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A COMPARATIVE STUDY OF ANTI-CORROSION TECHNIQUES AT COPPER–ALUMINIUM JOINTS

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Abstract
The integration of copper–aluminium (Cu–Al) joints in automotive, electrical, and HVAC systems has increased due to the demand for lightweight designs combined with efficient electrical and thermal performance. However, the inherent electrochemical mismatch between copper and aluminium results in galvanic interactions that accelerate interfacial corrosion, ultimately limiting joint reliability. This work presents a comparative assessment of six corrosion mitigation approaches, namely zinc-based interlayers, electroless nickel coatings, aluminium anodizing, chromate and trivalent conversion coatings, dielectric isolation techniques, and polymeric sealing systems. Each method is evaluated with respect to corrosion protection capability, service durability, production compatibility, cost efficiency, and environmental considerations. Based on the comparative analysis, practical selection criteria are formulated to assist engineers in selecting appropriate anti-corrosion solutions for varying operational conditions.

KEYWORD: Copper–aluminium joints; galvanic interaction; zinc interlayer; electroless nickel coating; anodized aluminium; conversion coating; dielectric isolation; polymer sealing.

I. INTRODUCTION

Dissimilar metal joining between copper and aluminium (Cu–Al) has gained considerable attention in modern engineering systems, as it enables the integration of copper's superior electrical and thermal transport properties with aluminium's low density and economic advantages. Despite these benefits, the electrochemical potential difference between the two metals establishes a galvanic couple in which aluminium behaves anodically relative to copper, leading to accelerated material degradation at the joint interface. This degradation is further intensified under moisture exposure or in chloride-containing service environments, ultimately restricting operational longevity. The present work focuses on a systematic evaluation of six commonly implemented anti-corrosion approaches and introduces a comparative framework intended to support the selection of suitable protection strategies for practical engineering applications.

II. BACKGROUND: GALVANIC CORROSION IN CU–AL JOINTS

Galvanic degradation arises when two metals with different electrochemical potentials are joined in the presence of an electrically conductive environment, resulting in preferential dissolution of the more active material. In copper–aluminium assemblies, aluminium functions as the anodic component of the galvanic couple and is therefore susceptible to intensified corrosion. This effect is commonly localized in regions such as welded interfaces, fastener contact areas, and confined gaps where electrolyte retention is promoted. Experimental investigations reported in the literature indicate that Cu–Al joints lacking protective measures exhibit rapid deterioration when subjected to aggressive conditions such as salt-fog testing or marine atmospheres. Consequently, the implementation of surface modification strategies and corrosion-conscious joint design has become critical for reducing galvanic damage and extending component service life.

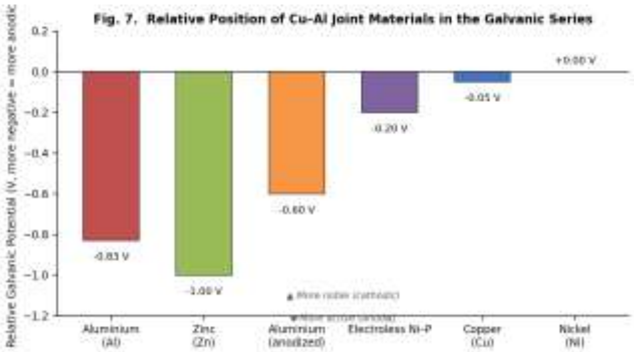

Fig. 1. Relative position of Cu-Al joint materials in the galvanic series. Aluminium sits far anodic to copper, driving the galvanic attack; protective layers (anodized Al, Zn, Ni-P) shift the effective interfacial potential closer to copper, reducing the driving force for corrosion.

III. ANTI-CORROSION TECHNIQUES

A. Zinc Interlayer / Zn-Rich Coatings

Zinc-based protection systems are widely utilized in Cu–Al joints due to zinc's electrochemical activity relative to both copper and aluminium, enabling it to function as a sacrificial material under corrosive conditions. When incorporated as an interlayer in solid-state joining processes such as ultrasonic welding or friction stir welding, zinc not only enhances corrosion resistance but also restricts the formation of brittle copper–aluminium intermetallic compounds at the interface. In addition to interlayers, zinc-rich paints and thermally sprayed zinc coatings are commonly applied in HVAC installations to provide surface-level protection. The effectiveness of these approaches is inherently time-dependent, as corrosion protection diminishes progressively with the depletion of the zinc layer.

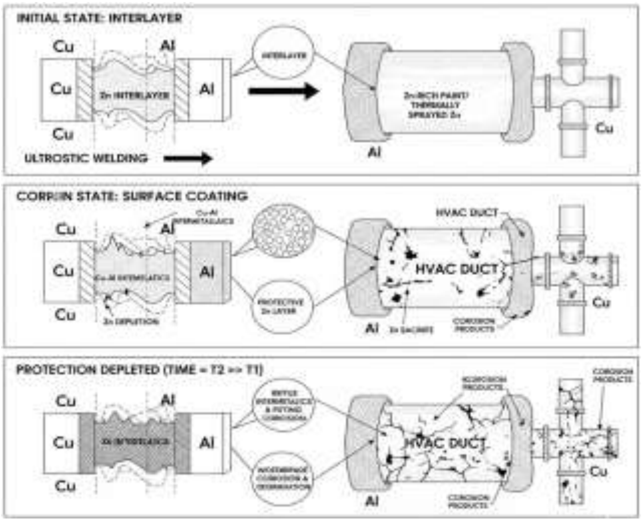

Fig. 2. Zinc-based protection in Cu–Al joints: interlayer application, sacrificial surface coating, and progressive depletion over service life.

B. Electroless Nickel (EN) Barrier

Electroless nickel–phosphorus (Ni–P) coatings are widely applied as protective layers in Cu–Al assemblies due to their ability to form uniform, non-crystalline deposits that act as effective diffusion barriers. By isolating the underlying metals from the surrounding electrolyte, these coatings significantly reduce ionic movement and interrupt galvanic interactions between copper and aluminium. Such characteristics make electroless nickel particularly suitable for electrical connectors and contact components, where minimal coating thickness must be balanced with long-term durability. However, the corrosion protection performance of EN coatings is highly dependent on deposition quality, as defects or porosity within the coating can create localized pathways for corrosive attack.

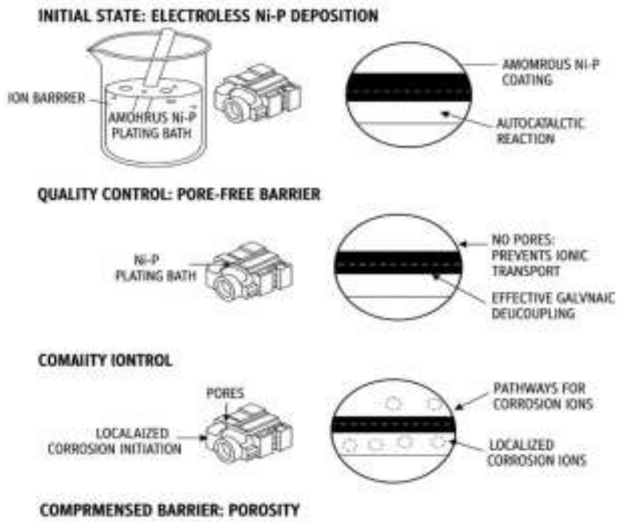

Fig. 3. Electroless nickel (EN) barrier process: deposition, pore-free ionic barrier, and failure pathways introduced by coating porosity.

C. Anodizing Aluminium

The anodizing process modifies the aluminium surface by generating a controlled oxide layer composed primarily of aluminium oxide (Al_2O_3), which exhibits high electrical resistivity and restricts the flow of galvanic currents between dissimilar metals. Subsequent sealing of the porous oxide structure further enhances corrosion resistance by limiting electrolyte ingress. Despite its effectiveness, the protective capability of anodized layers can be locally reduced by mechanical damage, machining operations, or the introduction of fasteners that disrupt the continuity of the oxide film.

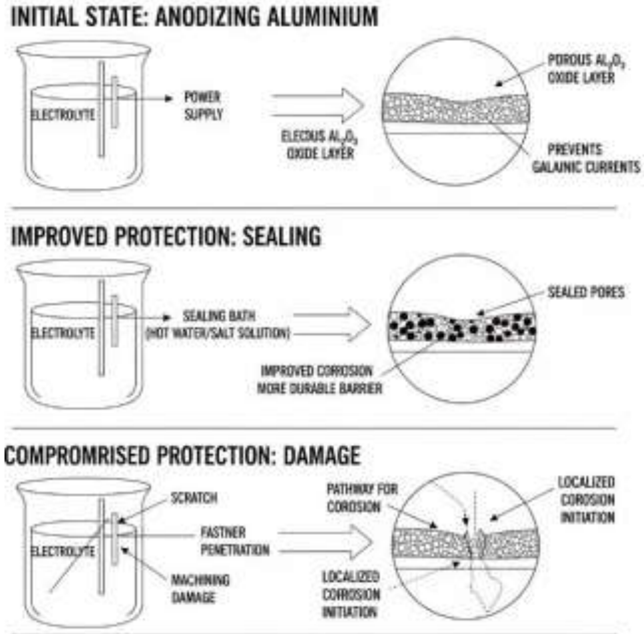

Fig. 4. Anodizing of aluminium: oxide layer formation, pore sealing for improved protection, and localized damage from scratches or fasteners.

D. Chromate / Trivalent Conversion Coatings

Chromate-based conversion treatments are employed on aluminium surfaces to generate chemically bonded surface layers that enhance passivation and improve corrosion resistance. While coatings containing hexavalent chromium have historically demonstrated superior protective performance, their use has become increasingly restricted due to environmental and health concerns associated with chromium toxicity. As a result, trivalent chromium conversion systems have emerged as viable alternatives and are now widely implemented. These coatings are frequently used as surface pretreatments, providing improved adhesion and corrosion resistance when combined with subsequent paint or sealing layers.

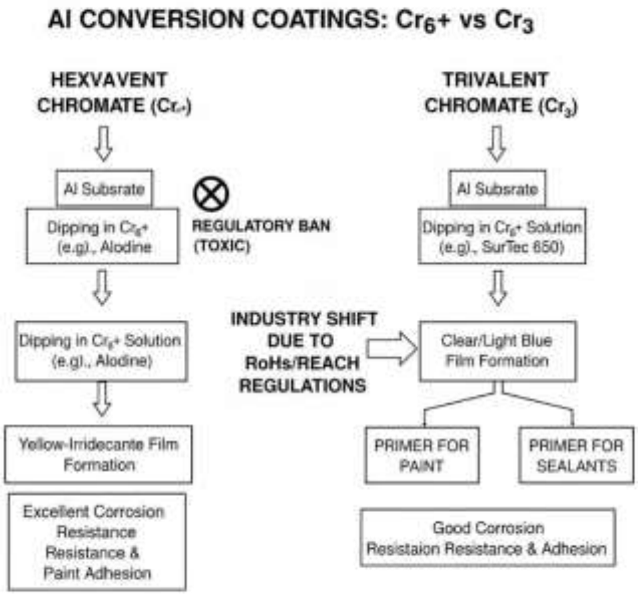

Fig. 5. Aluminium conversion coatings: hexavalent chromate versus trivalent chromate processing routes.

E. Dielectric Isolation (Gaskets, Bushings, Heat-Shrink)

Dielectric isolation relies on the use of electrically insulating components, including gaskets, bushings, and heat-shrink sleeves, to physically separate copper and aluminium elements within a joint. This physical separation removes electrical continuity between the dissimilar metals, thereby suppressing the electrochemical interactions responsible for galvanic corrosion. Such isolation methods are extensively applied in flanged connections and HVAC piping systems where dissimilar metals must be joined. The effectiveness of this approach is strongly influenced by the mechanical performance of the insulating materials, which must retain their integrity under sustained mechanical loads as well as repeated thermal cycling during service.

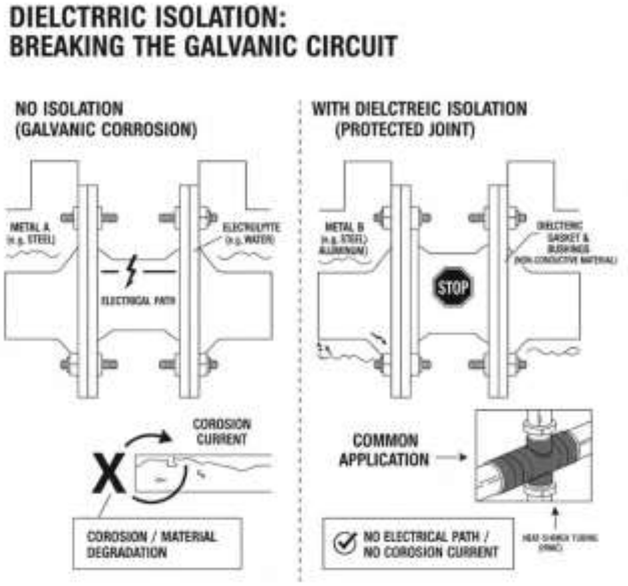

Fig. 6. Dielectric isolation breaking the galvanic circuit, with heat-shrink tubing shown as a common HVAC application.

F. Polymeric Sealing

Polymer-based protection methods utilize sealants, adhesive systems, and surface coatings to create a continuous barrier that restricts the ingress of moisture and corrosive species at the Cu–Al interface. Among these materials, epoxy formulations are frequently selected due to their combined ability to provide effective environmental sealing and contribute to structural load transfer within the joint. The success of polymeric encapsulation, however, is highly dependent on application quality, as defects such as entrapped air pockets, discontinuities, or insufficient coverage can promote localized corrosion by allowing electrolyte access to confined regions.

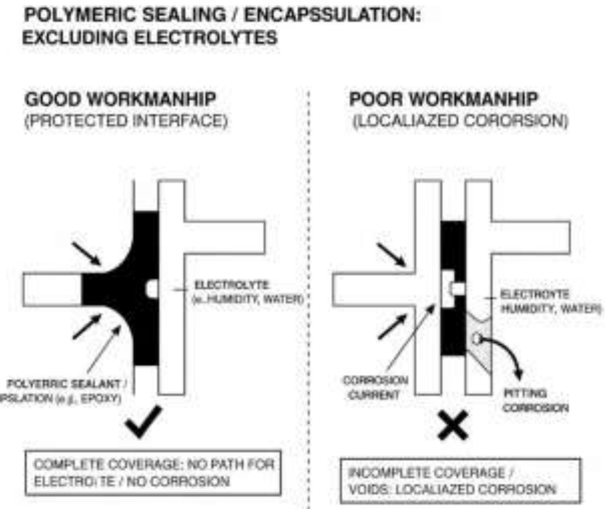

Fig. 7. Polymeric sealing and encapsulation: complete coverage excludes electrolyte, while incomplete coverage permits localized pitting corrosion.

IV. COMPARATIVE ANALYSIS

Table I summarizes the six anti-corrosion techniques with respect to corrosion resistance, durability, manufacturing compatibility, key limitations, and typical applications. Figure 8 translates the qualitative ratings from Table I into a visual comparison across four key selection criteria.

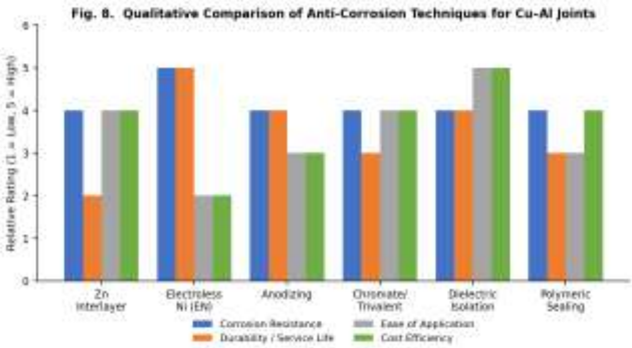

Fig. 7. Qualitative comparison of the six anti-corrosion techniques across corrosion resistance, durability, ease of application, and cost efficiency (relative ratings derived from Table I).

TABLE I. COMPARATIVE ANALYSIS OF TECHNIQUES

Technique	Corrosion Resistance	Durability / Service Life	Manufacturing & Application	Key Limitations	Typical Applications / Outcome
Zinc Interlayer / Zn-Rich Coatings	High initially due to sacrificial anodic protection	Moderate; decreases once Zn is consumed	Simple coating or interlayer insertion; compatible with welding and coating processes	Limited lifespan; requires sufficient Zn thickness	Cu–Al joints, HVAC systems, welded dissimilar metal assemblies
Electroless Nickel (Ni–P) Barrier	Very high when coating is dense and pore-free	High; excellent wear and corrosion resistance	Requires controlled chemical deposition and surface preparation	Porosity or poor deposition can lead to failure	Electrical connectors, precision components, Cu–Al interfaces
Anodizing Aluminium	High; electrically insulating oxide layer blocks galvanic action	High if surface remains intact	Electrochemical process; requires sealing for best performance	Vulnerable to scratches and penetrations	Aluminum parts exposed to Cu fasteners or humid environments
Chromate / Trivalent Conversion Coatings	Very high for hexavalent; moderate to high for trivalent systems	Moderate to High depending on coating system	Thin-film chemical conversion; often used as primer	Thin layer; usually requires topcoat	Aerospace, automotive, painted Al–Cu assemblies
Dielectric Isolation (Gaskets, Bushings, Heat-Shrink)	High as long as isolation remains intact	High if mechanical integrity is maintained	Simple mechanical installation; no chemical processing	Mechanical degradation under load or thermal cycling	Flanged joints, piping systems, HVAC tubing
Polymeric Sealing / Encapsulation	High when fully sealed; prevents electrolyte ingress	Moderate to High depending on material and workmanship	Applied by coating, potting, or adhesive bonding	Voids or incomplete coverage accelerate localized corrosion	Structural bonding, electronic encapsulation, sealed joints

V. CONCLUSION

The comparative evaluation confirms that corrosion protection strategies for Cu–Al joints must be selected based on service conditions rather than a single optimal solution. Dense barrier systems such as electroless nickel coatings and anodized aluminium layers demonstrate superior longevity by limiting electrochemical interaction, while dielectric isolation methods effectively interrupt galvanic pathways in mechanically assembled joints. Zinc interlayers remain particularly advantageous in solid-state welding processes, where they simultaneously control intermetallic formation and provide sacrificial protection. Although conversion coatings and polymer-based sealing approaches offer economical implementation, their long-term effectiveness is strongly influenced by surface preparation, coating integrity, and application quality. Combined or hybrid protection schemes, including anodizing followed by sealing or nickel barriers supplemented with polymer encapsulation, consistently deliver enhanced durability when exposed to aggressive chloride-containing environments. Figure 9 consolidates these findings into a quick selection guide relating typical application conditions to the recommended technique.

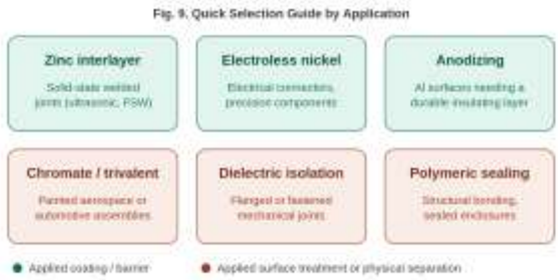

Fig. 8. Quick selection guide relating typical Cu-Al joint applications to the recommended anti-corrosion technique.

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