Cold Spray-Based Connector Technology for Reliable Connections in HVDC Submarine Cables

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ABSTRACT

To help expand electrical grids, the Alu-Cu Connector enables reliable joining of large Al or Cu conductors for AC and DC applications using cold-sprayed conductive Al-Ag and Cu-Ag coatings. Connections are possible without prior surface cleaning and ensure long-term electrical/mechanical bonding. In HVDC submarine cables, water blocking compounds (WBCs) challenge conventional methods. The Alu-Cu Connector encapsulates WBCs beneath the coating, preventing leakage and suppressing Al_2O_3 *formation. Even under unlikely extreme WBC leakage, no degradation occurs during thermal cycling. The outer Ag coating preserves high thermal stability by shielding inner Al coating. Results confirm the connector's robustness for demanding HVDC applications.*

KEYWORDS

Connector, Cold Spray Coating, HVDC Cable Jointing, Water Barrier Compound, Aluminium Conductor, Copper Conductor

INTRODUCTION

The global shift toward electrification is accelerating, driven by renewable energy expansion, electrified transport, and cross-border interconnections. This transformation places growing demands on electrical transmission infrastructure across all voltage levels. Alongside the need for new high-voltage (HV) transmission lines, many existing systems – particularly in Europe – are aging and nearing the end of their operational lifetimes, adding pressure for replacement and modernization. To meet these demands, HV cables with increasingly large conductor cross-sections – exceeding 3,000 mm² [1] and reaching up to 4,500 mm² (presented at CIGRE 2022 session) – are being deployed in both alternating current (AC) and direct current (DC) systems to ensure future capacity, reliability, and resilience.

Copper (Cu) has traditionally been the preferred conductor material for HV cables due to its excellent electrical conductivity, which minimizes resistive losses over long distances. Its high thermal conductivity, mechanical strength, and compatibility with various insulation systems have further supported its use in demanding environments. More recently, aluminum (Al) has gained traction, especially in large-scale transmission projects, where its lower cost per current carrying capacity makes it a compelling alternative. As conductor sizes grow, aluminum's economic advantage becomes more pronounced. Transmission lines often span over several 100 km, while individual cable sections are typically limited to around 1 km for land cables. These sections must be joined in-field with connections that are both electrically and mechanically reliable over the system's lifetime.

Several joining techniques are currently used, each with strengths and limitations. Shear-bolt connectors are widely adopted for their simplicity and ease of installation. However, maintaining stable electrical contact over time in aluminum conductors remains a known challenge in the industry, which is due to oxidation at contact points, increasing resistance and degrading performance. These issues tend to emerge during long-term testing and operation or under high-load conditions (short-circuits) and may currently be underreported as most installed systems operate far below the maximum load levels. Welding is generally considered the most robust method for joining large conductors (≥1600 mm²), as it fuses individual strands into a single body, eliminating the need for radial inter-strand electrical contact required for shear-bolt connection. Yet welding is slow, labor-intensive, and requires skilled personnel and careful thermal management – such as forced cooling – to avoid damaging nearby insulation. It also demands complete removal of any organic or inorganic materials at the conductor ends, including WBCs, enamel coatings, and oxide layers.

ALU-CU CONNECTOR

To address these challenges, a universal, reliable, and compact connector – referred to hereafter as the Alu-Cu Connector – was developed and commercialized. It is designed for use with both copper and aluminium conductors in AC and DC systems. The Alu-Cu Connector is optimized for fast in-field installation without the need for extensive surface preparation or any cleaning. It consists of four main components (Figure 1):

1. A mechanical compression system (pull clamp),
2. A cold-sprayed (CS) contact layer,
3. A flexible silver (Ag) contact element, and
4. An axial force-transferring and locking system (outer shells).

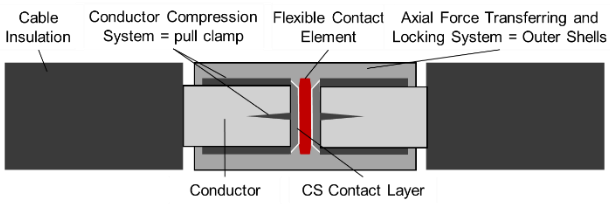


Fig. 1: Systematic illustration of components used in the Alu-Cu Connector.

<u>(1) Mechanical Compression – pull clamp</u>

Conventional radial clamping techniques – such as hydraulic crimping (requiring tools exceeding 100 kg) or shear bolt connectors – often introduce severe local deformation of strands and necessitate large ferrules to ensure sufficient holding strength. These methods aim to achieve both high axial holding force and low, stable electrical contact resistance.

In contrast, the pull clamp in the Alu-Cu Connector is designed solely to establish mechanical interlocking between the clamp and the conductor strands. It employs an axial crimping approach, avoiding the drawbacks of traditional systems. This is achieved through a flexible internal collet and an expanding central wedge, over which a conical-shaped conus is pulled to generate high compression force (Figures 2 and 3). The conical geometry, combined with the collet's flexibility, enables efficient force transfer while significantly reducing the required hydraulic power. As a result, tool weight is reduced from approximately 100 kg (in conventional systems) to around 15 kg, making portable in-field installation feasible.

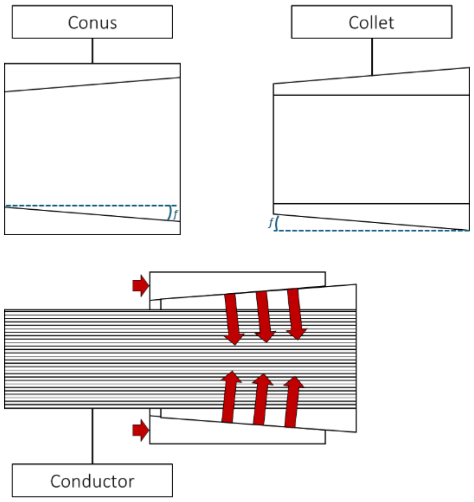


Fig. 2: Schematic diagram of the collet and conus, illustrating the underlying pull-and-clamp mechanism.

Once the conus is fully engaged over the collet, any protruding parts are cut off. At this point, conductor ends are compressed into a flush surface, ready for subsequent coating.

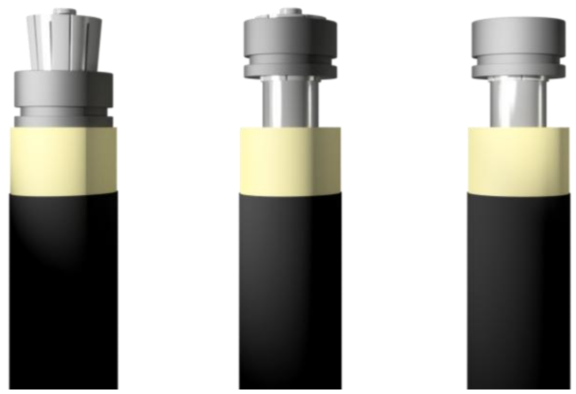


Fig. 3: Pull clamp components.

(2) CS Contact layer

At the heart of the technology, the Alu-Cu Connector uses cold-sprayed coatings to unify conductor strand ends into a single conductive body, similar to welding. However, unlike welding, cold spraying is a solid-state, low-temperature process. The feedstock material remains below its melting point. Thermal damage to surrounding insulation is avoided, eliminating the need to remove organic or inorganic materials at the deposition zone. During cold spraying, fine metallic particles (typically micrometer-sized) are dragged into a heated, high-pressure gas stream and accelerated to supersonic velocities through a converging-diverging nozzle (Figure 4). Upon impact, particles deform plastically and bond to the substrate via kinetic energy. Bonding occurs only if the particles exceed a material-specific critical velocity, ensuring sufficient deformation and oxide disruption at the interface.

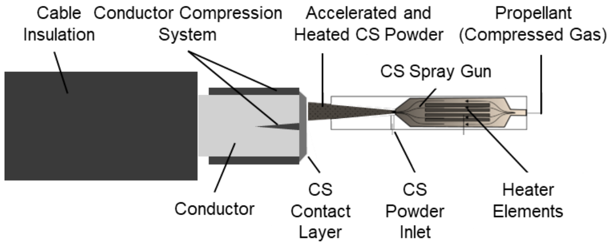


Fig. 4: Cold Spray Process.

The bonding mechanism relies on the displacement of surface oxides – on both particles and substrate – during impact, resulting in clean metal-to-metal contact and a dense, conductive coating. The process is highly tuneable: for instance, particle velocity can be increased by adjusting gas pressure and temperature, while critical velocity can be lowered by optimizing particle morphology, size distribution, and the use of peening media. The spray gun traverses the conductor's surface in a controlled pattern, building up the coating layer-by-layer with precise control over thickness and uniformity.

In the Alu-Cu Connector, the cold-sprayed coating consists of two layers (Figure 5). The inner layer is aluminium (for Al conductors) or copper (for Cu conductors), typically 1–2 mm thick, and ensures direct electrical contact with the strands, thereby forming a unified conductive body. The outer layer is silver, deposited as a dense coating to seal the inner layer from oxygen exposure and prevent electrical degradation. Ag is applied as a thin layer (several hundred micrometres) to minimize material costs.

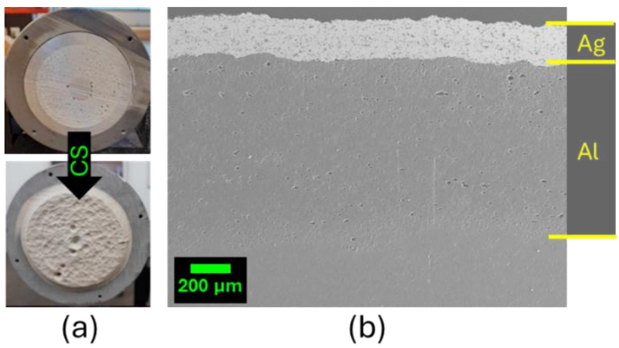


Fig. 5: (a) Alu-Cu Connector before and after CS coating application. (b) Cross-sectional view of the CS coating.

The beneficial effect of Ag coating is demonstrated in Figure 6, comparing the temperature stability during a thermal cycling test – inspired by Cigre TB758 – of the Alu-Cu connector with two coating configurations: one with a final Ag layer (Al–Ag coating) and one with only Al. Each cycle includes at least a 2.5 h stability phase maintaining the reference conductor at 120 °C ± 2 °C. A high-current loop setup (up to 6 kA) was employed (Figure 7), which enabled comparison between a 5 m reference Al conductor and two 2.5 m conductor ends connected by the Alu-Cu Connector. A custom injection system using the same CS contact layer and flexible Ag contact element as the Alu-Cu Connector facilitated quick connection to busbars. Currents up to 4.5 kA are used to heat the reference conductor to 120 °C, then the current is reduced to ~3.4 kA to maintain reference temperature. Connector temperatures were continuously measured at multiple points (TK1–8) and compared to the reference conductor.

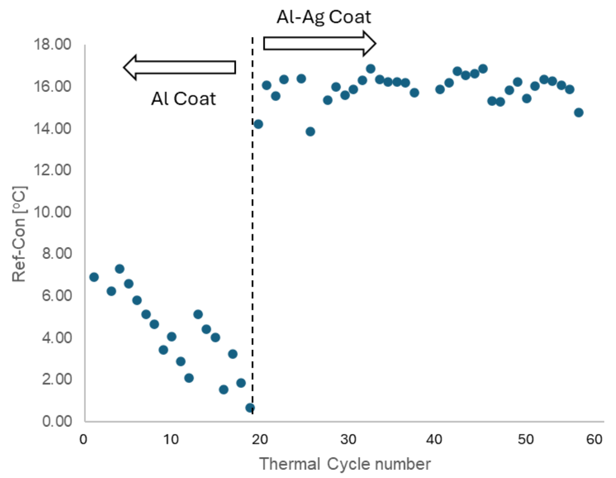


Fig. 6: Average temperature difference during the stability period at 120 °C ± 2 °C between the Reference Conductor (TK4) and Alu-Cu Connector (TK3), using either the Al coating (first 20 cycles) or the final Al–Ag coating (last 40 cycles).

Figure 6 presents the average temperature difference observed during the stability period between the Reference Conductor without a connector (TK4) and the Connector (TK3), both before (first 20 cycles) and after the application of the additional Ag coating (subsequent 40 cycles). When only Al coating is used, the connector exhibits a temperature increase of approximately 7 °C, reaching that of the reference conductor after the initial 20 cycles. In contrast, the Al–Ag coating configuration maintains a desired lower and stable temperature throughout the remaining 40 cycles, with the connector being 14–17 °C cooler than the reference conductor. These results clearly demonstrate the protective effect of the Ag coating. The proposed mechanism is that the Ag coating inhibits oxidation of the underlying Al coating, thereby preserving the electrical performance of the contact interface over time.

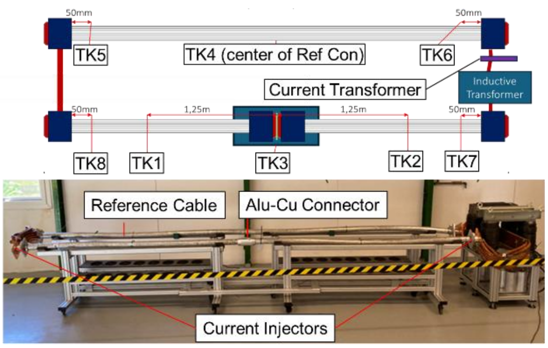


Fig. 7: Thermal test loop configuration.

(3) Flexible Ag contact element

Between the coated ends, a flexible Ag contact element is inserted (Figure 1). This element conforms to the CS surface topography under compression, ensuring even distribution of contact points and providing a stable, low-resistance electrical connection. Using silver for both the outer coating and the flexible element ensures high material compatibility via Ag-to-Ag-to-Ag contact. Silver is selected for its excellent and stable electrical conductivity.

(4) Axial Force Transfer – Outer Shells

After cold spraying and placing the flexible Ag contact element between the coated conductor ends, two outer shells are fitted over the pull clamp components. Spring-loaded bolts at the rear apply axial force across the contact zone, compressing the flexible contact element to complete the connection. This pre-tension from the bolts can handle maximum axial test forces above 80 kN, which ensures stable connection during cable installation and operation. The final connector assembly is shown in Figure 8.

Fig. 8: Final Al-Cu Connector.

RESEARCH MOTIVATION AND AIM

This paper presents the latest evolution of the Alu-Cu Connector, extending its applicability from AC to DC cable systems. Previous work demonstrated its promise for Al and Cu conductors [2,3], but did not confirm long-term thermal and electrical stability for aluminium conductors – first presented here in Figure 6. Additionally, the suitability of the Alu-Cu Connector for HVDC cables, with their specific challenges, had not been previously addressed. In AC cables, conductor strands often include an insulating layer to mitigate losses from skin and proximity effects – typically enamel for Cu and naturally formed Al_2O_3 for Al. DC cables do not suffer from these effects and therefore Cu conductors do not use insulating strand layers. However, for Al conductors Al_2O_3 formation cannot be avoided, and DC cables generally include other materials at the conductor ends, especially in submarine applications. WBCs – such as swelling tapes, powders, or paste – are used to prevent water ingress and protect the cable core. Like enamel coatings in AC cables, WBCs are difficult to remove but must be cleaned away to ensure reliable connection when using conventional methods.

The aim of this study is to evaluate the suitability of the Alu-Cu Connector for HVDC cables, which offers the advantage of enabling installation without prior cleaning of WBCs or other surface materials.

EXPERIMENTAL INVESTIGATION OF THE ALU-CU CONNECTOR FOR HVDC KEY-STONE ALUMINIUM CONDUCTOR WITH WBC

Coatings were applied and tests conducted using a 3000 mm² keystone aluminium conductor incorporating a WBC.

Before cold spraying, a brief 1-minute grinding step was performed to eliminate gaps between conductor strands. This step also removes any WBC residue from the conductor surface (Figure 9), ensuring a clean and flush surface for coating.

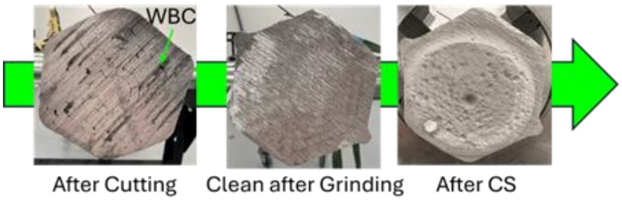


Fig. 9: Surface grinding results in a clean, WBC-free conductor surface suitable for CS coating.

Cold spraying was carried out using a custom in-field terminator unit, operating at low pressure and low temperature with compressed air. Post-deposition analysis included cross-sectional scanning electron microscopy (SEM) and elemental mapping via SEM-EDS, focusing on carbon – a key component of the WBC. Simple thermal management during spraying effectively prevented WBC migration toward the conductor/coating interface (Figure 10). The results show a clear transition: from WBC exposure at the interface (Figure 10a) to successful encapsulation beneath the deposited coating (Figure 10b). This confirms that the risk of WBC leakage into the contact zone can be well controlled during the cold spray process.

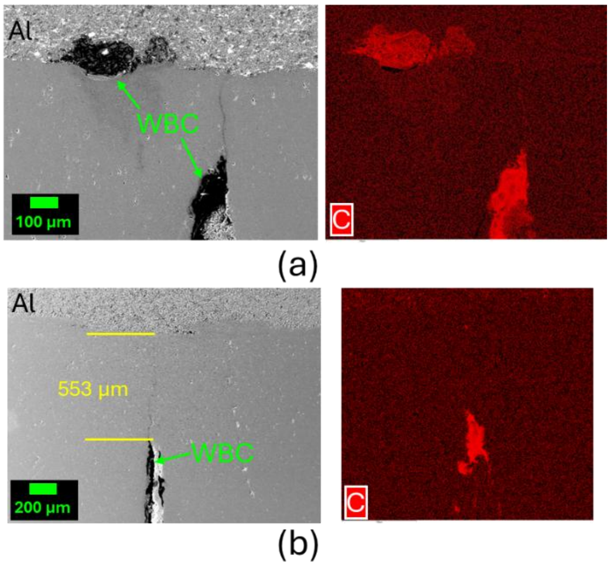


Fig. 10: SEM image and corresponding SEM-EDS elemental C map showing (a) WBC leaking to the conductor/coating interface, and (b) WBC effectively encapsulated below the coating following cold spray application.

Next, thermal cycling tests were performed at both coating and connector levels for the connector where WBC leakage during CS application is prevented (cf. Figure 10b). These tests assessed the thermal stability of the Alu-Cu Connector when WBC may become liquid at cable service temperatures.

At coating level, 30 mm thick coated conductor sections were subjected to accelerated thermal cycling within the nominal cable service range (10–90 °C) over 30 days using a Binder MK 56 chamber. Samples underwent 500 cycles with 3 °C/min heating and cooling ramps. K-type thermocouples monitored surface temperatures continuously. SEM analysis of all strands in the cross-sectional sample after 500 cycles confirmed that the WBC remained confined below the coated surface, with no leakage into the conductor/coating interface. Figure 11 illustrates this result for a representative strand, consistent with observations across the entire sample.

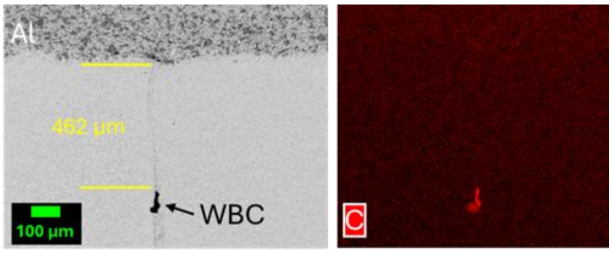


Fig. 11: Representative SEM image and corresponding SEM-EDS elemental C map after 500 thermal cycles, showing WBC effectively encapsulated below the coating.

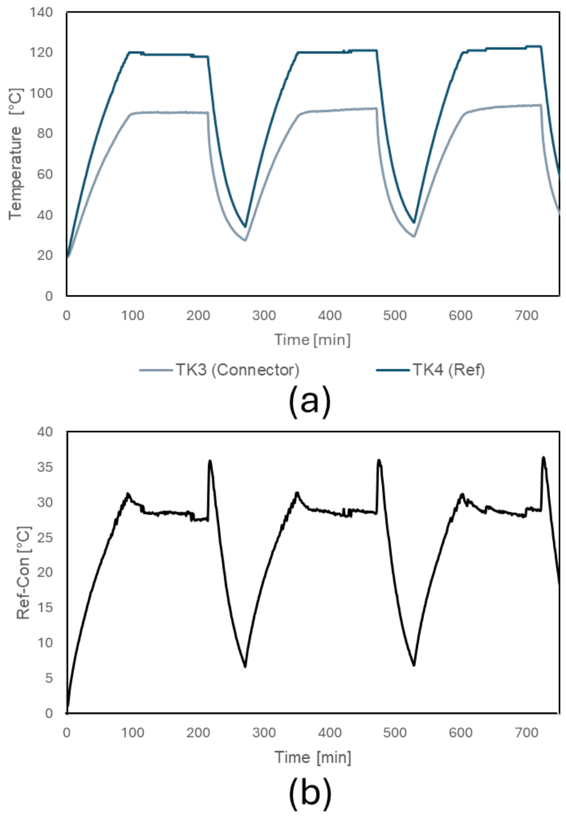
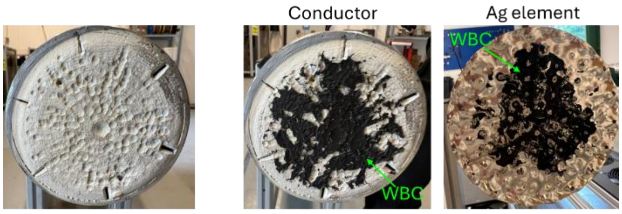


Fig. 12: Stable temperature profile for both:
(a) Absolute temperatures of the Alu-Cu Connector (TK3) and the Reference Conductor (TK4).
(b) Temperature difference between the Reference Conductor (TK4) and the Alu-Cu Connector (TK3).

On connector level, Cirgre TB 758 inspired tests were conducted using the configuration illustrated in Figure 7. Each cycle lasted for 4.5-hour, including a 2-hour stability phase during which the reference conductor was maintained at 120 °C ± 2 °C. Results in Figure 12 demonstrate that the Connector (TK3) consistently maintained a stable temperature, being lower than that of the Reference Conductor (TK4). (Figure 12a shows the absolute temperature values, while Figure 12b illustrates the temperature difference between TK4 and TK3.) Given that WBCs are semi-conductive, leakage into the conductor/coating interface may be expected to interfere with current transfer, increasing electrical resistance and consequently raising temperature due to ohmic losses. However, no such degradation is observed during stability phases and across cycles in Figure 12. The consistently lower temperature compared to the reference conductor and the high thermal stability show the Alu-Cu Connector's promise for HVDC applications incorporating WBCs.

Extreme leakage scenario

To further assess the connector's robustness when used with WBC-incorporating Al conductors under extreme conditions, a harsh thermal test was performed. In this test, WBC was deliberately spread across the coated conductor surface prior to connection (Figure 13b), in contrast to a clean surface shown in Figure 13a. Although such a scenario is highly unlikely in practice – given that WBC has been shown to remain encapsulated well below the coating surface (see Figures 10b and 11) – this test provides valuable insight into the connector's tolerance to worst-case conditions. The thermal cycling was performed using the same configuration as illustrated in Figure 7. To ensure current flow through the coating–Ag element–coating electrical path, rather than bypassing via the outer shells, electrically insulating Kapton tape was applied to the outer and rear surfaces of both conus components, as well as the inner surfaces of the two half shelves (Figure 14).



(a) (b)

Fig. 13: (a) Clean Conductor surface; (b) WBC deliberately spread over conductor surface and flexible Ag contact element.

Results in Figure 15 present the average temperature difference during the final 15 minutes of the 2-h stability phase between the Reference Conductor (TK4) and the Connector (TK3), comparing configurations with clean surfaces and those with WBC applied prior to joining. The plotted value – $\Delta T = (TK4 - TK3)_{WBC} - (TK4 - TK3)_{Clean}$ – isolates the thermal effect of WBC exposure by subtracting the baseline temperature difference of the clean configuration. The data show a negligible difference, with the WBC-exposed connector often being even slightly cooler. This confirms that the connector maintains electrical performance even under extreme WBC exposure, underscoring the high robustness of the Alu-Cu Connector and its suitability for HVDC applications incorporating WBCs.

CONCLUSION

Electrical conductors are increasing in size and complexity to meet rising energy demands. The commercial Alu-Cu Connector provides a reliable solution for joining high cross-sectional Al and Cu cables in both AC and DC systems. It features an innovative design that integrates axial mechanical compression, cold-sprayed Al–Ag coatings, and a flexible Ag contact element, enabling stable electrical and mechanical performance. Crucially, it allows installation without prior cleaning or removal of organic or inorganic surface materials – overcoming a major limitation of conventional methods such as shear-bolting, crimping, and welding.

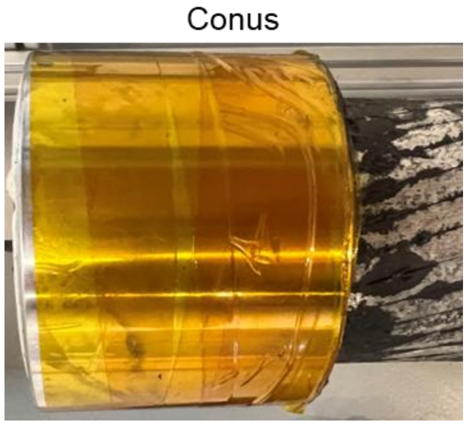


Fig. 14: Application of electrically insulating Kapton tape to prevent current bypass.

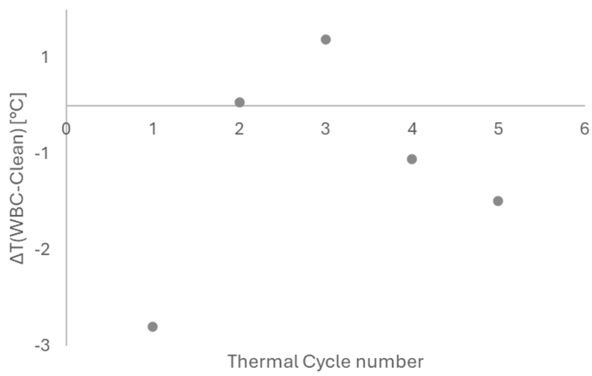


Fig. 15: Average temperature difference for each thermal cycle during the final 15 minutes of the 2-hour stability period, defined as $\Delta T = (TK4 - TK3)_{WBC} - (TK4 - TK3)_{Clean}$, comparing connectors with WBC applied versus clean surfaces.

Submarine HVDC cables often include WBCs, which are difficult to remove and can compromise joint performance when using traditional techniques. This study demonstrates that the Alu-Cu Connector can be installed without prior cleaning; simple thermal management during cold spraying ensures that WBCs remain encapsulated beneath the coating, preventing leakage during thermal cycling and maintaining electrical integrity. Even under an extreme and unlikely scenario where WBC was deliberately applied to the conductor surface before connection, the Alu-Cu Connector showed no thermal or electrical degradation during cycling, performing on par with clean samples. The outer cold-sprayed Ag coating plays a key role in maintaining low contact resistance over time by shielding the inner Al coating from oxidation.

These results demonstrate that the Alu-Cu Connector is not only suitable for conventional AC applications but also robust and well-suited for demanding HVDC environments, including submarine cables with WBCs.

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GLOSSARY

WBC(s): Water blocking compound(s)

HV: High Voltage

Al: Aluminium

Cu: Copper

Ag: Silver

AC: Alternating Current

DC: Direct Current

CS: Cold Sprayed

SEM: Scanning Electron Microscopy

EDS: Energy-Dispersive X-ray Spectroscopy