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A Brief Review on Interfaces of Copper Welded to Different Materials

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Abstract

In engineering applications, three high-conductivity metals are primarily used such as copper (Cu), aluminum (Al), and silver (Ag). Each has its unique set of properties that affect specific engineering applications. In fact the choice of conductor depends on a mixture of cost, technical parameters, and environmental conditions. Among these, Copper is widely valued in engineering applications due to its antimicrobial property, excellent electrical (about 100% IACS) and thermal conductivity, corrosion resistance, ease of connection, and mechanical as well as recyclable properties. However, welding copper alloys to dissimilar metals, such as steel, aluminum, nickel (Ni)-based alloys, and titanium (Ti), poses significant challenges due to differences in physical properties, metallurgical compatibility, and thermal behavior. This review paper explores the current state of research and technological developments in the welding of copper to copper alloys and other dissimilar metals. It provides a comprehensive overview of various welding techniques, including laser welding, fusion welding, solid-state welding (e.g., friction stir and explosive welding), and advanced hybrid methods. Emphasis is placed on the mechanisms of joint formation, metallurgical interactions at the weld interface, formation of intermetallic compounds, and the impact of process parameters on the quality of joints for copper welded to stainless-steel, steel joints, aluminum, titanium, brass, magnesium (Mg), molybdenum (Mo), tin (Sn), nickel alloy, and tantalum (Ta). The goal of this review is to consolidate existing knowledge, identify key technical challenges, and highlight future directions for research and industrial applications to weld copper for different engineering applications, including characterization of the interface with different techniques such as metallurgical microscope, scanning electron microscope (SEM), micro-Vickers hardness testing, etc. The literature review suggests that adopting advanced computational modeling techniques such as artificial intelligence, smart manufacturing, and data-driven design to support the creation of a robust Cu joint with other novel materials is highly essential.

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INTRODUCTION

Copper and its alloys have long played a vital role in industrial and technological applications owing to their unique combination of properties, including high thermal and electrical conductivities, corrosion resistance, and good formability [1]. However, modern engineering systems increasingly rely on multi-material structures that combine the benefits of different metals to achieve lightweight, cost-effective, and high-performance assemblies [2]. Consequently, there is a growing need to develop reliable and efficient methods for joining copper alloys to dissimilar metals, such as carbon steel, stainless steel, aluminum, titanium, and nickel-based super alloys [3].

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These characteristics cited earlier make them indispensable in sectors such as power generation and transmission, electronics, marine engineering, HVAC systems, and automotive manufacturing [3, 4].

Welding copper alloys to dissimilar metals presents a complex set of challenges because of significant differences in melting points, thermal conductivity, and coefficients of thermal expansion, which often lead to excessive heat loss, incomplete fusion, distortion, and the formation of brittle intermetallic compounds [5, 6].

In recent years, various joining techniques have been investigated and applied, including traditional fusion welding processes (such as TIG, MIG, and laser welding) [7, 8, 9] and solid-state welding methods, such as friction stir welding (FSW), explosion welding, and diffusion bonding. Moreover, the inherent properties of copper, such as its tendency to absorb heat quickly and oxidize at elevated temperatures, complicate the selection of appropriate welding techniques and process parameters [10]. Innovations in filler material design, surface engineering, and thermal control have also contributed to improving joint integrity and performance [11–12]. By compiling the findings from recent studies and industrial practices, this paper seeks to inform future research and support the development of robust and reliable joining strategies for hybrid metal structures involving copper alloys [13]. The present review aims to provide a comprehensive overview of state-of-the-art techniques for welding copper alloys to other metals. It discusses the underlying metallurgical principles, analyzes recent advances in technology, and highlights both practical and theoretical challenges that remain unresolved [14].

KEY PROPERTIES OF COPPER ALLOYS RELEVANT TO WELDING

Copper alloys exhibit a unique set of physical and chemical properties that make them both attractive and challenging when it comes to welding, particularly to dissimilar metals. Understanding these properties is essential for selecting appropriate welding techniques and mitigating joint-related issues [14].

High Thermal Conductivity

Pure copper has one of the highest thermal conductivities among engineering metals, typically around 390–400 W/m·K for pure copper. This characteristic causes rapid heat dissipation from the weld zone, making it difficult to maintain the localized temperatures necessary for proper fusion. Consequently, welding copper alloys often requires higher heat input, more powerful sources, or preheating to compensate for heat loss [15].

High Electrical Conductivity

Copper's excellent electrical conductivity, second only to that of silver, is a key reason for its widespread use in electrical and electronic applications. However, this property can interfere with some welding processes, such as resistance welding, where current flow may be diverted or unevenly distributed because of copper's low electrical resistance [16, 17].

Wide Range of Alloy Compositions

Copper alloys include a diverse group of materials, such as brasses (copper–zinc), bronzes (copper–tin), cupronickels, and copper–beryllium alloys. These alloys vary significantly in terms of their melting points, hardness, and corrosion resistance. For example, the addition of zinc in brass reduces the melting point, whereas the addition of nickel improves the strength and resistance to corrosion and thermal fatigue [18].

Compatibility with Dissimilar Metals

The metallurgical compatibility between copper alloys and other metals plays a critical role in weld quality. In many cases, the formation of brittle intermetallic compounds at the interface (particularly when welding to aluminum or titanium) must be carefully controlled to ensure structural integrity [19, 20].

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Oxidation Tendency at High Temperatures

During welding, copper readily forms oxides on its surface when exposed to air, which can hinder weld penetration and create defects. These oxides are often hard and brittle, thereby affecting the mechanical performance of the joint. Proper shielding gases, fluxes, or surface cleaning are necessary to control oxidation [21].

Coefficient of Thermal Expansion (CTE)

Copper alloys generally have a higher coefficient of thermal expansion (CTE) than most steels and other structural metals; this mismatch creates significant challenges during welding. Differences in CTE induce thermal and residual stresses during heating and cooling cycles, which can lead to distortion, warping, or cracking – particularly in thick sections, complex geometries, or applications subjected to cyclic thermal loading. Additionally, the large mismatch in melting temperatures between copper alloys and dissimilar metals further intensifies these problems, making joint integrity more difficult to maintain [22].

Softness and Formability

Although copper is easily formable and ductile, it can also be prone to distortion under welding-induced thermal cycles. Some copper alloys, particularly those strengthened by cold work or precipitation hardening, may lose their mechanical properties in the heat-affected zone (HAZ) if not properly managed [23].

CHALLENGES IN WELDING COPPER ALLOYS TO OTHER METALS

Challenges in welding copper alloys to other metals primarily arise from major disparities in their physical, thermal, and metallurgical properties. These challenges can affect joint integrity, mechanical performance, and long-term reliability. Understanding the nature of these difficulties is critical for selecting suitable welding methods, optimizing process parameters, and designing joints that meet performance requirements.[24]

Differences in Melting Points

Pure copper melts at approximately 1085 °C, whereas aluminum melts at approximately 660°C, and some steels at over 1400 °C. This disparity can lead to incomplete fusion, localized melting, or overheating of the lower-melting-point metal, resulting in poor joint quality or material degradation [25].

Formation of Intermetallic Compounds (IMCs)

When dissimilar metals are joined, especially copper to aluminum, titanium, or nickel alloys, brittle intermetallic phases tend to form at the fusion zone or interface. These compounds often lack ductility and can severely reduce joint strength, making the weld more prone to cracking or premature failure under mechanical or thermal loading [26].

Thermal Conductivity Mismatch

Copper's high thermal conductivity implies that heat quickly dissipates from the weld zone, often making it difficult to maintain an adequate temperature for proper bonding. In contrast, metals, such as steel or titanium, retain heat for longer in the weld region. This mismatch complicates heat control, resulting in unbalanced heating, distortion, and nonuniform microstructures at the joint interface [27].

WELDING TECHNIQUES FOR JOINING COPPER ALLOYS TO OTHER METALS

Joining copper alloys to dissimilar metals is technically challenging because of copper’s high thermal conductivity, oxidation tendency, and risk of forming brittle intermetallic compounds. Welding

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methods are typically grouped into fusion welding, solid-state welding, and advanced hybrid techniques. In the current review, copper welded to different materials is described [28].

Copper (Cu) to Stainless Steel (SS)

Torkamany et al [2]. Torkamany et al. [2] examined the microstructures and mechanical properties of stainless steel/copper laser welded specimens by controlling the processing parameters of laser power and welding speed, considering the inclined angle of the laser beam and the offset in the direction of the stainless steel.

The surface appearance of the laser-welded Cu/SS joint is shown in Figure 1. The color of the weld was similar to that of the copper when the laser beam offset was 0 mm, as shown in Figure 1 (a). Melting of the copper was successfully inhibited when the laser beam was appropriately offset in the direction of the stainless steel, as shown in Figure 1 (b). Therefore, the processing parameters use of laser beam have a big impact on the copper's melting behavior and even the joint's microstructures.

A review on the fusion welding techniques for joining copper to SS was extensively conducted by Joshi et al [29]. and concluded that both laser beam welding and electron beam welding procedures can be enhanced and refined to provide superior joint quality and performance when attaching copper to SS.

Studies have demonstrated that the use of stainless-steel fillers can lead to cracking owing to poor mutual solubility and infiltration between copper and iron. Stainless-steel fillers, such as 316 L, also exhibit a lack of fusion on the copper side. The images indicate that the defect is more pronounced in SMAW (Shielded Metal Arc Welding) compared to GTAW (Gas Tungsten Arc Welding). GTAW uses a non-consumable electrode, and arc control and stability are superior, ensuring full heating of the faying surfaces, unlike SMAW, where inconsistent arc behavior often leads to incomplete fusion [29].

Cu–Steel Joints

Kalms, S., et al [3]. states that it is difficult to produce the copper–steel joints using traditional welding methods because of the significant differences in the thermal properties of copper and steel, such as melting points, thermal conductivity, and expansion coefficient. In laser and FSW joints between copper and stainless steel, the diffusion of Fe into Cu forms a transition zone that may include Fe–Cu solid solutions and IMCs, such as Cu6Fe5[3]. reported the formation of columnar grains near the fusion line, whereas equiaxed grains were observed in the weld nugget owing to dynamic recrystallization. The use of interlayers (e.g., Ni) reduces the brittle phase.

The joining of copper and stainless steel through laser beam welding (LBW) and friction stir welding (FSW) results in the formation of a transition region, primarily because Fe diffuses into the Cu side, as shown in Figure 2. Laser welding research indicates that beam offset plays a crucial role in weld pool behavior; a zero offset leads to full melting of copper, whereas shifting the beam toward stainless steel decreases copper melting [2]. In FSW, columnar grains develop near the interface, whereas dynamic recrystallization produces fine equiaxed grains within the stir zone [3, 4]. The use of interlayers, such as nickel, helps suppress intermetallic compound (IMC) formation and improves interface reliability [5]. The selection of fillers – including 316 stainless steel, copper-based fillers, and nickel alloys – strongly influences weld solidification; stainless-steel fillers may cause cracking, whereas 316 L fillers often result in insufficient fusion on the copper side.

(a) (b)

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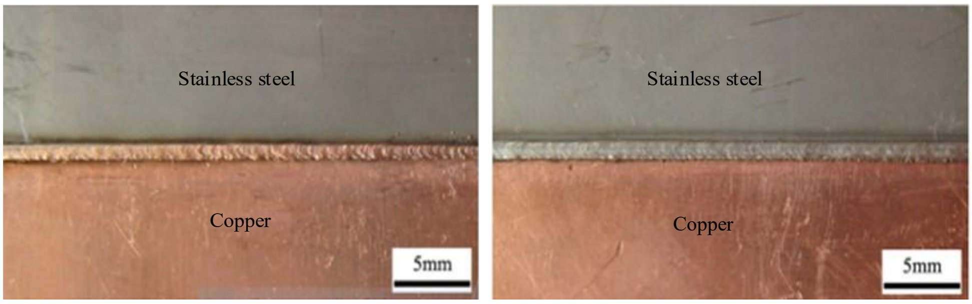

Figure 1. Surface appearance of the two welded interfaces: (a) laser beam offset 0mm, oblique angle 0°, (b) Laser beam offset 0.2mm, oblique angle 4° [2].

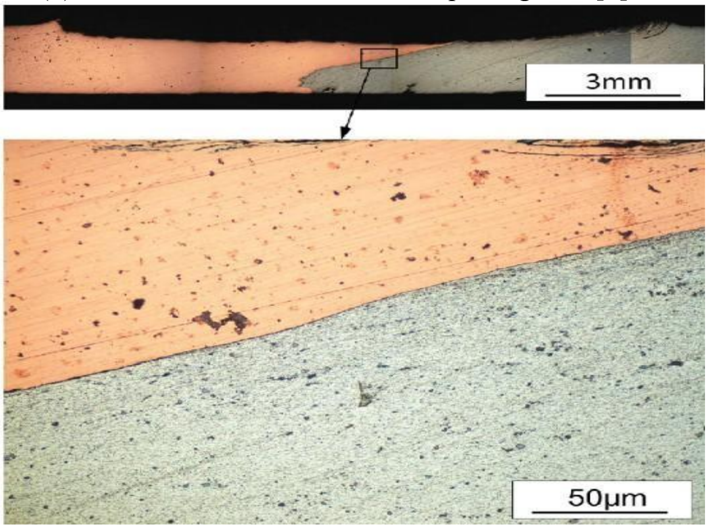

Figure 2. Laser beam welding of copper and steel [3].

Recent advancements using AI-driven adaptive control systems have enhanced the precision of dissimilar-metal welding [6]. It was reported that among welding techniques, GTAW generally produces better fusion quality than SMAW, because of its stable arc characteristics. Furthermore, hybrid welding approaches, such as ultrasonic-assisted FSW and dual-beam laser welding, help to minimize IMCs and optimize heat input [7].

Copper–Aluminium

Loureiro Liu et al [22]. Liu et al. [22] state that copper and aluminum alloys are widely known for their outstanding electrical and thermal conductivities, as well as excellent resistance to corrosion. However, some physical properties of these materials differ markedly, such as density and melting temperature. Specifically, copper density is about three times that of aluminum, which, in turn, has a melting temperature about 60% below that of copper [6, 8] the investigated tool offset toward both aluminum and copper, reporting a marked decline in weld quality when the tool was moved away from the material interface. Their results showed that shifting the tool does not favor proper Al–Cu FSW [6]. Likewise it was observed unsatisfactory welding performance for all offset conditions.

Both studies noted that offset welding produced greater intermetallic compound formation than centered-tool welding, contradicting some earlier findings. This increase was attributed to more intense mechanical mixing when one material became dominant in the stirring zone. Overall, the existing literature lacks agreement on how tool offset influences Al–Cu weldability. The welded microstructure of Cu/Al is shown in Figure 3, although several studies have reported an improved surface appearance when the tool is offset toward aluminum; the internal weld characteristics remain highly inconsistent

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[9]. These inconsistencies largely stem from variations in alloy combinations, sheet thickness, rotational/traverse speeds, and tool geometry. Because the tool governs heat input and material flow, its design plays a crucial role in determining weld morphology and IMC development. Thus, selecting an appropriate combination of tool offset and geometry is essential for achieving optimal Al–Cu FSW performance [6, 15].

Friction stir welding (FSW) has been adopted to join Cu-Al metals [9]. In this study, the joints produced a layered microstructure in the stir zone, consisting of dynamically recrystallized fine grains and discrete intermetallic phases (IMCs), such as Al2Cu, Al4Cu9, and AlCu. It was reported that thick and continuous IMCs could reduce ductility and cause brittle failure. It was concluded that tool design and rotational speed significantly influence the extent of intermixing and IMC formation [4].

Copper to Titanium

Paul [24] states that the copper/titanium (Cu/Ti) composite is one of the most important metal combinations. They are typically considered candidate materials for applications requiring high conductivity in corrosive environments. The joints used as transition pieces, for example, in the cathodes of electrolyzers for copper production, coated titanium anodes for chromium plating, and anodes in chlor-alkali electrolysis [25, 26]. Here, high direct-current flow leads to increased heat dissipation and initiates diffusion across the bonding interface. This diffusion lead to new phase formation, which may have a substantial effect on the Figure 4 shows welded Ti/Cu joints. Previous studies have linked bonding parameters and explosive loading conditions to interface waviness in cladding; however, Cu/Ti interfaces remain insufficiently explored. Earlier work associated waviness with bonding mechanisms and electro–mechanical performance [25]; however, subsequent findings indicated that interfacial microstructural complexity, rather than waviness alone, governed clad properties. In Cu–Ti joints, brittle intermetallic compounds (TiCu, Ti2Cu, and Ti3Cu4) are commonly formed and significantly degrade mechanical performance. Although advanced welding approaches were shown to restrict IMC growth, detailed SEM/TEM investigations and direct correlations between annealing-driven phase evolution and mechanical properties were still lacking [24, 25].

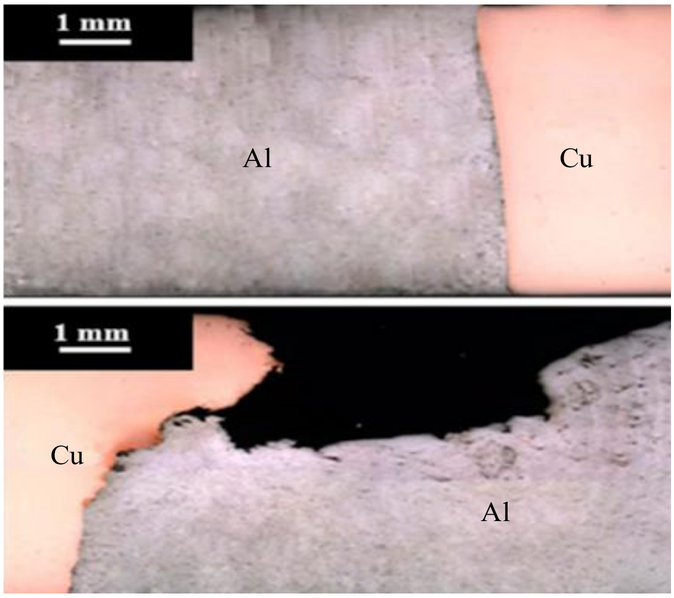

Figure 3. Explosive welding of copper and aluminium [22].

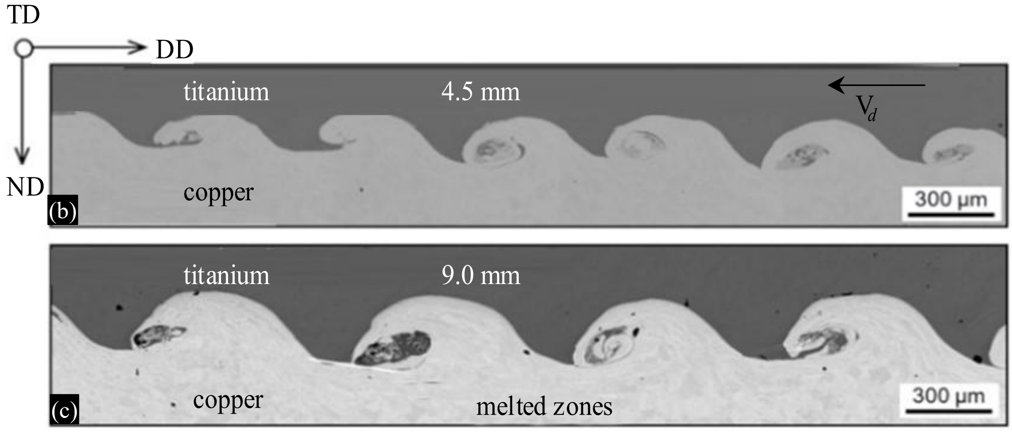

Figure 4. Schematic representation of explosive welding, along with the wavy interfaces observed in clads manufactured at a detonation velocity of 2500 ms^{-1} and stand-off distance of (b) 4.5 mm, and (c) 9.0 mm [24].

Cu to Brass

Welding copper and brass using conventional fusion welding techniques is challenging because of their high thermal properties. Copper has one of the highest thermal conductivities among metallic materials (approximately 401 W/m·K), resulting in rapid heat dissipation and necessitating the application of a very high heat input during welding. Similarly, brass (Cu–Zn alloys) has thermal diffusivity values that are 10–100 times greater than those of many steel and nickel alloys.

Erdem [27] stated when fusion welding processes such as tungsten inert gas (TIG) welding were employed, the temperature in the weld zone often exceeded the melting and boiling points of alloying elements. Previous investigations on brass weldability [3] reported that zinc, with a vaporization temperature of approximately 907°C, evaporates more readily than copper during welding because of its lower boiling point, resulting in significant elemental loss. In laser beam welding of copper–beryllium alloys, liquation cracking has been observed to reduce the hardness in the heat-affected zone (HAZ) and weaken the grain boundary strength. Friction stir welding (FSW), a solid-state joining process originally developed for aluminum alloys, is increasingly being applied to copper and its alloys to reduce alloying-element evaporation, compensate for rapid heat dissipation, and limit weld-zone strength loss, as shown in Figure 5. The copper base material exhibited elongated grains with deformation twins and a non-uniform particle size distribution, consistent with Erdem [27]. SEM–EDAX analysis showed ~98.5% Cu in recrystallized copper, ~64% Cu–36% Zn in brass, and an intermediate interfacial composition (~79% Cu–21% Zn). Recrystallized grains near the stir zone within the HAZ were coarser owing to annealing, whereas the grain size decreased toward the base material as the heat input diminished. These compositional and microstructural variations resulted from intense material flow and stirring during FSW, in agreement with earlier studies [26, 27].

Copper to Magnesium

Chen [29] et al. stated that welding processing was essential to make the Cu-Mg bimetals. However, the joining of Cu to alloys through conventional fusion welding processes remains challenging because of the significant difference in the melting points, formation of intermetallic compounds (IMCs), and severe thermal cracking. Investigated the TIG welding of Mg to Cu he found that metallic oxide and intermetallic compounds were the main reason that weak the joints strength. However to join these two metals by fiber laser-TIG hybrid welding the different morphologies including Mg–Cu eutectic structure, Mg–Cu intermetallic compound and Mg-Al-Cu ternary intermetallic compound were identified at the Mg-Cu interface. The surface morphology of the dissimilar weld seam revealed that the joint was coated with a thin layer of magnesium alloy, with minor flashes appearing along the edges. The cross-sectional microstructure showed that the nugget zone consisted of a mixture of magnesium

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and copper. An onion-ring pattern was visible in the lower region of the nugget, and its complex structure resulted from the flow behavior of the two dissimilar materials. No pores or defects were observed in Figures 6 (a) and 6 (b), confirming that the selected welding parameters successfully produced a sound joint.

Copper to Molybdenum

Zhou [30] stated that as shown in Figure 7 High Horizontal Collision Velocity (HCV) the melting point, thermal expansion coefficient, liquid metal density, laser absorption rate, and other physical property parameters of molybdenum and copper were significantly different, and it is easy to form defects, such as asymmetrical weld seams and macroscopic composition segregation. At the same time, there is no eutectic reaction or other metallurgical reactions between molybdenum and copper, and there exists a metallurgical incompatibility, which leads to relatively difficult metallurgical bonding at the interface of heterogeneous metals. The weldability of Mo was relatively poor. In the welding process, defects, such as pores, cracks, and grain coarsening, easily appear, and the strength and toughness of the joint are very low. Based on the analysis and reference of domestic and foreign research, this study proposes two measures to address the aforementioned problems: the method of laser beam offset was adopted to redistribute laser energy and produce joints with varying weld widths, and to examine the effect of base-metal melting. Ni was added to the molten pool to mitigate Cu–Mo incompatibility by promoting the formation of a Cu–Mo ternary system. The as-explosively-welded Mo/Cu clads exhibited good overall bonding, with no surface defects on the Mo plates. FE-SEM cross-sectional analysis revealed a wavy interface in all clads, confirming successful bonding. Interfacial cracks were observed only in Figures 7 (b) and 7 (d) for the HCV1 and HCV3 specimens, where cracks propagated along the interface and into the Mo plate, indicating welding conditions near or below the lower bonding limit. In contrast, for the LCV and HCV2 specimens as shown in Figure 7 (c), the clads exhibited defect-free interfaces and were selected for further analysis. The wave period in the LCV clads was at least five times larger than that in the HCV clads.

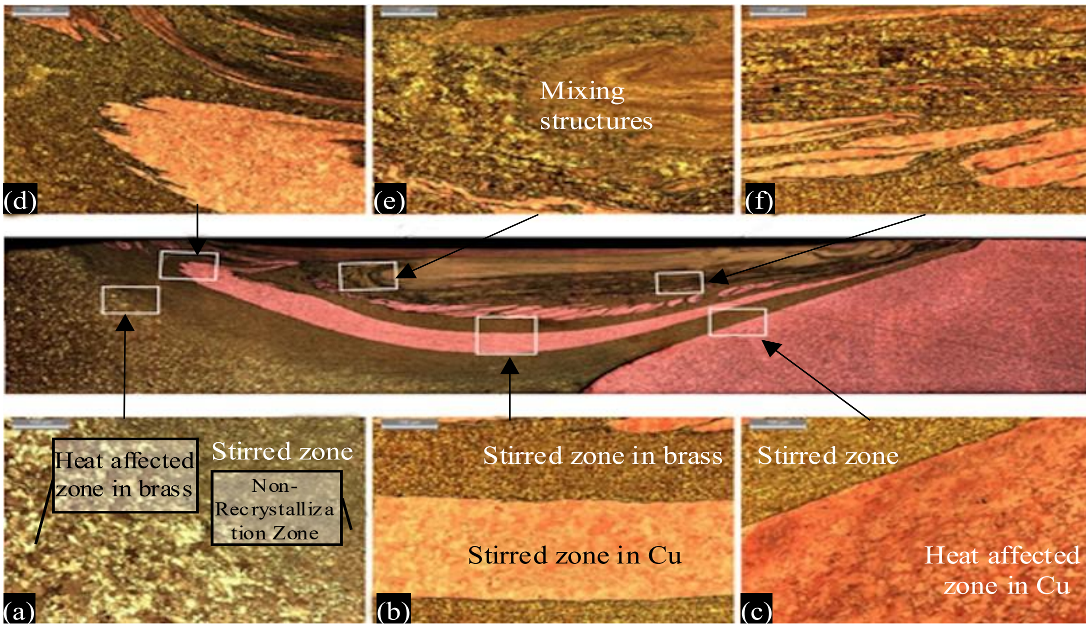

Figure 5. The detailed microstructure images for the different zones in: a HAZ+SZ in brass and b, c, d, e SZ, f-HAZ+SZ in copper [28].

Figure 6 (a). Surface appearance Copper to Mg [29]

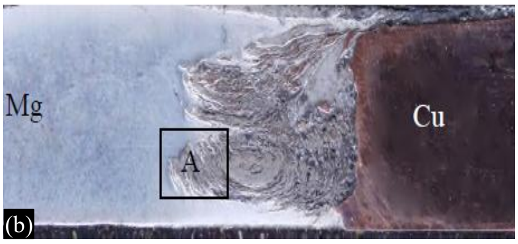

Figure 6 (b). Cross section view Copper to Mg [29]

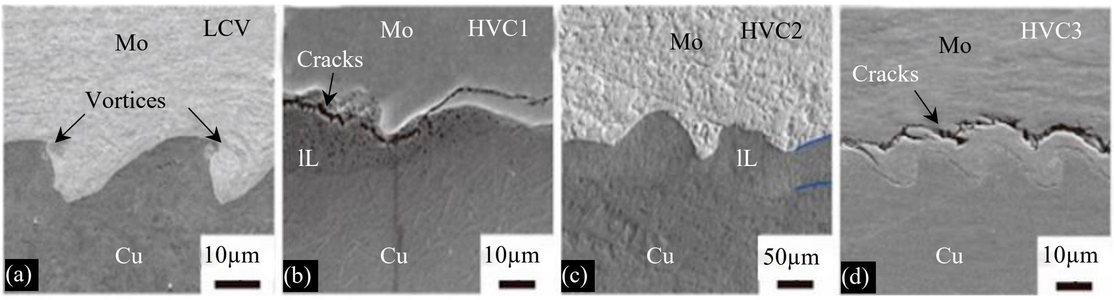

Figure 7. Cross-sectional field emission scanning electron microscope (FE-SEM) images of as explosive-welded clads produced at (a) LCV, (b) HCV1, (c) HCV2, (d) HCV3, [30].

Copper to Tin

The review indicated that interaction at the solder/base metal interface results in intermetallics formation [31,32]. These IMCs (intermetallic compounds) are responsible for the permanent bond of solder joints. However, intermetallics are brittle in nature. A thick IMC layer at the solder/substrate interface may degrade the reliability of solder joints. Hence, continuous uniform/thin layer of an IMC offers better wettability and excellent joint reliability. However, joining of Sn or Sn based alloys to Cu without formation of intermetallic compounds at interface is very difficult [33, 34].

Satyanarayan et al. [35, 36] stated that in current research, explosive welding of Sn and Cu plates using underwater shockwaves is proposed. Figure 8 shows the optical microstructures of the interfacial regions in underwater explosive-welded Sn/Cu joints, confirming that pure Sn and Cu can be effectively joined using this technique. Higher-magnification images show that both the wavelength and amplitude of the wavy interface decrease as the water standoff distance increases. At d = 30 mm, large interfacial waves formed owing to severe plastic deformation of the plates, with average wavelengths and amplitudes of approximately 98 μm and 50 μm, respectively. When the distance increased to d = 40 mm, these values decreased significantly to approximately 14 μm and 6 μm, and further decreased to approximately 8 μm and 3 μm at d = 50 mm. Samples welded at d = 60 mm exhibited wavy features; however, the waves were only in limited regions and were smaller than those at 50 mm. Overall, these observations indicate a transition from a wavy to a smoother interface at a water distance of d = 60 mm.

Cu to Nickel alloy

Mali [37] stated that the literature overview shows that the influence of the thickness of the intermediate layers on the mechanical properties of composites welded from dissimilar materials is not fully understood. Therefore, in this study, laminate composite materials consisting of layers of commercially pure titanium and nickel alloy were obtained by explosive welding using barriers made of thin plates of tantalum and copper. The influence of the thickness of the copper layer on the microstructure and mechanical properties of explosively welded Cu/Ni alloy composites was examined because of their mutual insolubility and the absence of chemical compounds in the Cu/Ni systems. Figure 9 shows the microstructures of the copper layers with the smallest and largest thicknesses after

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chemical etching. The 0.1 mm copper layer displayed the most uniform structure (Figure 9a), characterized by heavily deformed and elongated grains across its entire cross section. In contrast, the 0.7 mm copper layer exhibited a severely deformed structure only near the interfaces with the tantalum and nickel alloy plates (Figure 9b), where the deformed region was approximately 40–50 µm thick.

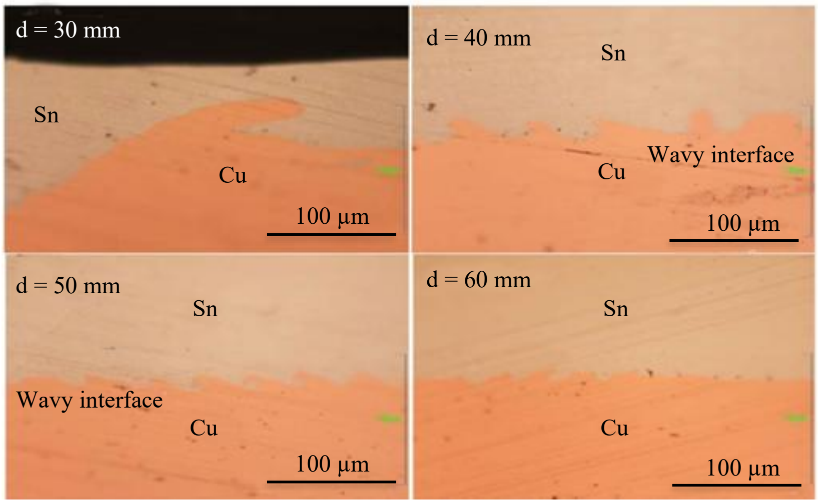

Figure 8. Optical microstructures of explosive welded Sn/Cu joints [31].

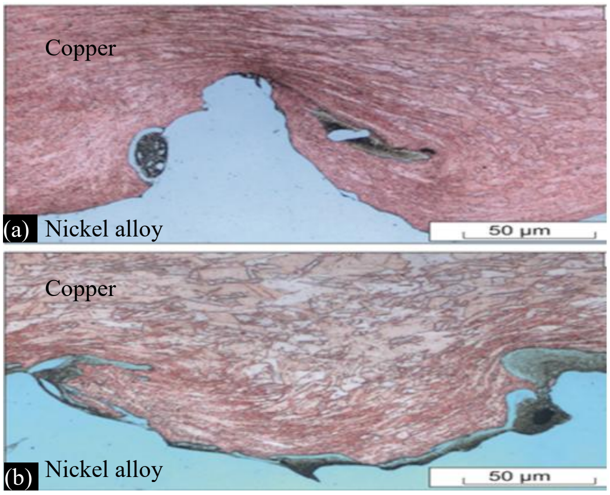

Figure 9. Structure of Cu/Ni alloy laminate composites with copper plates [33].

Copper to Tantalum

Welded joints of metal-intermetallics with normal mutual solubility in both the liquid and solid states have been investigated previously. Commercially pure titanium was chosen as the metal, and orthorhombic titanium aluminides ("aluminides" for short) were selected as the intermetallic compound. To determine the importance of the presence of mutual solubility of the starting materials for explosion welding, metals (copper–tantalum) that form immiscible suspensions in the liquid state were selected.

Greenberg [38] stated that apart from the previously used welding regime (Cp), a copper–tantalum joint was produced using an alternative mode (Cw), resulting in a distinctly wavy interface exhibiting asymmetry with respect to the vertical plane, as shown in Figures 10a and b. The interface displayed a wavelength of approximately 100–200 µm and an amplitude of approximately 100 µm, and a localized melting zone with a characteristic vortex-like structure was clearly visible in Figure 10b.

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Similarly, the interface shows a generally regular wavy morphology, although it includes waves with varying amplitudes and nearly straight segments; the average wavelength and amplitude are approximately 140–150 and 50 µm, respectively. Instead of the parallel bands typically associated with a corrugated surface, the observed image consists of randomly distributed white, black, and gray spots, indicating that the transition zone is composed of three distinct types of regions. The presence of these regions provides strong evidence for the formation of cusps, which are characteristic interface inhomogeneities that play a significant role in interfacial adhesion.

Furthermore, tantalum particles released from the gray regions during copper etching were observed on the tantalum surface. Because the melting of a refractory metal such as tantalum (with a melting point of approximately 3300 K) is highly unlikely during explosion welding, the formation of these particles is inferred to occur in the solid state. Consequently, the presence of tantalum particles serves as direct evidence of jetting-related mechanisms (GF), which are discussed in the following section [33].

EFFECT OF WELDING PARAMETERS

Welding speed, power, and cooling rate directly impact the microstructure:

- High cooling rates promote fine-grained microstructures and reduce IMC thickness.
- Preheating helps minimize thermal gradients and residual stress.
- A low heat input avoids grain coarsening in the heat-affected zone.
- SEM and EDS analyses from several studies confirm that the joint strength is highest when a thin, discontinuous IMC layer and refined grains are achieved at the interface.

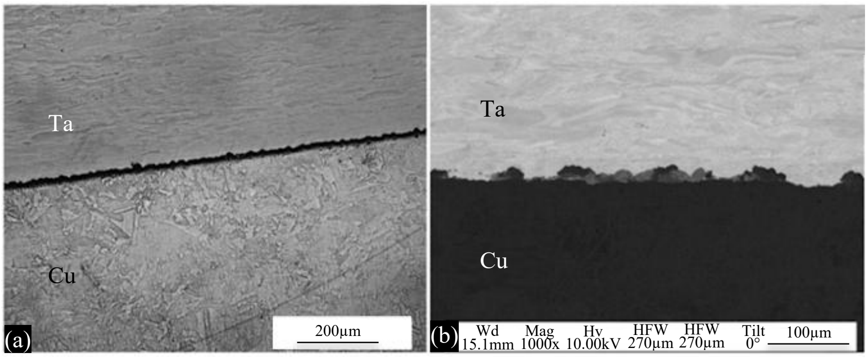

Figure 10. Transverse section of a plain interface: (a) in (Cp) copper–tantalum joint (OM), (b) in (Cp) copper–tantalum Joint (sem),[38].

CONCLUSION

Welding copper alloys to dissimilar metals remains a complex engineering challenge because of the substantial differences in their thermal, physical, and chemical properties. High thermal conductivity, rapid oxidation, and intermetallic compound formation make the process particularly difficult, especially when fusion welding is employed.

However, a wide array of welding techniques, ranging from traditional arc welding to modern solid-state and hybrid methods, has been successfully adapted to address these challenges. Strategic approaches involving filler metal design, interlayer application, surface preparation, and thermal management have proven effective in improving joint performance. Recent advancements in welding technologies, materials engineering, and process control, along with the growing use of computational modeling and artificial intelligence, are rapidly transforming the field and enabling the manufacture of robust copper-to-dissimilar-metal joints.

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As industries continue to demand more efficient, lightweight, and multifunctional systems, further research and innovation in this area are essential. The integration of advanced materials, smart manufacturing techniques, and data-driven design will likely shape the next generation of joining technologies for copper alloys.

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