of about tens of micrometers extend to several millimeters. It is indicated that these cracks only exist in interface area without any cracks arising in the cable body or recovery insulation with a uniform and continuous morphology. These cracks identify the locations of mechanical weakness, which will contribute to and even dominate the discharging channels of dielectric failures. Subsequently, we further use scanning electron microscopy (SEM) to obtain detailed structural information of interface region in EMJ.
The liquid-nitrogen brittle-fractured cross-sections in cable body, recovery insulation, and interface region are individually characterized by SEM with low magnification (×150) and small ratio scanning scale in a scanning range of 700 μm × 700 μm, as shown in Figure 4. The cable body and recovery insulation exhibit a uniform and smooth texture. In contrast, the cracks in interface region, which have been roughly observed by optical microscopy, display as the strings of voids about 100 μm in size, which just identifies the width of cracks. Structural defects in interface region, which have been inevitably introduced in EMJ fabrication processes, are attributed to the inefficient interpenetration between cable body and recovery insulation. These defects are shown by the cracks on fractured surfaces in millimeter scale as observed by the optical microscope, while being particularly elaborated as the strings of voids in micrometer-resolution SEM characterizations.

**Figure 3.** Optical microscopy photos of interface region in extruded molding joint (EMJ) samples with the indications of defected cracks.

**Figure 4.** SEM images of fractured surfaces localized at (a) cable body, (b) recovery XLPE, and (c) interface region in cross-linked polyethylene (XLPE) EMJ.

### 3.2. SEM Characterization of Crystal Morphology

The microstructure of XLPE consists of crystalline and amorphous regions at room temperature. In crystalline region, XLPE molecules condensate into spherical polycrystals (spherulites) with a diameter in tens of micrometers. The spherulites are formed by the closely stacked lamellae being parallel to the radial directions and centering around spherulites nucleus. In the process of XLPE crystallization, in order to reduce the surface energy, the XLPE molecular chains are regularly and repeatedly folded into a crystal lattice with an unchanged chain length and bond angle, thereby forming a crystal lamella in a thickness of about 10 nm [13]. The areas outside the spherulites are fulfilled by amorphous XLPE condensations. Although the semi-crystalline micro-structure of polymers is too complicated to be legibly comprehended, the random coil model proposed by Flory has been widely approved that the amorphous polymer molecules are engaged in a random coil conformation with the molecule chains being randomly entangled and arbitrarily penetrated [14]. During the injection of melt polyethylene, melt fronts are blended with the cable insulation layer which although in a cross-linked structure shows a certain viscoelastic state at the temperature range of 110–125 °C. Thus,
the macromolecules of injected molten PE are capable of being fused with the molten XLPE of cable body to realize entanglement and penetration [15]. Nevertheless, the cross-linking network structure would highly restrict the movement of macro-molecular chains of cable XLPE, resulting in different structures from both sides of the interface area due to the imperfect entanglement fusion between the cable body and recovery insulation layers. Therefore, the residual interface stresses produced in crystallization process lead to the micro-cracks in interface region. It is reasonably suggested that the voids originate from the destruction of amorphous regions. The previous studies showed the thermal, mechanical, and dielectric properties of XLPE are closely related to these microstructures, as reported by Andjelkovic that the tensile strength and elongation-at-break of XLPE insulation cables are positively correlated with crystallinity [16].

As shown in Figure 5, the crystalline textures of cable and recovery XLPE are relatively smooth without any significant conformation defect. The typical lamella structure and the spherulites with a diameter of about 10 μm are shown after corroding the amorphous domain, while the ridge-like uneven micro-textures appearing on fractured surface indicate the fracture routes through cracks. The restriction of the cross-linking structure in cable body on the entangled movement and even crystallization process of the macromolecular chains is an elaborated manifestation of micro-cracks shown in macroscopic morphology. After surface has been corroded, the considerable disordered arrangements of lamellae are found to demonstrate the poor crystallinity of interface region.

We have dedicated to molecular dynamics simulations of calculating the interaction and force between the polymer chains connected by cross-linking bonds in the XLPE macromolecule structure with a PE-cross-linked network, in comparison to the Van der Waals force between low density polyethylene molecules. The theoretical results show significant mechanical contributions of cross-linking bonds to the interaction between XLPE macromolecular chains. The prospective calculation analyses are in progress and expected to be published in subsequent articles.

**Figure 5.** SEM crystalline textures of fractured XLPE (a) cable body, (b) recovery insulation and (c) interface region.
3.3. Electric Tree Inception and Propagation

Electrical-tree inception voltages fitted with two-parameter Weibull distribution for the three regions in XLPE EMJ are shown in Figure 6, with the shape parameters and the characteristic tree inception voltage being accordingly listed in Table 1. The inception voltage of cable body is 7.8 kV, while recovery insulation and interface region show 11.5% and 30.8% lower inception voltages of 6.9 kV and 5.4 kV respectively. The evident reduction in electric tree inception voltage of interface region is attributed to the micro-cracks in interface region [17]. Charge carriers (electrons or holes emitted from the tip of needle electrode) can accelerate and gain much higher energy under concentrated electric field in the free spaces of voids in cracks, so as to destroy molecular bonds and develop carbonized discharging channels (tree like damages) under a lower inception voltage [18].

![Electric tree inception and propagation](image)

**Figure 6.** Weibull two-parameter statistics of electrical-tree inception voltages for cable body, recovery insulation, and their interface.

**Table 1.** The characteristic electrical-tree inception voltages in 63.2% probability and shape parameters of Weibull distributions fitted in 95% confidence interval.

| Samples       | Shape Parameter | Inception Voltage /kV | Decrease Percentage /% |
|---------------|-----------------|-----------------------|-------------------------|
| Cable body XLPE | 13.34           | 7.8                   | 0                       |
| Recovery XLPE  | 8.04            | 6.9                   | 11.53                   |
| Interface      | 10.07           | 5.4                   | 30.76                   |

Electrical-tree propagation experiments are carried out by applying 7.8 kV voltage to the needle electrode for a time interval of 6000 s. As the propagation characteristics shown in Figure 7, the electrical-trees are initiated into a sparse dendrite geometry with a smaller diameter of tree channels and a significantly longer tree length in interface region than that in cable body and recovery insulation. With the prolongation of applying voltage, the density and diameter of tree channels in cable body and recovery insulation increase gradually as the geometry altering from a sparse branch to a dense and concentrated structure. In contrast, the electrical-trees in interface region persist in the dendritic structure from the initiation to the late stage of growth with an accelerated growth rate. The tree grows not only in the electric field direction, but especially along the direction of interface extension, as it is noted from the sample geometry. The lateral (direction of interface extension) development of tree branches is obviously faster than the vertical (electric field direction) development. As shown in Figure 8, a substantial part of tree branches coincides with the cracks, implying the higher probability of tree propagation along cracks with a faster growth rate, which leads to the remarkable anisotropy of growth characteristics.
3.4. Growth Kinetics of Electric Trees

Electrical-trees usually start at the microscopic structural defects, where the structure deterioration zones with micro-cracks are caused by stress concentrations and thermodynamic drives under electric field and expand to submicroscopic trees, which will finally develop into electrical-tree aging area with macroscopic fractal structures [19]. According to the growth kinetics of the electrically induced micro-cracks in non-crystalline polymer materials, the probability of forming submicroscopic trees can be predicted from its length $L_B$ (m) as following:

$$\text{growth rate of submicroscopic tree} \propto \frac{1}{L_B}$$

implying the higher probability of tree propagation along cracks with macroscopic fractal structures [19].

Figure 7. Electrical-tree growth of XLPE EMJ in (a) cable body, (b) recovery insulation, and (c) interface region.

Figure 8. Electrical-tree propagation along the crack in interface region of XLPE EMJ.
can be determined by calculating the breaking rate of polymeric bonds [20]. The growth rate of submicroscopic trees can be predicted from its length $L_B (m)$ as following:

$$\frac{dY}{dt} = v_0 \exp \left( \frac{U_e - U_0}{kT} \right),$$

$$v_0 = L_B \left( \frac{\omega}{2\pi} \right), \quad U_e = l\pi\varepsilon E^2$$

where $Y (m)$ denotes submicroscopic tree growth quantity, $\omega/2\pi$ (Hz) is intrinsic frequency of atomic vibrations, which indicates the performances associated with molecular vibrations in polymer materials, $U_e$, and $U_0$ (Joule) symbolize the released electrostatic energy and the required activation energy respectively during micro-crack expansions, $\varepsilon$ (F/m) is dielectric permittivity, $E$ (V/m) is local electric filed, $\alpha$ represents the performance parameter associated with molecular vibrations in polymer materials, $l$ (m) signifies the linear dimension of micro-cracks, $k$ is Boltzmann constant, and $T$ (K) is thermodynamic temperature. A dynamic model for time-dependent growth rate of electrical-trees is given by integrating Equation (3) on time $t$ of applying electric voltage to obtain the growth quantity of all submicroscopic trees:

$$Y = L_B \left( \frac{\omega}{2\pi} \right) \exp \left( \frac{al\pi\varepsilon E^2 - U_0}{kT} \right)t$$

The electrical-tree characteristics described in Equation (4) are directly related to the density of micro-cracks in XLPE with a semi-crystalline structure. The exacerbation in molecular polarization and carrier transports for structure defects manifests as the distinctive electric field in cracks.

According to the material dielectric characteristics (relative dielectric constant, electrical conductivity and dielectric loss factor) in different regions of cable joint, the local electric field distributions near cracks are simulated by the finite element method as implemented in COMSOL multi-physics software, with the results being shown in Figure 9. The white triangular region represents the tip electrode inserted into specimen, the circular regions indicate the void (air) micropores in defect cracks, and the intervals between the circles are identical to XLPE matrix. The electric fields in the air micropores of cracks are remarkably higher than that of XLPE matrix, with an obvious concentration of electric fields at the interval (XLPE) between the two adjacent micropores. The dielectric breakdown strength (DBS) and dielectric constant of air micropores in cracks are significantly lower than that of XLPE matrix. Thus, the electric field inside micropores will exceed DBS of air when the tip electrode is located in cracks or the electrical-trees develop to the surface of micropores under electric field. Consequently, the micro-pore surface is carbonized by the instantaneous electric breakdown of air in micropores, causing a considerable enhancement of electric field in XLPE interval between the adjacent micropores and lead to a preferred trend of electric-tree propagation along the string of micropores. Therefore, the electrical-tree will grow consecutively along the crack (a string of micropores) through a subsequent form of internal-breakdown, surface inception and inter-pore crossing. In addition, it is noted from the electric field distributions that the location of tip electrode (tree front) on micropore surface or in interval XLPE will not affect the trend of electrical-tree propagation through the string of micropores in an almost identical process of electric field enhancements, as illustrated by the comparison of left and right panels in Figure 9.
Figure 9. Electric field distributions when initiation tip (identical to tree front) approaching to the string of micropores (crack) in interface region of cable joint, locating on the micro-pore surface (left panels) or into the XLPE interval (right panels). The sequence of figure panels from top to end indicates the developing process of the carbonized breakdown channel through the string of micropores in electrical-tree propagation.

The discharge avalanche theory and fractal geometry indicate that the electrical-tree growth should be considered as a random growth process of fractal clusters consisting of discontinuous micro-cracks [21,22]. Therefore, the growth quantity of electric trees can be defined as the sum of all-part clusters. Based on the fractal structure of electrical-trees, the growth quantity \( Y \) and tree length \( L_B \) varying with the growing time can be evaluated from the growth length \( L \) along electric field and the fractal dimension \( D_f \) of electrical-trees as follows:

\[
Y = (L/L_B)^{D_f}, \\
L = L_B^{(1+1/D_f)} \left( \frac{\exp\left(\frac{\alpha l \delta^2 - U_0}{kT}\right)}{2\alpha l} \right)^{1/D_f} \mu^{1/D_f}
\] (5)

The growth length \( L_B \) increases and decreases exponentially with the increase of local electric field and activation energy respectively. Furthermore, electric field distribution could be approximately calculated as following:

\[
E = \frac{2U}{r \ln(1 + 4R/r)}
\] (6)

where \( U = 7 \, \text{kV} \) is the applied voltage to the tree-initiation tip electrode, \( r = 3 \, \mu\text{m} \) indicates the curvature radius of tip electrode, \( R = 3 \, \text{mm} \) identifies the distance between tip and plate, by which the \( al \) is derived from activation volume \( \Delta V \) (m3) under electric field [23]:

\[
al = \Delta V / 2\pi\varepsilon E^2 , \quad \Delta V = 2.7 \times 10^{-20} \, \text{Joule}
\] (7)

The tree length versus the fractal dimension of the recovery insulation XLPE in cable joint is calculated from Equations (5)–(7) [24]. The activation volume of interface region in cable joint is fitted
from the experimental results of the fractal dimension of electrical-trees, as the results being shown in Figure 10. The fractal dimension of electrical-trees in macroscopic scale implies a longer growth along electric field, as shown by the consistent experimental and theoretical results for cable body or recovery insulation in cable joint. In comparison, the variation slope (absolute value) of electrical-tree length as a function of fractal dimension is appreciably smaller for the interface region, implying that the electrical-tree growth length with the same fractal dimension is significantly reduced along the direction of electric field due to the insulation failure caused by the dielectric breakdown of air micropores in cracks, resulting in the expedited electrical-tree growth along multiple cracks with more circuitous trajectories and a larger activation volume (Equation (7)) in a dispersed geometry, as manifested by the increased fractal dimension of electric trees. Based on the experimental fractal dimension of electrical-trees in the XLPE matrix of cable body, the fractal graphic trees are drawn though a string of polygons in which the fractal dimension is set as 2 to simulate the breakdown process of air micropores in electrical-tree growth, as shown in Figure 10b, which concisely elucidates the propagation mechanism of electrical-trees passing cracks in interface region of factory cable joints. Calculation and experimental results coordinately demonstrate the significant increase of activation energy volume in interface region of cable joints, suggesting that the micro-pore defects produced in the melt access process lead to the rapid growth of electrical-trees in interface region with a propagation rate greatly higher than that in the XLPE matrix of cable body and recovery regions.

![Graph](image_url)

**Figure 10.** (a) Experimental and calculation results of growth length versus fractal dimension of electric trees; (b) 2-dimensional simulation results of tree propagation in pure material (up panel) and though a string of polygons (bottom panel) in which the fractal dimension is set as 2 to represent the breakdown process of air micropores in electric tree growth.

3.5. Electrical Breakdown in the Interface Region

The EMJ joint of 500 kV cable XLPE fabricated by a cable factory in China undergoes the electric breakdown experiments with the applied electrical voltage being increased in a step-up mode of 100 kV/step. A complete carbonized breakdown channel (main breakdown channel) is recognized by heating EMJ sample to be transparent, as shown in Figure 11a. In particular, the planar carbonized region vertical to electric filed implies that the substantial inception and fast propagation of electrical-trees are preferentially occurring at interface area between cable body (bottom) and recovery insulation (top) due to the defect cracks, which can stimulate the partial discharging and dielectric failure along the electric field (perpendicular to interface region of factory joint) that will finally develop into the complete electrical breakdown from internal conductive core to the outer shielding layer of insulation.
Cable. Electrical-trees have been initiated from the weak points (strings of voids) propagate very fast along cracks in interface region under the high electrical field so as to intrigue the main breakdown channel initiating from the interface region and propagating along electric field.

![Image of electrical breakdown](image1.png)

**Figure 11.** (a) Electrical breakdown originating from interface region; (b) polarizing fluorescence microscopy images of the carbonized discharging channel in a breakdown EMJ.

In order to reveal the mechanism of dielectric breakdown of EMJ, the slice samples near breakdown initiation point are investigated by optical microscopy. As shown in Figure 11b, some carbonized channels with a diameter of tens of micrometers extend through hundreds of micrometers in interface region of XLPE EMJ. It is noted that the carbonized channels propagate essentially along the crack’s route after they have once met together. This implies that the voids in the cracks of interface region expedite the formation of discharging channels and thereby cause the electrical-trees developing preferably along the cracks, which can be recognized as weak points. Because the electrical energy is primarily released through and concentrated on the discharging channels, these discharging micro-channels will eventually develop into main breakdown channels. Therefore, the carbonized micro-channels may be the precursor to the insulation damage of XLPE cable initiated in interface region of EMJ. Once a tree-like micro-channel develops into the main breakdown channel in electrical-tree experiments, no crack-patterned micro-channel will be further engendered because the electrode electrical field in this situation is not as divergent as the needle-to-plate configuration. The further deduction supports the conclusion that the cracks in interface region dominate the dielectric breakdown of commercial high-voltage cable connectors, which is directly attributed to the inefficient inter-fusion of macromolecular chains at the interface of cable body and recovery connection. It is a promising technological strategy of ameliorating the polyethylene extruding and cross-linking processes of recovery insulation with a suitable temperature and time for highly efficient fusion of macromolecular chains between cable body and recovery XLPE to impede the generation of interface cracks and thus increase the reliability of EMJ fabrications.

4. Conclusions

In high interest of investigating the electrical breakdown channels in EMJs of XLPE submarine cables, the substantial cracks observed by optical microscopy and SEM in interface region manifest as strings of voids with the sizes of 10–100 µm which are verified to account for electrical insulation damages. Considering the limitation of macromolecule chains entanglement and penetration actions during interface fusion in EMJ fabrication processes, these cracks are characterized by SEM to be derived from the abnormal arrangement of lamellae in interface region.

Electrical-tree inception and propagation tests distinguish the poor insulation properties of interface region in EMJ, showing about 30% lower of tree inception voltage which can be attributed
to that the long free paths of charge carries in the cracks of interface region will trigger discharging from needle electrode. The electrical-tree propagation with a fast speed along the direction vertical to electric field is also due to the existence of cracks in interface region. By heating a breakdown sample of EMJ into the transparent state, we obtain an in-situ image of the breakdown channel initiating from the interface region and propagating along electric field direction. Optical microscopy is also employed to observe the microstructure of interface region in EMJ, which demonstrates different sizes of localized carbonization channels being around the cracks in interface region. This phenomenon just confirms our previous series of associations.

Even though the imperfection of fusion interface will inevitably exist in the connection processes of EMJ fabrications, we hold the opinion that the fusion of cable body and recovery insulation may be improved by adjusting physical conditions such as elevating temperature in a long duration time of reactions and applying pressure etc. in EMJ preparation processes.

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