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# A Brief Review of 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.*

**Keywords:** Copper, dissimilar metals, explosive welding, interface characterization, wavy interface

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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 superalloys [3].

These characteristics 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 the 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 tungsten inert gas (TIG), MIG, and laser welding) [7–9] 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 processing 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 of recent studies and industrial practices, this study seeks to inform future research and support the development of robust and reliable joining strategies for hybrid metal structures involving copper alloys [13]. This review aims to provide a comprehensive overview of the 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 for welding, particularly with 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 required for proper fusion. Consequently, welding copper alloys often requires a higher heat input, more powerful sources, or preheating to compensate for heat loss [15].

### High Electrical Conductivity

The excellent electrical conductivity of copper, which is 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 the 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, hardnesses, and corrosion resistance. For example, the addition of zinc to 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 the weld quality. In many cases, the formation of brittle intermetallic compounds at the interface (particularly when welding aluminum or titanium) must be carefully controlled to ensure structural integrity [19, 20].

### Oxidation Tendency at High Temperatures

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

### Coefficient of Thermal Expansion

Copper alloys generally have a higher coefficient of thermal expansion (CTE) than most steels and other structural metals, which creates significant challenges during welding. Differences in the CTE induce thermal and residual stress 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 the melting temperatures of copper alloys and dissimilar metals further intensifies these problems, making it more difficult to maintain joint integrity [22].

### Softness and Formability

Although copper is easily formable and ductile, it is 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 the 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 the performance requirements [24].

### Differences in Melting Points

Pure copper melts at approximately 1085°C, whereas aluminum melts at approximately 660°C, and some steel 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

When dissimilar metals are joined, particularly 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

The high thermal conductivity of copper implies that heat dissipates rapidly from the weld zone, often making it difficult to maintain an adequate temperature for proper bonding. In contrast, metals such as steel and titanium retain heat for a longer duration in the weld region. This mismatch complicates heat control, resulting in unbalanced heating, distortion, and non-uniform 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 during welding. Welding methods are typically grouped into fusion welding, solid-state welding, and advanced hybrid techniques. In the current review, copper welded to different materials was described [28].

 

**Copper to Stainless Steel**

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/stainless steel joint is depicted in Figure 1. The color of the weld was similar to that of copper when the laser beam offset was 0 mm, as shown in Figure 1(a). The melting of copper was successfully inhibited when the laser beam was appropriately offset in the direction of stainless steel, as shown in Figure 1(b). Therefore, the processing parameters of the laser beam have a significant impact on the melting behavior of copper and the microstructure of the joint.

Joshi et al. extensively reviewed fusion welding techniques for joining copper to stainless steel [29]. They 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 stainless steel.

Studies have demonstrated that the use of stainless-steel fillers can lead to cracking owing to poor mutual solubility and infiltration between Cu and Fe. 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 in SMAW, where inconsistent arc behavior often leads to incomplete fusion [29].

**Copper–Steel Joints**

Kalms et al. [3] states that it is difficult to produce copper–steel joints using traditional welding methods because of the significant differences in the thermal properties of copper and steel, such as the melting point, 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 $Cu_6Fe_5$ [3]. reported that 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 brittleness.

The joining of copper and stainless steel through laser beam welding (LBW) and 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 the 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 improve 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.

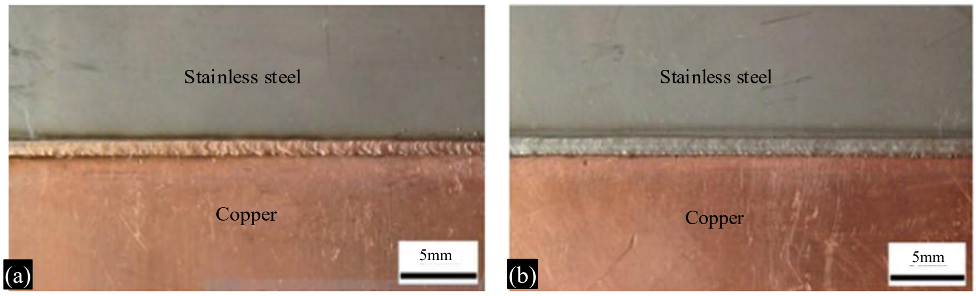


**Figure 1.** Surface appearance of the two welded interfaces: (a) laser beam offset 0 mm, oblique angle 0°, (b) Laser beam offset 0.2 mm, oblique angle 4° [2].

 

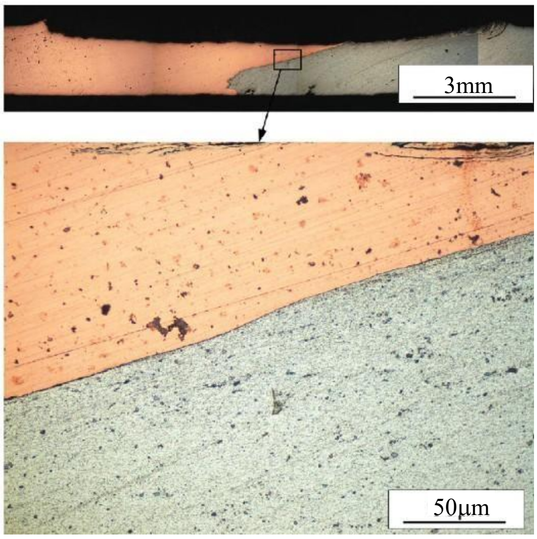

**Figure 2.** Laser beam welding of copper and steel [3].

Recent advancements in AI-driven adaptive control systems have enhanced the precision of dissimilar-metal welding [6]. It has been 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 minimize IMCs and optimize the heat input [7].

**Copper–Aluminum**

Liu et al. [22] stated that copper and aluminum alloys are widely known for their outstanding electrical and thermal conductivities and excellent resistance to corrosion. However, some physical properties of these materials differ markedly, such as their density and melting temperature. Specifically, the copper density is approximately three times that of aluminum, which, in turn, has a melting temperature approximately 60% lower than that of copper [6, 8]. The investigated tool offset toward both aluminum and copper reported 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]. In addition, unsatisfactory welding performance was observed for all the offset conditions.

Both studies noted that offset welding produced greater IMC formation than centered-tool welding, contradicting earlier findings. This increase was attributed to the more intense mechanical mixing when one material became dominant in the stirring zone. Overall, the existing literature lacks agreement on how the 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 [9]. These inconsistencies largely stem from variations in the alloy combinations, sheet thickness, rotational/traverse speeds, and tool geometry. Because the tool governs the heat input and material flow, its design plays a crucial role in determining the 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].

FSW has been adopted to join Cu–Al metals [9]. In this study, the joints exhibited a layered microstructure in the stir zone, consisting of dynamically recrystallized fine grains and discrete intermetallic phases (IMCs), such as $Al_2Cu$, $Al_4Cu_9$, and AlCu. It has been reported that thick and continuous IMCs can reduce ductility and cause brittle failure. They concluded that the tool design and rotational speed significantly influenced 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 led to new phase formation, which may have a substantial effect. 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 IMCs (TiCu, $Ti_2Cu$, and $Ti_3Cu_4$) 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].

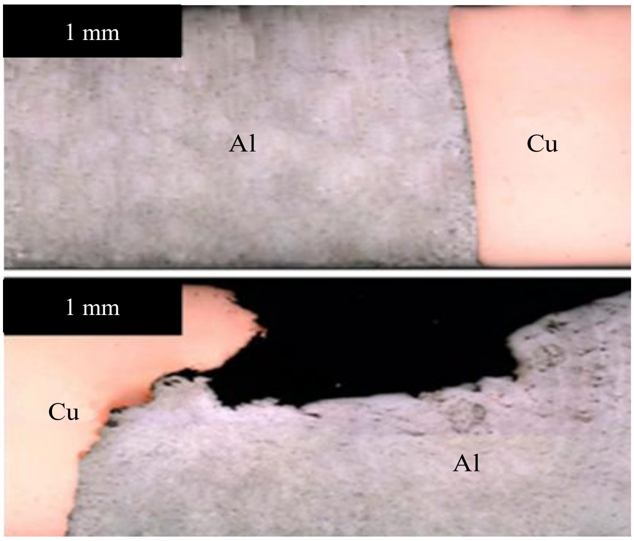


**Figure 3.** Explosive welding of copper and aluminum [22].

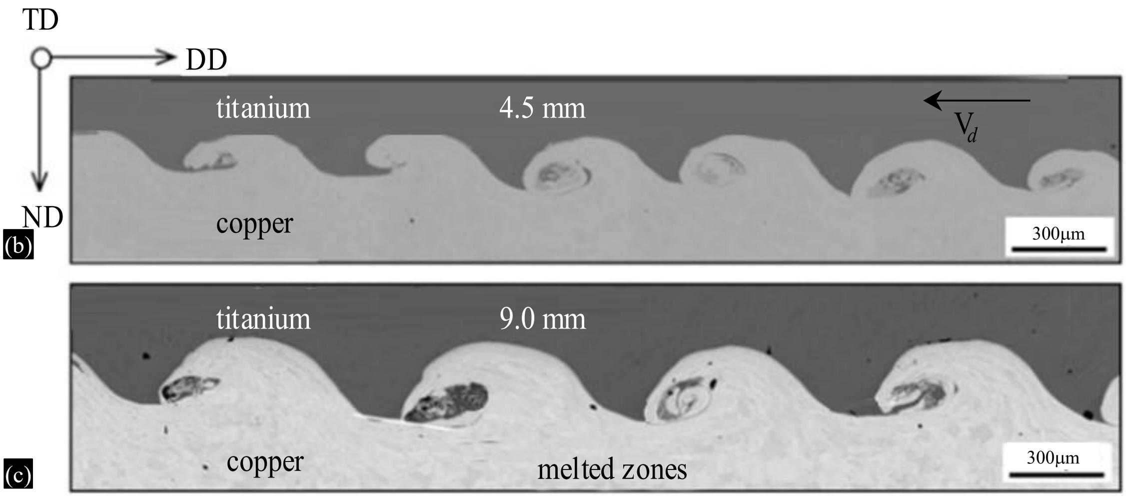


**Figure 4.** Schematic representation of explosive welding, along with the wavy interfaces observed in clads manufactured at a detonation velocity of 2500 $ms^{-1}$ and stand-off distance of (b) 4.5 mm, and (c) 9.0 mm [24].

 

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**Copper 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 Ni alloys.

Erdem [27] stated that when fusion welding processes, such as TIG welding, are employed, the temperature in the weld zone often exceeds the melting and boiling points of the 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 the LBW of copper–beryllium alloys, liquation cracking reduces the hardness in the HAZ and weakens the grain boundary strength. 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 the recrystallized copper, ~64% Cu–36% Zn in the brass, and an intermediate interfacial composition (~79% Cu–21% Zn). The 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 the intense material flow and stirring during FSW, which is in agreement with earlier studies [26, 27].

**Copper to Magnesium**

Chen et al. [29] stated that welding processing was essential for making Cu–Mg bimetals. However, joining Cu to alloys through conventional fusion welding processes remains challenging because of the significant difference in melting points, formation of IMCs, and severe thermal cracking. The TIG welding of Mg to Cu and found that metallic oxides and IMCs were the main reasons for the weakening of joint strength. However, to join these two metals by fiber laser-TIG hybrid welding, different morphologies, including Mg–Cu eutectic structure, Mg–Cu IMC, and Mg-Al-Cu ternary IMC, 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 along the edges. The cross-sectional microstructure revealed that the nugget zone comprised a mixture of Mg and Cu. 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 Figure 6(a) and (b), confirming that the selected welding parameters successfully produced sound joints.

**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.

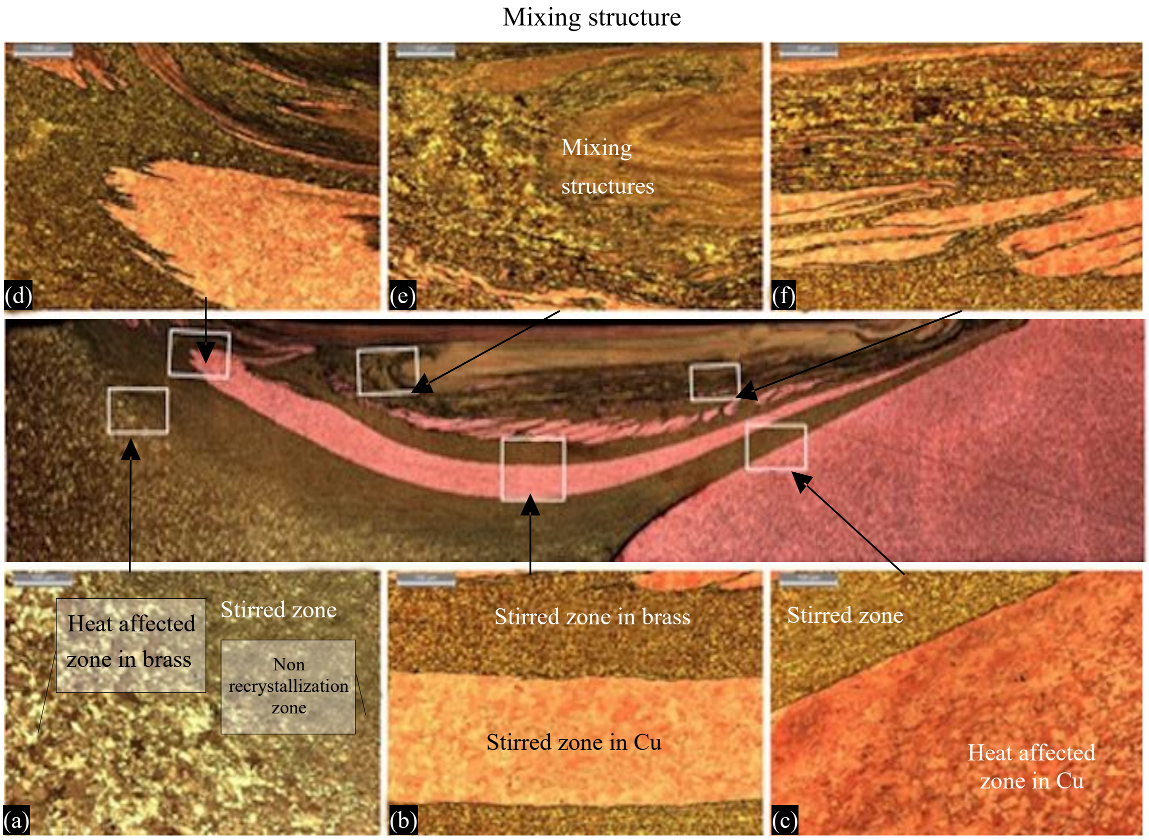


**Figure 5.** The detailed microstructure images for the different zones in (a) HAZ+SZ in brass, and (b) to (e) SZ, f-HAZ+SZ in copper [28].

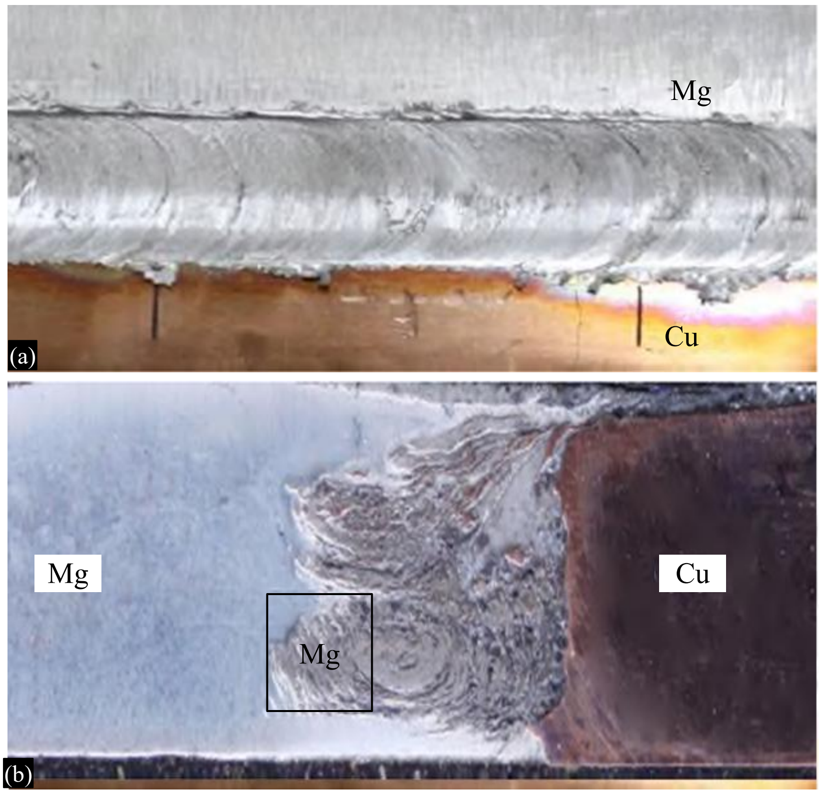


**Figure 6.** (a) Surface appearance of copper to Mg [29]; (b) Cross-sectional view of copper to Mg [29].

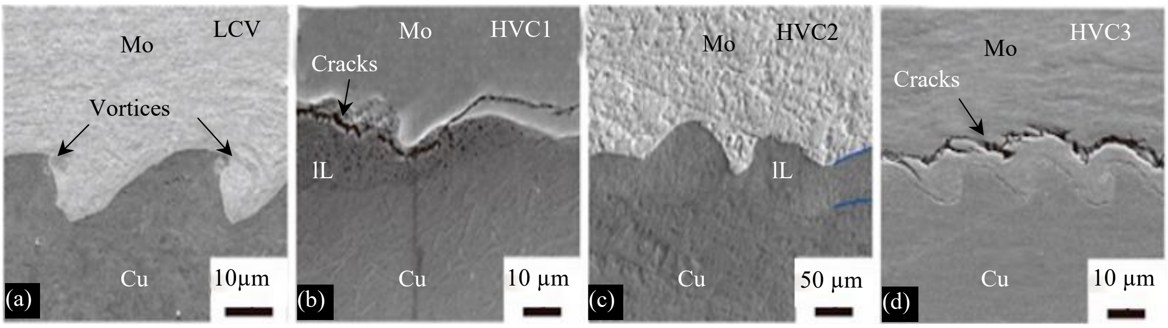


**Figure 7.** Cross-sectional field emission scanning electron microscope (FE-SEM) images of as explosive-welded clads produced at (a) LCV, (b) HCV1, (c) HCV2, and (d) HCV3 [30].

FE-SEM cross-sectional analysis revealed a wavy interface in all clads, confirming successful bonding. Interfacial cracks were observed only in Figure 7(b) and (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 low collision velocity (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.

**Copper to Tin**

The review indicated that interactions at the solder/base metal interface result in intermetallic formation [31, 32]. These IMCs are responsible for the permanent bonding of solder joints. However, intermetallic is brittle. A thick IMC layer at the solder/substrate interface may degrade the reliability of the solder joints. Hence, a continuous uniform/thin layer of an IMC offers better wettability and excellent joint reliability. However, joining Sn or Sn-based alloys to Cu without the formation of IMCs at the 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 the underwater explosive-welded Sn/Cu joints, confirming that pure Sn and Cu can be effectively joined using this technique. Higher-magnification images showed that both the wavelength and amplitude of the wavy interface decreased as the water stand-off distance increased. At d = 30 mm, large interfacial waves formed owing to the 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, respectively. 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 d. Overall, these observations indicate a transition from a wavy to a smooth interface at a water distance of d = 60 mm.

**Copper to Nickel alloy**

Mali [37] stated that an overview of the literature 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 alloys 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 Cu/Ni systems. Figure 9 shows the microstructures of the copper layers with the smallest and largest thicknesses after chemical etching. The 0.1 mm copper layer displayed the most uniform structure (Figure 9(a)), 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 Ta and Ni–Cu alloy plates (Figure 9(b)), where the deformed region was approximately 40–50 μm thick.

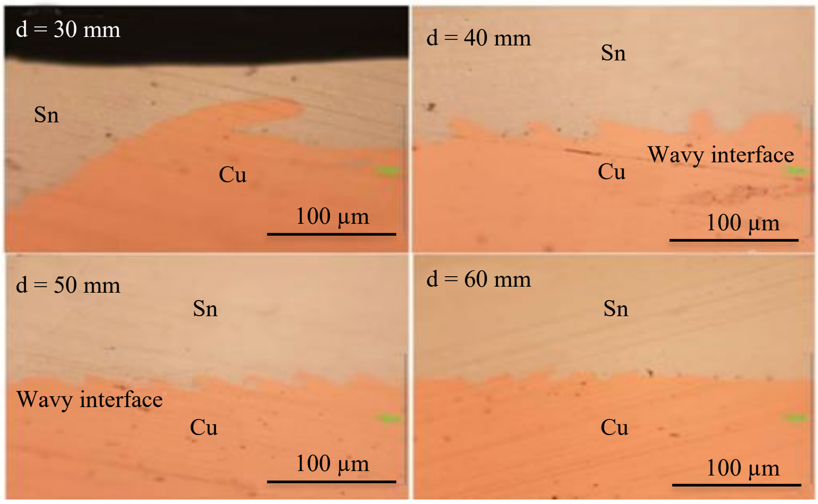


**Figure 8.** Optical microstructures of explosive-welded Sn/Cu joints [31].

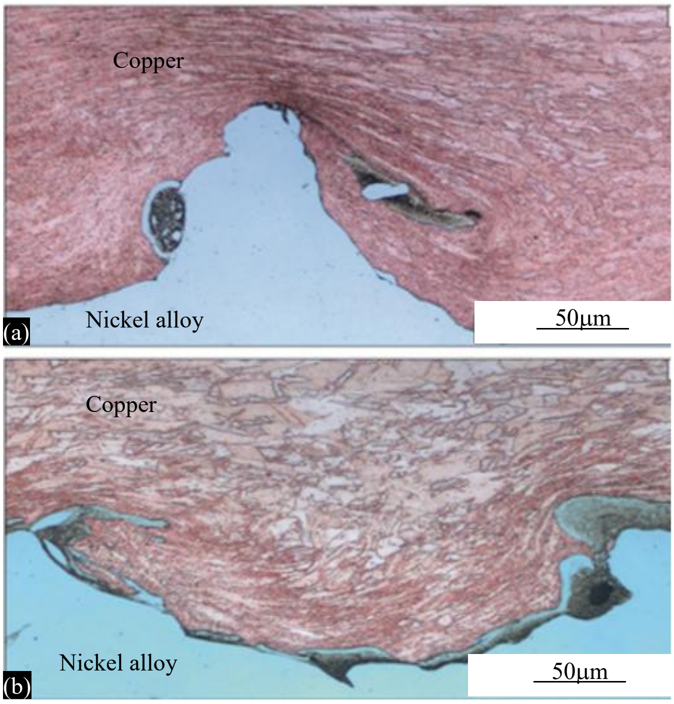


**Figure 9.** Structure of Cu/Ni alloy laminate composites with copper plates [33].

**Copper to Tantalum**

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

Greenberg [38] stated that apart from the previously used welding regime (Cp), a Cu–Ta 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 Figure 10(a) 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 (Figure 10(b)).

 

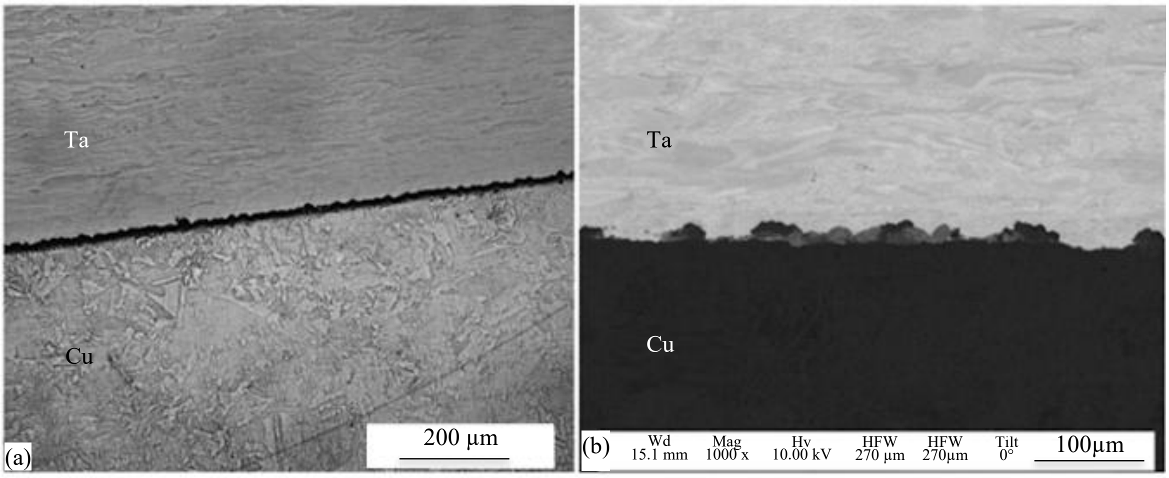


**Figure 10.** Transverse section of a plain interface: (a) in (Cp) copper–tantalum joint (OM), (b) in (Cp) copper–tantalum joint (SEM) [38].

Similarly, the interface exhibited a generally regular wavy morphology, although it included waves with varying amplitudes and nearly straight segments; the average wavelength and amplitude were approximately 140–150 and 50 µm, respectively. Instead of the parallel bands typically associated with a corrugated surface, the observed image consisted of randomly distributed white, black, and gray spots, indicating that the transition zone comprised 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 Ta 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 HAZ.
- Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analyses from several studies confirm that the joint strength is highest when a thin, discontinuous IMC layer and refined grains are formed at the interface.

## 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 IMC formation make the process particularly difficult, especially when fusion welding is used.

However, a wide array of welding techniques, ranging from traditional arc welding to modern solid-state and hybrid methods, have been successfully adapted to address these challenges. Strategic approaches involving filler metal design, interlayer application, surface preparation, and thermal management have proven to be 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, have rapidly transformed the field and enabled the manufacture of robust copper-to-dissimilar-metal joints.

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

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