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Enhancing the Bonding of Insulated Homogeneous Interfaces in Factory Joints via Ultrasonic Vibration

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Abstract. The interface between the body and recovery insulation in factory joints is susceptible to localized electromechanical weaknesses, potentially compromising the long-term reliability of high-voltage direct current (HVDC) submarine cable systems. This study introduces ultrasonic vibration into the insulation recovery process of these joints. The effects of ultrasonic treatment are evaluated through tensile tests, thermal elongation tests, DC breakdown tests, and space-charge characterization. Results demonstrate that ultrasonic treatment significantly enhances interfacial tensile properties, improves deformation stability under thermal loading, increases the DC breakdown strength of the insulation interface, and significantly suppresses negative space-charge accumulation. These improvements are attributed to the high-frequency acoustic pressure and localized temperature rise induced by ultrasonic vibration, which promote molecular-chain melting and rearrangement, thereby reducing microscopic defects. This study provides an innovative method for the insulation recovery forming process in factory joints to improve interfacial reliability.

Introduction

Against the backdrop of global energy transition, the demand for long-distance and large-scale integration of renewable energy is steadily increasing. High voltage direct current (HVDC) transmission technology, with its advantages of low loss and large capacity, especially when combined with cross-linked polyethylene (XLPE) insulated cables, has become a core solution for offshore wind power integration and regional interconnections [1]. Nevertheless, the reliability of HVDC cable systems faces significant challenges, with factory joints representing key weak points [2,3].

During the manufacturing of factory joints, a "secondary bonding interface" forms between the cable body insulation and the recovery insulation [4]. Located within the thermal press cross-linking transition zone, this interface is susceptible to microscopic defects, uneven crystallization, and space charge accumulation. These issues lead to electric field distortion and accelerated insulation aging [5]. Prior studies indicate that controlling interface roughness and degassing processes can improve crystallization behavior and suppress charge accumulation [6]. In advanced manufacturing, ultrasonic technology has been applied in fields such as polymer welding to enhance interface properties. By generating high-frequency vibration-induced thermal and mechanical effects, ultrasonic treatment strengthens interface bonding and eliminates defects [7–11].

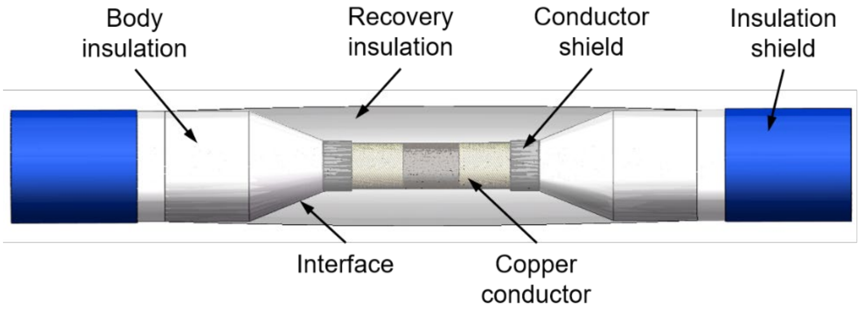

Fig. 1. Schematic diagram of the factory joint structure in high-voltage submarine cables.

In this study, ultrasonic vibration was introduced during the insulation recovery molding process of factory joints to enhance the secondary bonding at the interface. First, an ultrasonic vibration enhanced bonding platform was established. Subsequently, through tensile tests, thermal elongation tests, DC breakdown tests, and space charge tests, the changes in mechanical and electrical properties of the insulated interface under ultrasonic treatment were investigated. Finally, the mechanism underlying ultrasonic vibration enhancement was elucidated.

Materials and Methods

An ultrasonic vibration-enhanced bonding platform was developed by modifying a MAXWIDE® ME-1800 ultrasonic welding system (Minghe, Taiwan). The system includes an ultrasonic generator controller, power supply, pneumatic controller, operation time controller, stroke controller, and an automatic overload protection device.

Based on the thermal properties of XLPE (Fig.2), the conventional forming process for factory joint insulation recovery involves extrusion at 110~120°C, followed by vulcanization molding at 160~170°C. In the developed ultrasonic vibration-enhanced process, ultrasound is applied directly to the interface before the vulcanization step. The ultrasonic parameters were set to a frequency of 20 kHz with 50% amplitude. The vibration cycle was programmed as 4 seconds of ultrasonics followed by a 2-second pause interval. During operation, the sonotrode was automatically traversed along the interface, as illustrated in Fig.3.

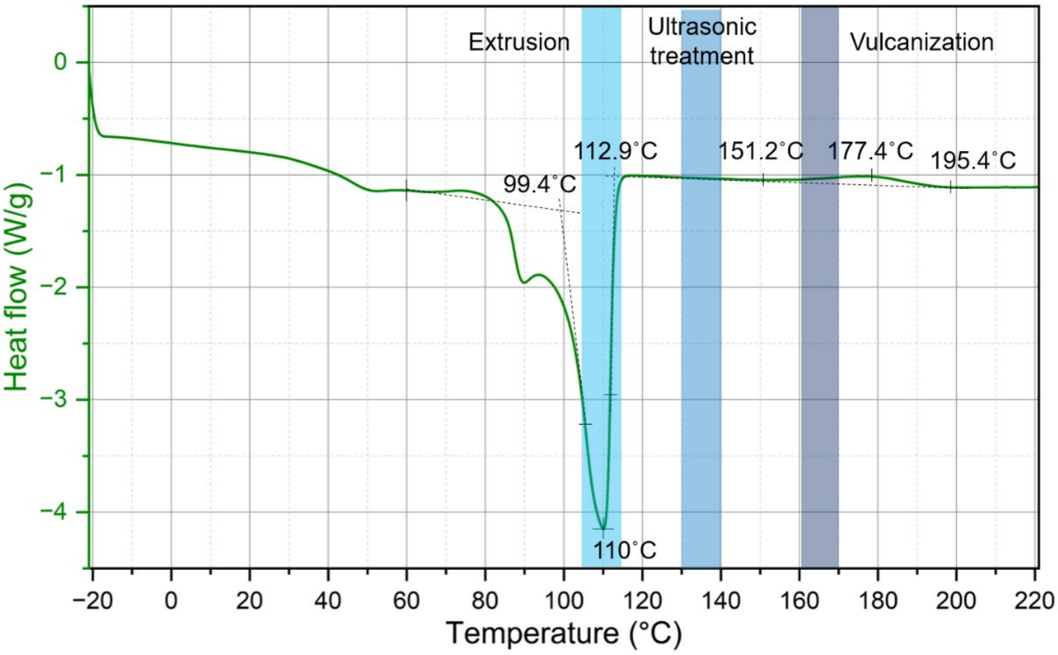

Fig. 2. Non-isothermal DSC curve of the XLPE material used for the factory joint.

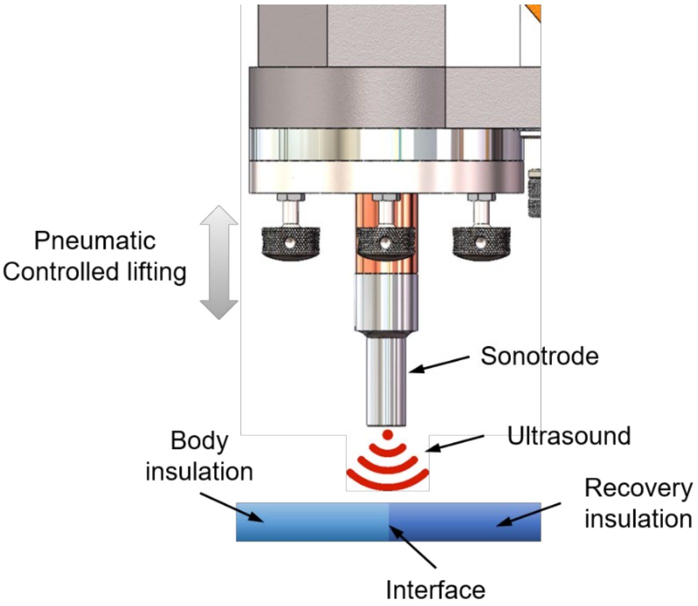

Fig. 3. Schematic diagram of the ultrasonic vibration-enhanced process for interfacial bonding.

Real-time monitoring of acoustic pressure and temperature was performed at the interface, as shown in Fig.4. This revealed that ultrasonic vibration induces a rapid local temperature increase, reaching 130°C within 4 seconds and stabilizing at approximately 140°C. Furthermore, an instantaneous high-frequency acoustic pressure of about 120 kPa can be generated within milliseconds.

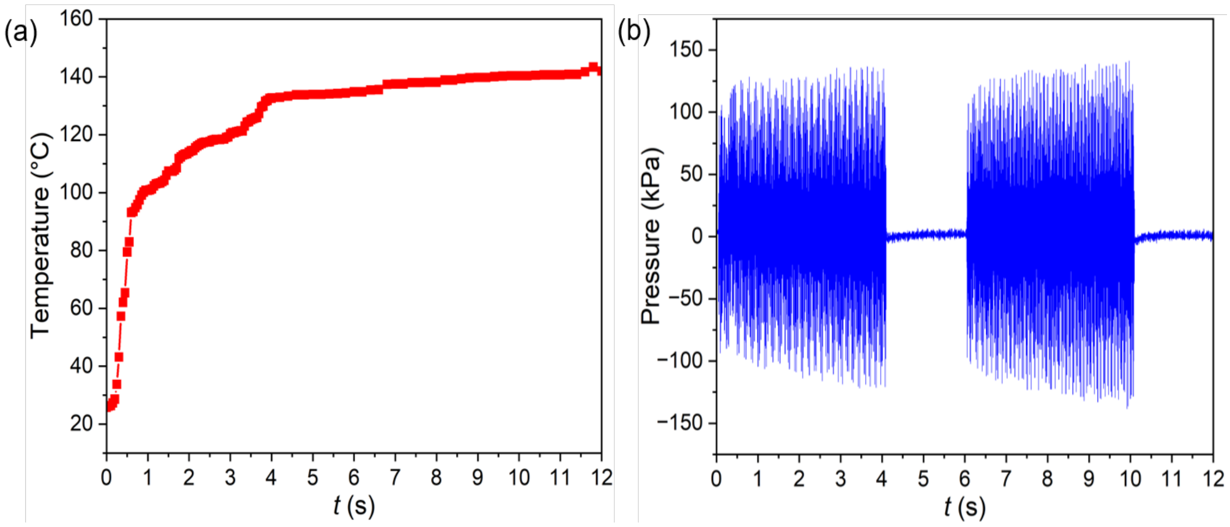

Fig. 4. (a) High-frequency acoustic pressure and (b) temperature distribution curves at the interface during ultrasonic treatment.

For mechanical characterization, tensile tests were performed on a Sans UTM6104 universal testing machine at a crosshead speed of 200 mm/min, in accordance with the GB/T 1040-2006 standard. Thermal elongation properties of samples were evaluated following IEC 60811-202:2023 guidelines. To assess electrical performance, DC breakdown strength tests were conducted using a ZJC-100kV DC breakdown strength tester (Beijing Zhonghang Times Instrument Co., Ltd). The tests employed a pillar-to-pillar configuration with a diameter of 25 mm. A voltage ramp rate of 2 kV/s was applied until breakdown occurred. Spatial charge distribution within the factory joint specimens was characterized using the pulsed electro-acoustic (PEA) method. Prior to measurement, samples were subjected to a DC electric field of 20 kV/mm at 30°C for 30 minutes (polarization phase), followed by a depolarization period of 10 minutes.

Results and Discussion

- **Mechanical Properties Enhancement**

The mechanical behavior of the body and recovery insulations was illustrated in Fig.5. Both maintained a tensile strength of approximately 19 MPa and an elongation at break of about 600%. These results indicated no significant difference between them. For the conventional processed interface samples, the tensile strength and elongation were measured at 10.7 MPa and 336%, respectively. With the application of ultrasonic treatment, the interfacial bonding quality was significantly enhanced, as evidenced by an increase in tensile strength to 12.7 MPa, representing an improvement of approximately 20% compared to the conventional processed samples. Additionally, the elongation at break reached 458%, corresponding to an increase of about 40%.

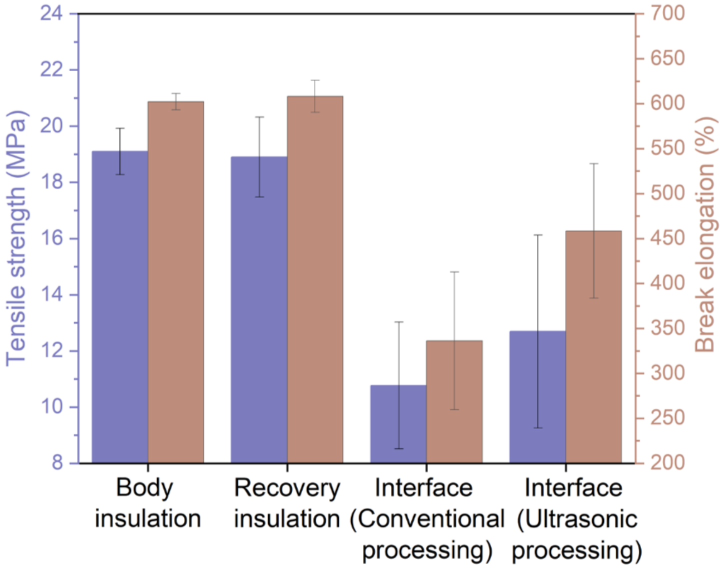

Fig. 5. Tensile properties of factory joint XLPE insulation.

- **Thermal stability improvement**

As illustrated in Fig.6, the thermal elongation rates of body and recovery insulation were similar, at 60% and 64%, respectively, with both exhibiting zero permanent elongation. Compared to the conventional group, ultrasonic treatment reduced thermal elongation from 127% to 110% and permanent elongation from 9% to 3%. These findings indicated that ultrasonic vibration effectively enhances the dimensional stability of the interface under thermal loading.

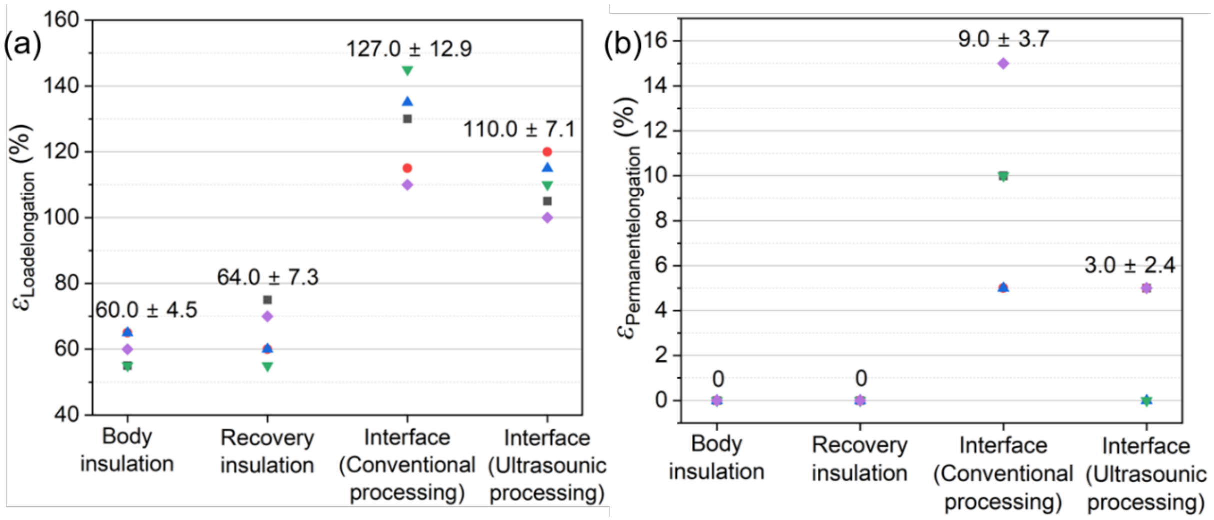

Fig. 6. Thermal Elongation Properties of factory joint XLPE insulation (a) Load elongation (b) Permanent elongation.

- **DC breakdown behavior**

The DC breakdown strength of the insulation was characterized based on Weibull statistics analysis, as illustrated in Fig.7. The body insulation and the recovery insulation exhibited comparable breakdown levels, with characteristic breakdown strengths of approximately 395 kV/mm and 360 kV/mm, respectively. In contrast, the conventional processed interface samples demonstrated a reduction in breakdown strength to about 297 kV/mm. Following ultrasonic treatment, the breakdown strength increased notably to around 334 kV/mm, representing an improvement of about 13% relative to the conventional processed interface samples. These findings indicated that the ultrasonic application effectively enhanced the both interfacial breakdown strength and stability of the insulation.

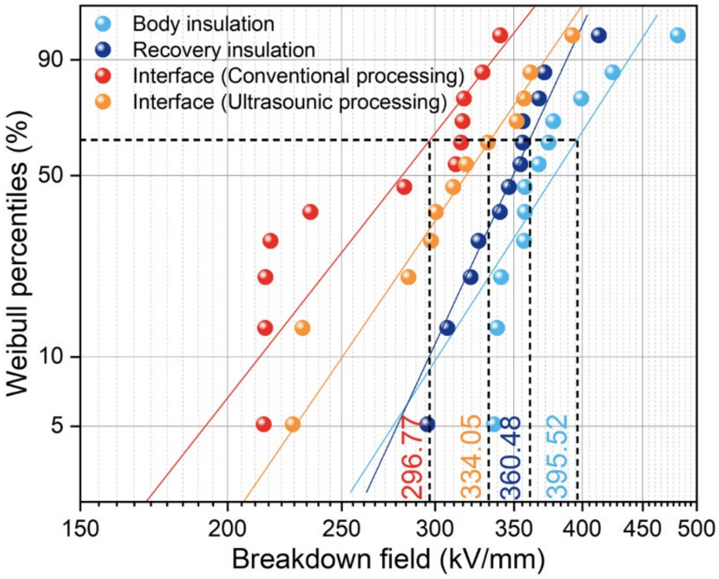

Fig. 7. DC Breakdown Strength of factory joint XLPE insulation.

- **Space charge suppression**

The space charge results (Fig.8) clearly demonstrated the variations in carrier injection, migration, and trapping across distinct interface conditions. During the initial phase of DC electric field application, charge injection primarily initiates near the electrode, with electrons being preferentially injected from the cathode and migrating toward the anode under the electric field influence. The charge cloud progressively extended along the sample thickness. Trap distributions and non-uniform conductivity hindered deep penetration of space charges. Consequently, charges accumulate locally.

In the conventional processed samples, interfacial negative charge accumulation was enhanced. The interface tended to retain charges, causing distortion of the local electric field and heightened energy injection, potentially triggering electrical treeing, local heat accumulation, or micro-defect discharge. Consequently, the interface became a vulnerable site for breakdown initiation, leading to reduced and more scattered breakdown strength. In contrast, ultrasonic treatment effectively suppressed the accumulation of negative charges at the interface. The high-frequency sound pressure and local temperature rise promoted secondary reinforcement of melt bonding, thereby mitigating the effects of trapping and charge retention. This resulted in a more uniform local electric field, thus enhancing breakdown strength and stability.

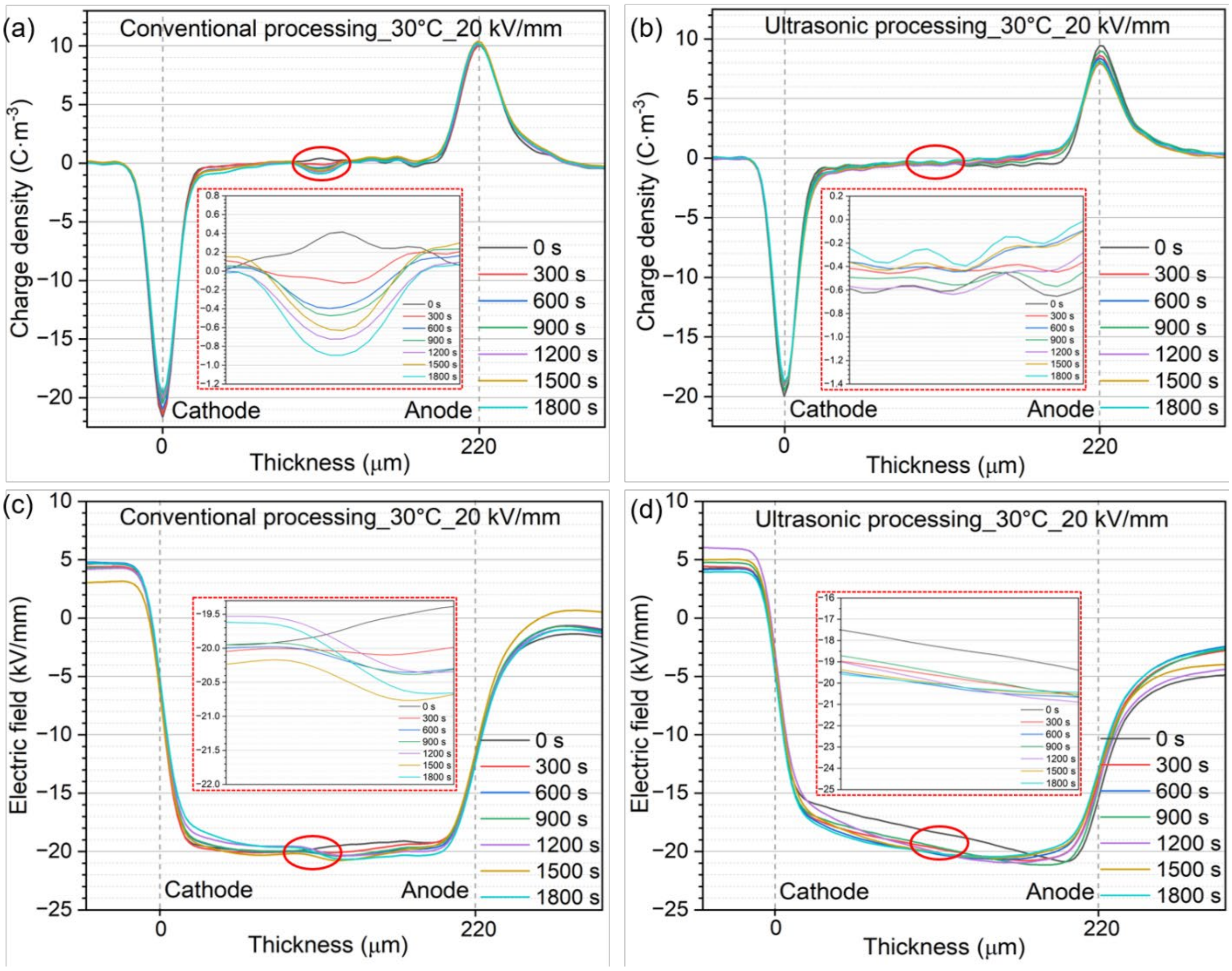

Fig. 8. Space charge profiles at various time under 20 kV/mm at 30˚C: (a) Charge density of conventional processed interface sample, (b) Charge density of ultrasonic processed samples, (c) Electric field of conventional processed interface sample and (d)Electric field of ultrasonic processed samples.

Summary

This study implements ultrasonic vibration in the recovery insulation forming process in HVDC cable factory joints, achieving significant improvements in both mechanical and electrical properties at the body/recovery insulation interfaces.

(1) Through ultrasonic treatment, the interfacial tensile strength increased by approximately 20%, and the elongation at break increased by about 40%. Both thermal elongation rate and permanent elongation rate were significantly reduced, signifying significant enhancement in interfacial deformation stability and bonding quality.

(2) Compared with conventional processing, ultrasonic processing increased the DC breakdown strength of the insulation interface by approximately 13%. Furthermore, space charge accumulation was effectively suppressed, and the interfacial electric field distribution became more uniform, thereby enhancing voltage withstand capability and long-term reliability.

(3) Ultrasonic high-frequency acoustic pressure and local temperature rise effectively promoted molecular chain melting, rearrangement, and interface densification, consequently eliminating microscopic defects and charge traps.

Acknowledgment

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