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Al/Cu BIMETALLIC ELECTRICAL JOINTS: STATE-OF-THE-ART WITH EMPHASIS ON CONTINUOUS-DRIVE FRICTION WELDING

Al/Cu BIMETALNI ELEKTRIČNI SPOJEVI: STANJE SAVREMENIH ISTRAŽIVANJA SA POSEBNIM OSVRTOM NA ZAVARIVANJE TRENJEM SA KONTINUIRANIM POGONOM

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Abstract: The increasing use of aluminum conductors while retaining copper terminals has increased the need for reliable Al/Cu transitions. Mechanical connectors remain practical, but their long-term performance depends on stable pressure-controlled contact despite oxidation, corrosion, thermal expansion mismatch, creep, stress relaxation, and fretting. Metallurgical transitions reduce this dependence. Continuous-drive friction welding (CDFW) is particularly attractive for cylindrical components because it is rapid, filler-free, and avoids bulk melting. This review relates CDFW parameters to material transfer, interface morphology, recrystallization, intermetallic-compound (IMC) formation, radial heterogeneity, electrical behavior, mechanical properties, fracture, and thermal exposure. Insufficient heat input produces incomplete bonding, whereas excessive heat input promotes softening, material loss, and IMC growth. Optimized short-cycle CDFW can produce complete bonding with approximately 0.5 μm Al_2Cu while retaining more than 92% of the theoretical Al/Cu conductivity and approximately the tensile strength of the Al base material. However, IMC thickness alone cannot describe joint integrity because phase composition, continuity, residual stress, radial distribution, and adjacent microstructure also influence fracture. Future development should therefore focus on phase-specific, spatially resolved, and service-life-oriented interface engineering.

Keywords: Al/Cu joints; continuous-drive friction welding; intermetallic compounds; electrical conductivity; mechanical performance

Rezime: Sve veća primena aluminijumskih provodnika uz zadržavanje bakarnih priključaka povećala je potrebu za pouzdanim Al/Cu prelaznim spojevima. Mehanički konektori i dalje predstavljaju praktično rešenje, ali njihova dugoročna pouzdanost zavisi od stabilnosti kontakta ostvarenog pritiskom, uprkos oksidaciji, koroziji, neusklađenosti koeficijenata toplotnog širenja, puzanju, relaksaciji napona i fretingu. Metalurški spojevi smanjuju ovu zavisnost. Zavarivanje trenjem sa kontinuiranim pogonom (CDFW) posebno je pogodno za cilindrične komponente jer je postupak brz, ne zahteva dodatni materijal i odvija se bez zapreminskog

topljenja. U ovom preglednom radu razmatraju se veze između parametara CDFW procesa i prenosa materijala, morfologije interfejsa, rekristalizacije, nastanka intermetalnih jedinjenja (IMC), radijalne nehomogenosti, električnih svojstava, mehaničkih svojstava, loma i termičkog izlaganja. Nedovoljan unos toplote dovodi do nepotpunog spajanja, dok prekomeran unos toplote podstiče omekšavanje, gubitak materijala i rast IMC. Optimizovanim kratkotrajnim CDFW postupkom može se ostvariti potpuno spajanje uz sloj Al_2Cu debljine približno 0,5 μm, pri čemu se zadržava više od 92% teorijske električne provodljivosti Al/Cu spoja i približno zatezna čvrstoća osnovnog materijala od Al. Međutim, sama debljina IMC nije dovoljna za opis integriteta spoja, jer na lom utiču i fazni sastav, kontinuitet, zaostali naponi, radijalna raspodela i susedna mikrostruktura. Buduća istraživanja zato treba usmeriti ka fazno specifičnom i prostorno razlučenom inženjerstvu interfejsa, uz razmatranje ponašanja tokom eksploatacionog veka.

Ključne reči: Al/Cu spojevi; zavarivanje trenjem sa kontinuiranim pogonom; intermetalna jedinjenja; električna provodljivost; mehaničke performanse

1. INTRODUCTION

1.1. From mechanical connections to metallurgical Al/Cu transitions

Copper remains widely used in electrical systems because of its high conductivity, whereas the lower density and cost of Al favor its increasing use in transmission and distribution. Since Cu remains common in terminals, busbars, switchgear, transformers, and contact elements, reliable Al/Cu transitions are increasingly required. Conventional solutions include butt connectors, crimped and screw-type lugs, bolted joints, and Al lugs with Cu contact elements, as illustrated in Figure 1 [1].

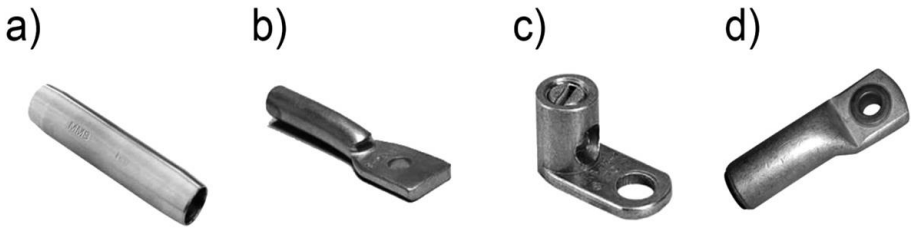


Figure 1. Representative conventional conductor-connection configurations relevant to Al/Cu transitions: (a) Cu butt connector, (b) Cu crimping lug, (c) Cu lug with screw, and (d) Al lug with inserted Cu ring. Reproduced from Milašinović et al. [1].

Mechanical connectors can initially exhibit low resistance, but current flows only through microscopic asperity contacts. Oxidation, galvanic corrosion, thermal-expansion mismatch, Al creep and stress relaxation, and fretting can progressively reduce the real metallic contact area [2–7]. The resulting resistance increase enhances local Joule heating and may accelerate further degradation. The main limitation of a mechanical Al/Cu connector is therefore not its initial conductivity, but maintaining low and stable contact resistance during service.

1.2. Metallurgical joining, CDFW, and Al/Cu incompatibility

Permanent metallurgical transitions reduce dependence on pressure-controlled contact. Al/Cu joints have been produced by cold-pressure and roll bonding, diffusion and explosive welding, ultrasonic and friction stir welding, brazing, laser joining, and rotary friction welding [2,8]. Wei et al. [8] showed that explosion welding produced a strong wavy interface, cold-pressure welding relied mainly on mechanical interlocking, whereas solid-liquid casting generated a thick, defective reaction region. Among these technologies, CDFW is particularly suitable for

cylindrical components because joining is rapid, avoids bulk melting, and generally requires neither filler metal nor shielding gas; friction generates heat and deformation followed by forging, so bonding depends on friction time, pressure, rotation, material transfer, and forging [9–12]. Insufficient heat input leaves unbonded regions, whereas excessive heat input promotes flash, softening, material loss, and IMC growth.

Al and Cu differ markedly in thermal properties, deformation, strength, and recrystallization behavior [13–17]. In addition, several IMCs may form during CDFW, including Al_2Cu, AlCu, Al_3Cu_4, Al_2Cu_3, and Al_4Cu_9 [12,18]. These phases differ substantially in electrical and mechanical properties. Braunovic and Alexandrov [19] reported electrical resistivities ranging from 8.0 to 14.2 μΩ·cm for several Al–Cu intermetallic phases, together with markedly phase-dependent hardness values (Table 1). Consequently, the interface must be considered simultaneously as an electrical and mechanical transition zone.

Table 1. Representative properties of several Al–Cu intermetallic phases reported by Braunovic and Alexandrov [19].

Phase	Symbol	Cu, wt.%	Al, wt.%	Hardness, kg/mm²	Electrical resistivity, μΩ·cm
Cu_2Al	γ_2	80	20	35	14.2
Cu_3Al_2	δ	78	22	180	13.4
Cu_4Al_3	ζ_2	75	25	624	12.2
CuAl	η_2	70	30	648	11.4
$CuAl_2$	θ	55	45	413	8.0

2. COMPARATIVE BASIS OF THE REVIEW

Direct comparison of Al/Cu friction-welding studies is complicated by differences in material condition, specimen geometry, machine design, rotation speed, pressure sequence, friction time, forging conditions, and process-duration definitions. Similar nominal parameters may therefore produce different thermomechanical histories. The studies considered here cover process parameters, bonding, IMC growth, radial heterogeneity, mechanical performance, thermal exposure, and optimized short-cycle CDFW [1,9–13,18,20–29]. The discussion therefore emphasizes recurring relationships between insufficient, optimum, and excessive heat input rather than a universally transferable parameter set.

3. CRITICAL REVIEW AND DISCUSSION

3.1. Mechanical-to-metallurgical transition and initial CDFW interface formation

Mechanical Al/Cu contacts degrade through oxidation, galvanic corrosion, thermal-expansion mismatch, creep, stress relaxation, fretting, and contamination [2–7]. Collectively, these mechanisms reduce real contact area and increase resistance, thereby intensifying local Joule heating. Metallurgical joining reduces this dependence on pressure-controlled contact but introduces a heterogeneous reaction zone.

Wei et al. [8] reported bonding strengths of approximately 104 MPa for explosion welding and 74 MPa for cold-pressure welding, while casting produced a defective 200–250 μm Al_2Cu-containing region. Ay et al. [20] likewise found friction-welded Al/Cu joints considerably stronger than diffusion-welded joints.

Within CDFW, forging is essential. Milašinović et al. [1] showed that friction alone did not fully eliminate the initial surface morphology (Figures 2a and 2b), whereas forging flattened and consolidated the interface (Figures 2c and 2d). Kimura et al. [11] similarly observed

progressive Al transfer and fewer unjoined regions with increasing forge pressure, confirming that IMC formation alone does not ensure complete bonding.

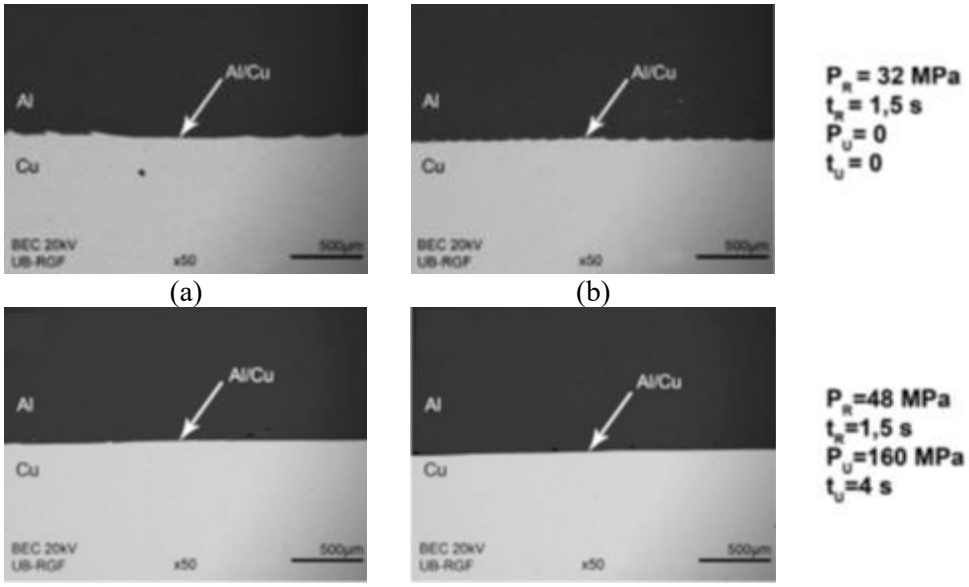


Figure 2. Morphological evolution of the Al/Cu interface at central and peripheral positions under different friction- and forging-stage conditions. P_R, t_R, P_U, and t_U stand for friction pressure, friction time, forging pressure, and forging time, respectively. Adapted from Milašinović et al. [1].

3.2. Microstructural evolution, heat-input window, and optimized CDFW interface

The mechanically affected region extends beyond the IMC layer. Milašinović et al. [27] showed that subsequent cold pressing strongly changed the hardness distribution, while the discontinuous reaction layer remained below ~0.2 μm (Figure 3a). Cold pressing also transformed a relatively smooth interface (Figure 3b) into a serrated one (Figure 3c) without measurable IMC growth. The adjacent Cu developed necklace-type recrystallized grains (Figure 3e), whereas Al exhibited a broader affected region (Figure 3g), reflecting their different recrystallization behavior [14–17].

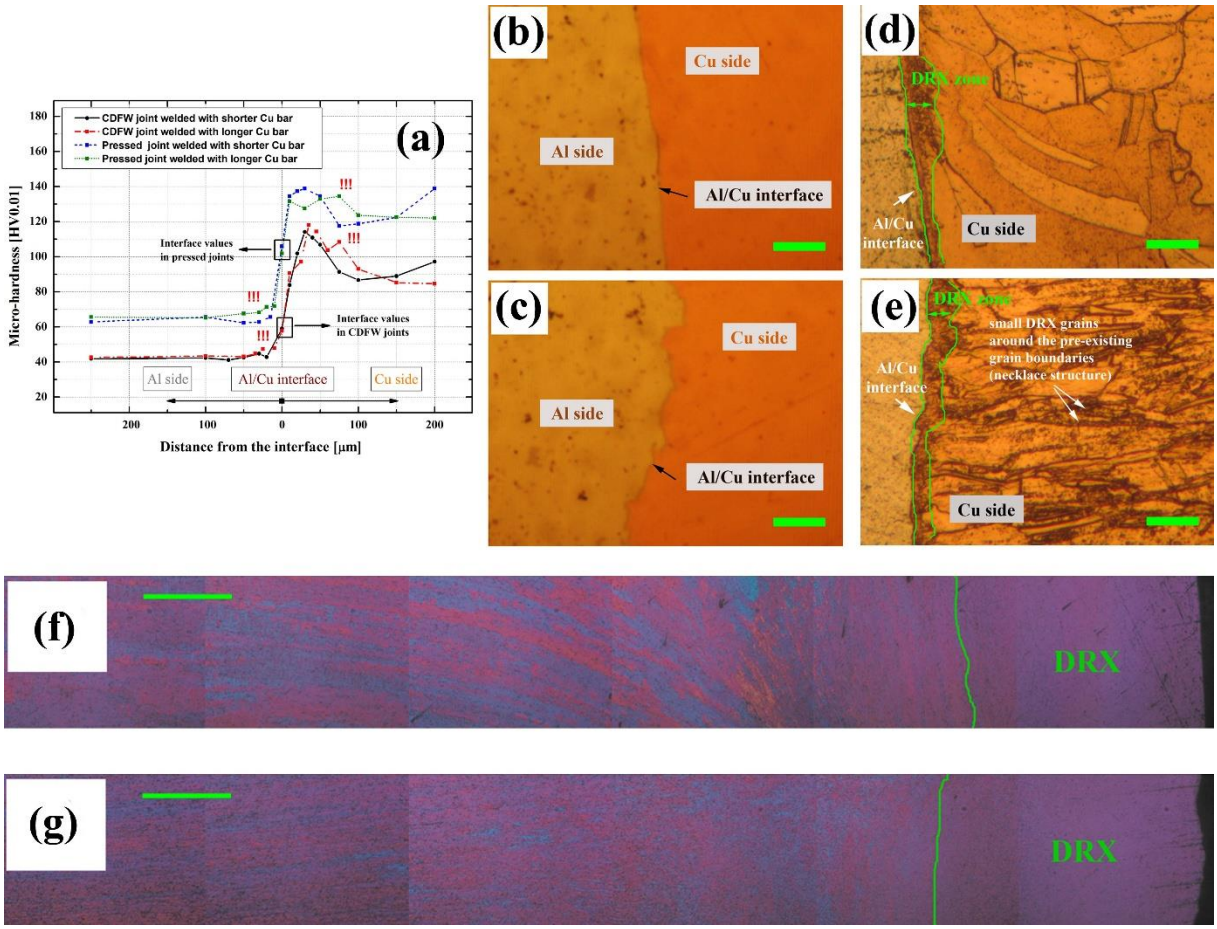


Figure 3. Microstructural and microhardness characteristics of CDFW Al/Cu joints before and after subsequent cold pressing: (a) microhardness distribution and discontinuous reaction layer; (b) relatively smooth as-welded interface; (c) serrated interface after cold pressing; (d) Cu microstructure before cold pressing; (e) necklace-type recrystallized Cu microstructure after cold pressing; (f) Al microstructure before cold pressing; and (g) Al microstructure after cold pressing. Adapted from Milašinović et al. [27].

Increasing heat input initially improves bonding but eventually promotes thermal softening and IMC growth. Wei et al. [12] showed that increasing friction time from 2 to 8 s enlarged the Al_2Cu/Al_4Cu_9 reaction region from ~0.7 to ~10 μm. Ratković et al. [13] reported an increase in UTS from 61 MPa at 4 s to 85 MPa at 8 s, followed by a decline at longer friction times, while Satish et al. [21] obtained ~135 MPa UTS but only ~0.5–1% elongation. Rotation speed exhibits a similarly non-monotonic effect: Zhu et al. [25] obtained ~212 MPa at 1000 rpm within the investigated range of 700–1200 rpm, yet all joints fractured at the interface and elongation remained below ~2.5%. Increasing heat input beyond that required for adequate bonding therefore does not necessarily improve overall performance.

Milašinović et al. [28] achieved a favorable balance using a short welding time, 2100 rpm, and high welding pressures. Lower-heat-input conditions retained local unbonded regions despite Al_2Cu formation, whereas condition C3, using a friction pressure of 66.7 MPa and a forging pressure of 222.2 MPa, produced complete Al transfer and an Al_2Cu layer of ~0.5 μm (Figure 4). Higher pressures increased deformation, flash formation, material loss, and energy consumption with little additional benefit. This agrees with Sahin [9], Ratković et al. [13], and Zhu et al. [25]: CDFW properties are non-monotonic because bonding, reaction kinetics, extrusion, thermal softening, and material transfer evolve simultaneously.

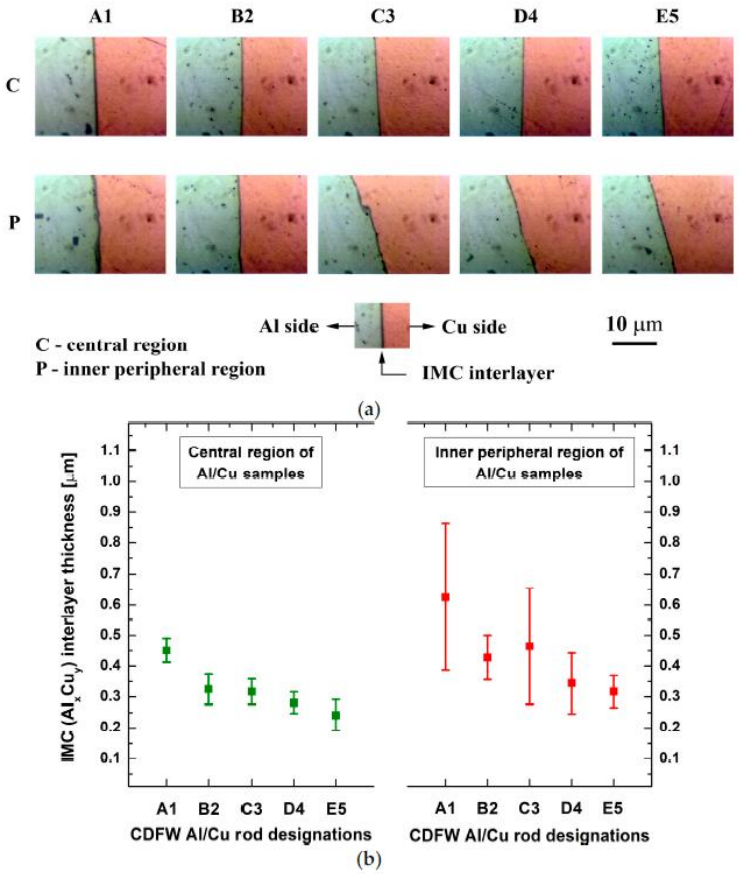


Figure 4. Interface morphology and Al_2Cu thickness under different short-cycle high-pressure CDFW conditions. Reproduced from Milašinović et al. [28].

3.3. Electrical and mechanical performance of thin CDFW reaction layers

For a planar multilayer normal to current flow, the IMC contribution to resistance can be approximated by:

$$\mathbf{R_{IMC}} = \sum\left(\frac{\rho_i \times t_i}{A}\right) \quad (1)$$

where $\boldsymbol{\rho_i}$ and $\boldsymbol{t_i}$ are the resistivity and thickness of phase $\boldsymbol{i}$, and $\boldsymbol{A}$ is the effective conducting area. Electrical behavior therefore depends on phase-specific rather than total IMC thickness.

Despite their higher intrinsic resistivity, submicrometer IMCs occupy only a small fraction of the current path. Short-cycle CDFW specimens consequently retain ~42.8–44.4 MS/m, exceeding 92% of the theoretical Al/Cu conductivity (Figure 5) [28].

Bulk conductivity, however, can mask local interface behavior. Wang et al. [30] showed that joints with similar initial reaction-layer thicknesses (~2 μm) exhibit different current distributions because the geometry and continuity of the IMC layer differ along the interface. After 350 °C/500 h exposure, the reaction region reaches ~50 μm and develops additional phases, cracks, and oxide-related features, increasing resistivity. Electrical performance therefore depends on phase resistivity, thickness, continuity, defects, oxides, and the effective current path.

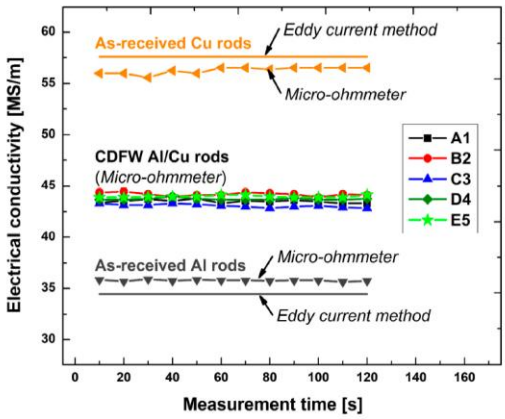
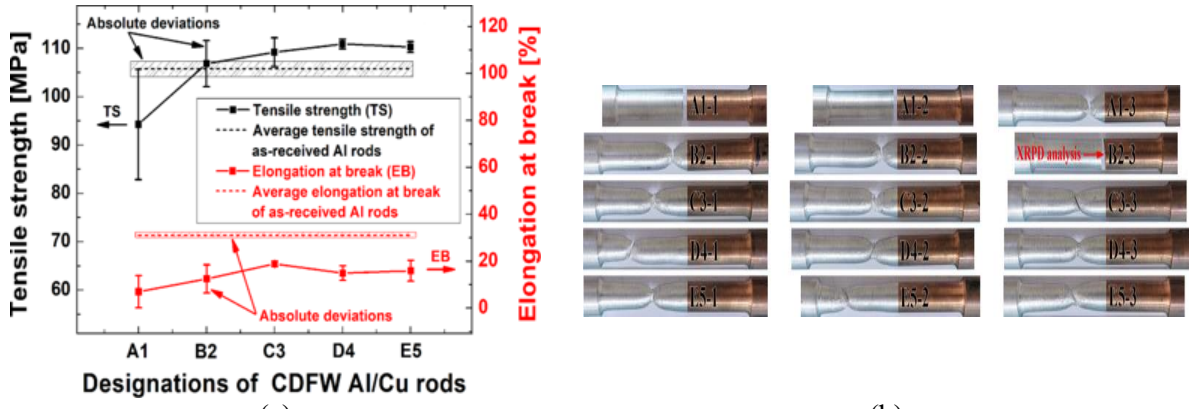


Figure 5. Electrical conductivity of Al, Cu, and Al/Cu specimens produced using different CDFW conditions. Reproduced from Milašinović et al. [28].

Mechanical assessment likewise requires more than UTS. Milašinović et al. [28] obtained ~94–111 MPa UTS and 6.9–18.8% elongation (Figure 6a). C3 reached ~100% strength efficiency and ~61% ductility efficiency relative to Al, while improved bonding displaced fracture farther into Al (Figure 6b).



(a) (b)

Figure 6. (a) Tensile properties and (b) fracture of short-cycle CDFW Al/Cu joints. Adapted from Milašinović et al. [28].

Muralimohan et al. [31] and Ay et al. [20] also reported Al-side fracture in strong joints, whereas Zhu et al. [25] obtained high UTS but interface fracture and low elongation. Strength, ductility, and fracture location should therefore be considered together.

3.4. Radial heterogeneity and thermal evolution

Radial heterogeneity is intrinsic to rotary friction welding because sliding velocity increases with radius. Pan et al. [18] measured IMC thicknesses of ~0.8 μm at the center, 1.4 μm at half-radius, and 1.9 μm near the edge. This modest variation corresponded to a transition from Al-HAZ fracture centrally to interface fracture outward, with reduced elongation (Figure 7). Average thickness can therefore conceal the region controlling failure. The as-welded interface is also only the initial condition. Milašinović et al. [26] showed that CDFW parameters affect subsequent thermal evolution. Treatment at 400 °C/10 min caused little overall thickening but changed the adjacent Cu, whereas 177 °C/230 h exposure produced further spatially non-uniform IMC growth (Figure 8).

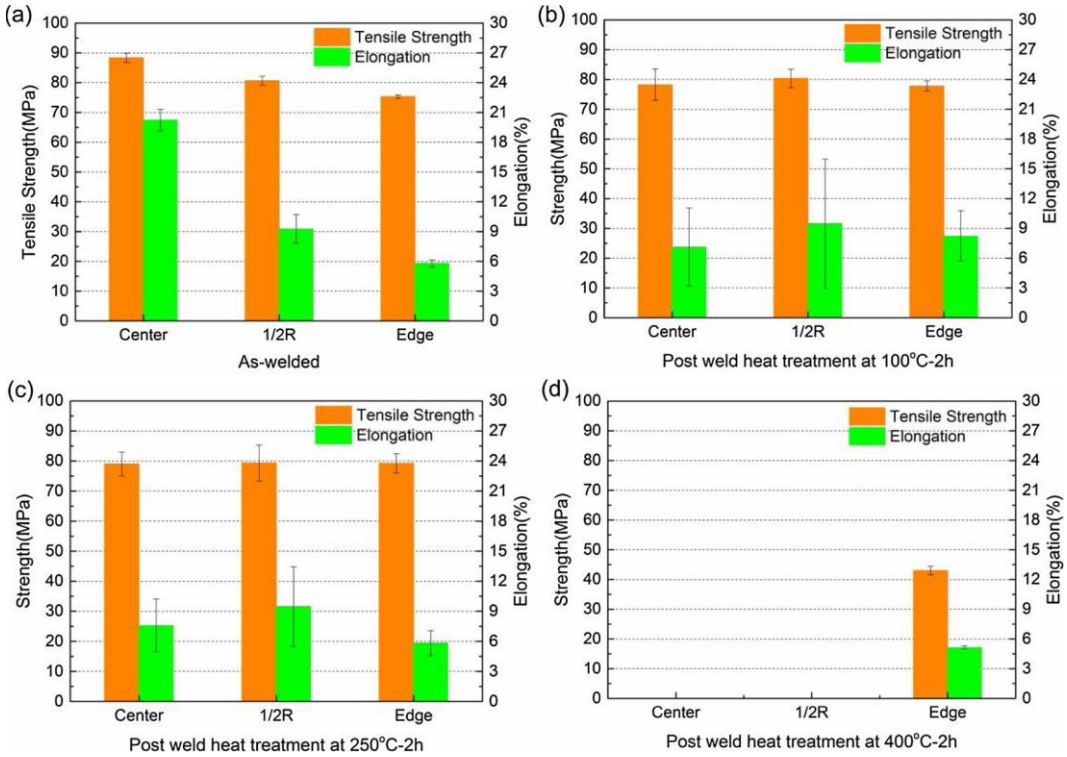


Figure 7. Radial variation of tensile strength and elongation in as-welded and post-weld heat-treated Al/Cu friction-welded joints. Reproduced from Pan et al. [18].

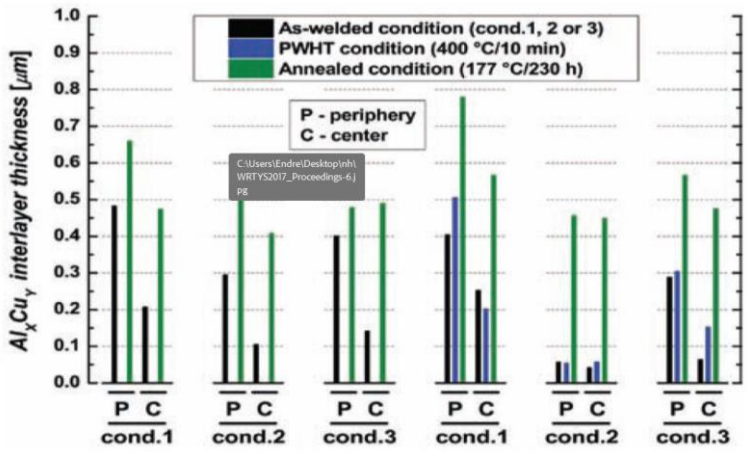


Figure 8. Central and peripheral Al_xCu_y interlayer thickness after welding and subsequent thermal exposure. Adapted from Milašinović et al. [26].

Cheepu and Susila [23] and Abbasi et al. [32] likewise reported thermally activated IMC growth. At greater thicknesses, deterioration becomes severe: Lee et al. [33] measured ~45 μΩ·cm resistivity at ~21 μm IMC thickness and ~85 μΩ·cm near 107 μm, while UTS approached zero after severe aging. Braunovic and Alexandrov [19] also demonstrated the importance of temperature and electrical current. Thus, submicrometer and tens-to-hundreds-of-micrometers reaction layers represent fundamentally different regimes: the former contribute little to overall resistance, whereas the latter become electrically and mechanically dominant.

3.5. IMC thickness, phase composition, and integrated interpretation

A commonly cited critical IMC thickness of ~2–5 μm is useful only as a general guideline. Pan et al. [18] observed interface-controlled fracture at only ~1–2 μm when Al_2Cu/Al_4Cu_9

boundaries became unfavorable, while Xue et al. [34] showed that specific phase boundaries can govern fracture. Joint integrity therefore depends on phase composition and sequence, continuity, defects, residual stress, radial position, and adjacent deformation as well as total thickness.

Gligorijević et al. [29] further demonstrated this limitation. Dynamically formed Al_2Cu/Al_4Cu_9 interfaces remained below ~1.6 µm, whereas static exposure at 325 °C generated $Al_2Cu/AlCu/Al_4Cu_9/AlCu_3$ multilayers up to ~7.3 µm (Figure 9). Despite being thicker, selected static structures showed higher UTS and comparable or improved elongation; one interface approximately seven times thicker than its dynamically formed counterpart retained comparable elongation and significantly higher UTS (Figure 10a). XRPD analysis of the fracture surfaces further confirmed the phase-sensitive nature of failure (Figure 10b): Al_2Cu was detected on the Al side, whereas the Cu-side fracture surface contained Cu together with AlCu, $AlCu_3$, and Al_4Cu_9. The presence of different IMCs on the opposing fracture surfaces indicates that fracture behavior is related not only to total reaction-layer thickness but also to the phase composition and internal phase boundaries of the interfacial region.

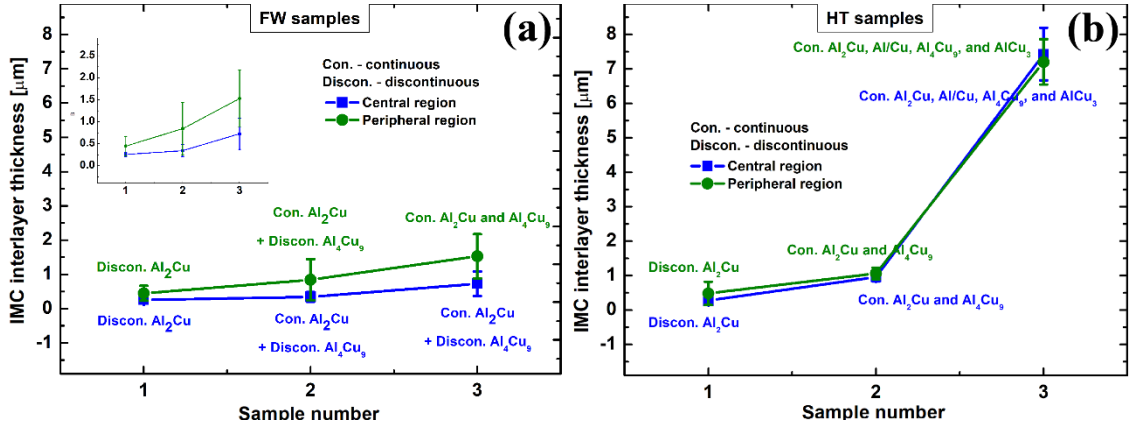
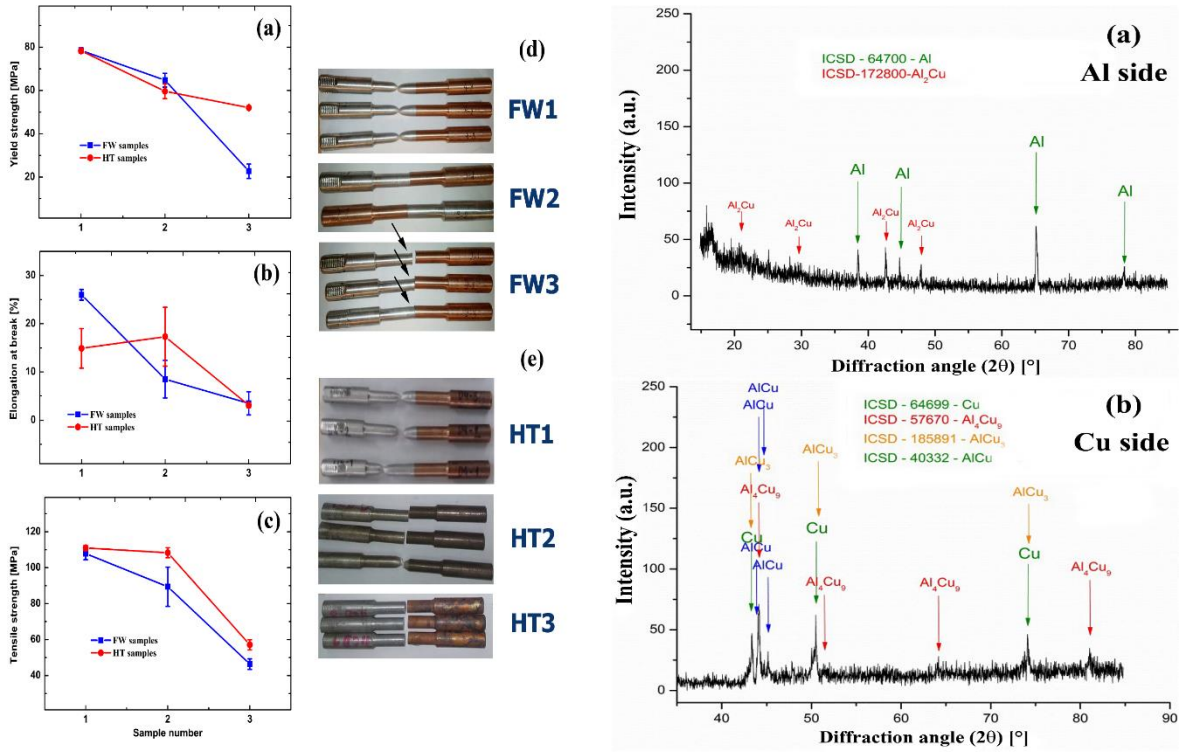


Figure 9. Comparison of dynamically formed (FW samples) and statically developed (HT samples) Al–Cu intermetallic structures and their central/peripheral thickness distributions. Reproduced from Gligorijević et al. [29].

These results do not imply that increasing IMC thickness is beneficial; rather, thickness cannot be interpreted independently of phase composition, formation route, continuity, and fracture path. Three practical regimes emerge. At submicrometer thickness, complete bonding and interface continuity dominate [27,28]. In the approximate 1–10 µm range, phase composition, phase boundaries, radial position, residual stress, and formation history become increasingly important [18,29]. At tens to hundreds of micrometers, the reaction region becomes functionally dominant: ~50 µm layers were associated with increased resistance and defects [30], whereas ~21 and ~107 µm layers showed resistivities of ~45 and ~85 µΩ·cm, respectively, together with severe loss of strength [33].

Comparison with other joining routes supports the same interpretation. Wei et al. [8] reported favorable behavior for a narrow wavy explosion-welded interface, moderate performance for cold-pressure welding despite the absence of a continuous IMC layer, and poor behavior for a defective cast reaction region ~200–250 µm thick. Thus, neither the absence of IMCs nor minimum IMC thickness alone guarantees optimum performance. The preferred condition is a fully bonded interface with controlled phase composition and morphology, limited defects, and sufficient thermal stability to suppress excessive growth during service.



(a) (b)

Figure 10. (a) Mechanical response and (b) phase-sensitive fracture evidence for dynamically welded and statically heat-treated Al/Cu joints: tensile-property comparison and representative XRPD fracture-surface analysis. Adapted from Gligorijević et al. [29].

4. CURRENT LIMITATIONS AND FUTURE PROSPECTS

4.1. Phase-specific, electrical, mechanical, and spatial characterization

Total IMC thickness should not remain the sole interface descriptor. Equation (1) shows that resistance depends on $\boldsymbol{\rho_i} \times \boldsymbol{t_i}$, while phase boundaries may provide fracture paths. Future studies should therefore report phase-specific thickness, phase composition, continuity, maximum local thickness, and radial distribution.

Bulk conductivity should be complemented by interface-focused measurements because submicrometer layers can be masked by much longer Al and Cu sections. Four-point or area-specific resistance measurements and conductive AFM could provide more direct structure–property relationships [30]. Mechanical qualification should likewise include elongation, fracture location, fractography, phase identification, and, where possible, residual stress. Center-to-edge differences [18,26,28,29] should also be considered.

4.2. Manufacturing history, service evolution, and accelerated aging

The as-welded interface is the starting structure rather than the final one. Thermal exposure modifies both IMC composition and morphology and the adjacent Al/Cu microstructure [19,23,26,31,32], while subsequent growth depends partly on the original joining condition.

Service conditions combine current, thermal cycling, mechanical restraint, and environmental exposure, whereas many aging studies consider temperature alone. Because temperature and electrical current can act jointly [19], future accelerated testing should couple electrical and thermal loading and relate structural evolution directly to resistance and mechanical integrity.

4.3. CDFW process monitoring and temperature measurement

Nominal settings do not fully describe the CDFW cycle. Axial force, rotational-speed history, torque, shortening, and temperature should therefore accompany nominal process parameters. Thermal studies [35–42] support such monitoring.

Temperature measurement is particularly challenging because Al has low, surface-dependent emissivity. Oxidation, roughness, coatings, and temperature affect apparent emissivity [43,44]; infrared measurements therefore require appropriate calibration or controlled surface conditions.

The desired framework is: process parameters → thermomechanical history → bonding and material transfer → interface composition and morphology → electrical and mechanical properties → service evolution → lifetime

5. CONCLUSIONS

The increasing use of Al with Cu terminals has increased the need for reliable Al/Cu electrical transitions. Mechanical connectors remain practical, but their long-term performance depends on maintaining stable metallic contact despite oxidation, galvanic corrosion, thermal expansion mismatch, creep, stress relaxation, and fretting. Increased contact resistance intensifies local Joule heating and may accelerate degradation.

CDFW provides an attractive metallurgical alternative because it is rapid, filler-free, and avoids bulk melting. Its heat-input window is limited: insufficient heat input causes incomplete bonding, whereas excessive heat input promotes deformation, thermal softening, material loss, and IMC growth. Optimum conditions therefore require sufficient heat generation and deformation for complete bonding without unnecessary thermomechanical loading.

The transition extends beyond the IMC layer because deformation, hardness changes, and recrystallization also occur in adjacent Al and Cu. Interface morphology may change considerably without measurable IMC growth, confirming that morphology and phase development are related but distinct characteristics.

Optimized short-cycle CDFW can produce complete bonding with an Al_2Cu layer of approximately 0.5 μm while retaining ~42.8–44.4 MS/m conductivity, more than 92% of the theoretical Al/Cu conductivity, approximately 100% tensile-strength efficiency, and about 61% ductility efficiency relative to Al. In contrast, extensive thermal growth markedly deteriorates electrical and mechanical performance.

IMC thickness alone is therefore not a universal criterion of joint quality. Thin Al_2Cu/Al_4Cu_9 structures may fail along unfavorable phase boundaries, whereas selected thicker statically developed multilayers can outperform thinner dynamically formed interfaces. Joint integrity depends on phase-specific thickness, phase composition and sequence, continuity, defects, residual stress, radial heterogeneity, and adjacent microstructure.

Future development should move beyond simple IMC-thickness limits toward phase-specific and spatially resolved interface control. The preferred joint should combine complete and reproducible bonding, controlled interface composition and morphology, low and stable electrical resistance, adequate strength and ductility, and predictable behavior during service.

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