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A Hybrid Joining Strategy for Al–Cu Bimetallic Sheets Produced by Friction Stir Welding

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Abstract. The production of Al–Cu bimetallic sheets is of increasing interest for applications requiring a combination of lightweight performance and high thermal or electrical conductivity. Conventional fusion welding techniques are unsuitable due to excessive intermetallic compound (IMC) formation and poor bonding quality. Solid-state processes such as Friction Stir Welding (FSW) provide an attractive alternative; however, most studies aim to minimize heat input in order to suppress IMCs. In this work, a different approach is proposed. A hybrid joining strategy is employed, intentionally using controlled heat input and tool penetration to generate an extended stirring zone and a pronounced hook geometry. This results in mechanical interlocking combined with metallurgical bonding at the Al–Cu interface. Large-area bimetallic sheets were fabricated by FSW lap welding using four parallel passes to enlarge the bonded region. Microstructural characterization revealed the formation of continuous hook structures along the interface, promoting effective mechanical interlocking between the aluminum and copper layers. The integrity of the bimetallic sheets was further evaluated by cold rolling, which demonstrated excellent resistance to delamination despite local cracking of brittle IMCs. The results confirm that exploiting hook formation, rather than suppressing it, can provide a robust and scalable strategy for manufacturing Al–Cu bimetallic sheets by FSW.

Introduction

Aluminum–copper (Al–Cu) bimetallic sheets are attractive for lightweight structures and multifunctional components where low density must be combined with high electrical and thermal conductivity. However, producing a reliable Al–Cu interface remains challenging with fusion-based joining, because the thermal cycle promotes the formation of brittle Al–Cu intermetallic compounds (IMCs) and leads to weak or discontinuous bonding. As a result, solid-state processes, and particularly friction stir welding (FSW), have been widely investigated as an alternative route for dissimilar metal joining [1].

Despite these advantages, Al–Cu FSW remains governed by a fundamental trade-off. Increasing heat input and material mixing generally improves interfacial contact and bonding continuity, but at the same time accelerates IMC formation and increases the risk of local brittleness. Consequently, a significant portion of the existing literature focuses on optimizing process parameters in order to reduce heat input and suppress IMC formation, while maintaining acceptable mechanical performance [1–4]. In Al5083/Cu lap configurations, rotational and welding speeds have been shown to strongly influence material flow, hook morphology, IMC distribution, and lap-shear behavior [2,3]. Low heat input strategies for Al–Cu lap joints have also been proposed, demonstrating that sound joints can be achieved when IMC growth is limited [4].

At the same time, it has been increasingly recognized that the hook feature formed during lap FSW is not simply a geometric imperfection. Hook morphology directly affects the effective bonding area and the mechanical load transfer path, and therefore can either deteriorate or enhance joint integrity depending on its size, orientation, and continuity [5,6]. Nevertheless, in most multipass FSW studies, the hook is treated as a defect to be minimized or eliminated in subsequent passes in order to obtain a more uniform interface [5]. Other studies report that deeper tool penetration and increased stirring can promote hook formation and increase bonded area, although this is often accompanied by increased IMC formation and associated cracking [6].

Motivated by these observations, the present work adopts a deliberately different manufacturing objective and joining philosophy. Rather than optimizing a single lap joint, the aim is to fabricate a large-area Al–Cu bimetallic sheet through the application of four parallel FSW passes, thereby enlarging the bonded interface in a controlled and scalable manner. Furthermore, instead of suppressing hook formation, a hybrid joining strategy is pursued. Controlled heat input and tool penetration are used to generate an extended stirring zone and a pronounced hook geometry, leading to mechanical interlocking combined with metallurgical bonding at the Al–Cu interface. The integrity of the resulting bimetallic sheet is finally evaluated through cold rolling, which acts as a stringent test of interfacial stability under severe plastic deformation.

Experimental Procedure

Commercial AA5083 aluminum alloy plates and commercially pure copper plates were used for the fabrication of Al–Cu bimetallic sheets. Both materials had an initial thickness of 3 mm. The nominal chemical composition of the AA5083 alloy is presented in Table 1. The copper plates consisted of commercially pure copper with a minimum purity of 99.9 wt.%, as specified by the supplier.

Table 1. Nominal chemical composition of AA5083 aluminum alloy (wt.%).

Element	**Mg**	**Mn**	**Fe**	**Si**	**Cr**	**Cu**	**Zn**	**Ti**	**Al**
wt.%	4.0–4.9	0.4–1.0	≤0.40	≤0.40	0.05–0.25	≤0.10	≤0.25	≤0.15	balance

Prior to welding, the faying surfaces were mechanically ground and degreased using ethanol in order to remove surface oxides and contaminants and ensure proper interfacial contact. Friction stir welding was performed using a conventional milling machine adapted for FSW operations. A schematic illustration of the process and tool geometry is presented in Fig. 1. The aluminum plate was positioned on the top side and the copper plate on the bottom side in a lap configuration. A non-consumable tool made of tool steel was used. The tool consisted of a cylindrical shoulder with a diameter of 20 mm and a threaded cylindrical pin with a diameter of 5 mm, a pin height of 4 mm, and a thread pitch of 1 mm, as shown in Fig. 1. A tool tilt angle of 3° relative to the welding direction was applied in order to improve material consolidation and avoid defect formation.

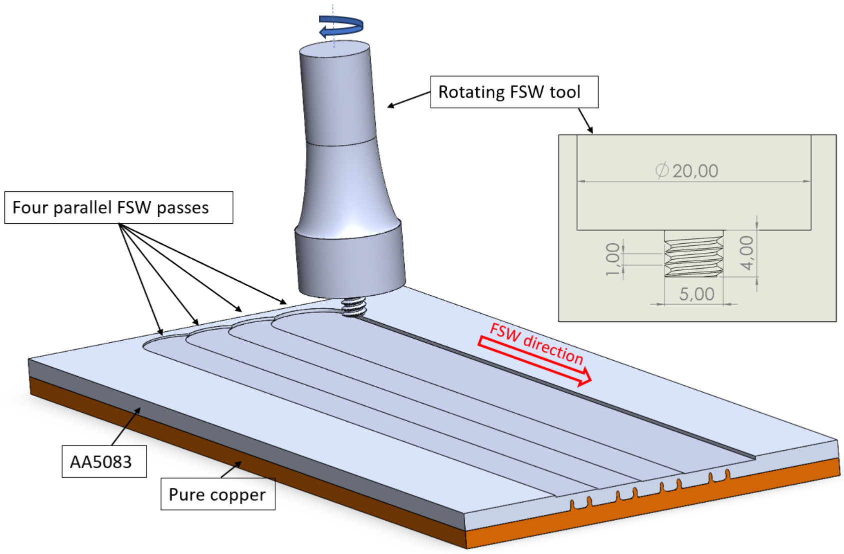

Fig. 1. Schematic illustration of the friction stir welding (FSW) process used to fabricate the Al–Cu bimetallic sheet, showing the rotating tool and the four parallel passes employed to produce a large-area bonded interface. The tool geometry and main dimensions are also indicated (shoulder diameter: 20 mm, pin diameter: 5 mm, pin height: 4 mm, thread pitch: 1 mm).

The welding parameters were selected to provide the maximum achievable heat input for the specific FSW machine. The tool rotational speed was set to 1000 rpm, while the traverse speed was fixed at 13 mm/min, corresponding to the minimum discrete travel speed and the maximum rotational speed available. This parameter combination was intentionally chosen to promote extensive material softening, large stir zones, and the formation of a pronounced hook geometry at the Al–Cu interface.

To fabricate a large-area bimetallic sheet, four parallel FSW passes were applied on each specimen under identical process conditions. The distance between adjacent passes was fixed at 8 mm, as determined through a preliminary investigation. This spacing was intentionally selected to avoid overlap between adjacent stir zones, allowing the independent development of pronounced hook geometries in each pass while maintaining continuity of the Al–Cu bonded region across the sheet width.

After welding, transverse cross-sections were extracted perpendicular to the welding direction for microstructural characterization. Standard metallographic preparation procedures were followed, including grinding and polishing. Optical microscopy was used to examine the overall morphology of the stir zones, hook structures, and interface continuity. Scanning electron microscopy was employed to investigate local microstructural features and intermetallic compound formation at the Al–Cu interface.

Cold rolling experiments were conducted to assess the structural integrity of the bimetallic sheets under severe plastic deformation. Prior to rolling, the upper surface of the welded specimen was milled by removing approximately 0.5 mm of material in order to eliminate surface flash generated during FSW and to ensure a flat and clean surface condition. The appearance of the bimetallic specimen after surface cleaning and prior to rolling is shown in Fig. 2a. Rolling was performed using a laboratory rolling mill equipped with integrated force and torque sensors, allowing real-time monitoring of rolling conditions (Fig. 2b). After rolling, the specimens were examined for interfacial damage, crack initiation, and possible delamination between the aluminum and copper layers.

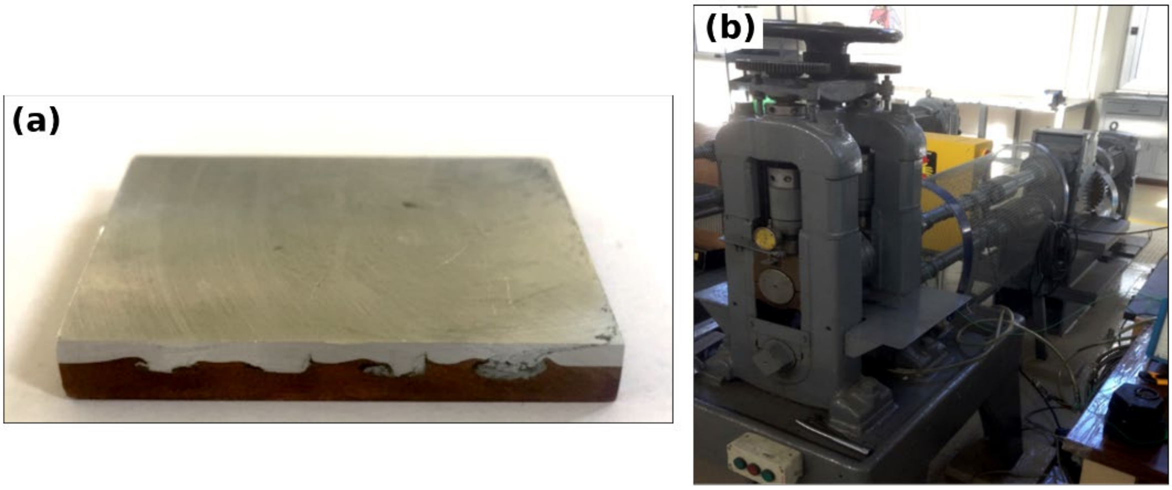

Fig. 2. (a) Al–Cu bimetallic sheet after surface preparation by milling, prior to cold rolling, and (b) laboratory rolling mill used for deformation experiments, equipped with integrated force and torque sensors.

Results and Discussion

Macroscopic characterization and development of large-scale bimetallic sheets

Macroscopic examination of the welded specimens confirms the successful fabrication of large-scale Al–Cu bimetallic materials. As shown in Fig. 3, the application of four parallel friction stir welding passes resulted in a continuous bonded region extending across the sheet width, indicating that the adopted process strategy functions as a manufacturing route for bimetallic sheets rather than as a localized joining technique.

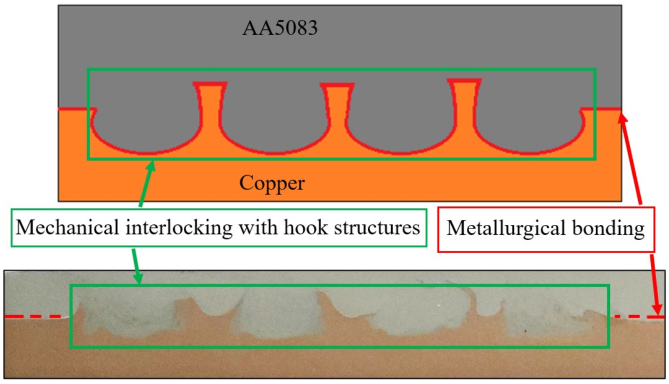

Fig. 3. Schematic illustration (top) and corresponding cross-section (bottom) of the Al–Cu bimetallic sheet, showing mechanical interlocking through hook structures and metallurgical bonding at the interface.

The macroscopic cross-sections reveal the formation of extensive stir zones, penetrating deeply into the copper layer. At the Al–Cu interface, pronounced and repetitive hook structures are clearly observed along the length of the welded region. The combined presence of large stir zones and well-developed hook geometries demonstrates that the selected high heat input conditions and tool penetration effectively promoted intense material flow and interfacial interaction.

The morphology of the hooks, together with their continuity across multiple passes, leads to a robust mechanical interlocking between the aluminum and copper layers. In parallel, the intimate contact generated by severe plastic deformation enables metallurgical bonding at the interface. Consequently, the Al–Cu bimetallic material is formed through a hybrid bonding mechanism, in which mechanical interlocking provides macroscopic structural integrity while metallurgical bonding contributes to interfacial cohesion.

Optical microscopy of the stir zone and hook morphology

Optical microscopy observations provide further insight into the microstructural features governing the bonding mechanism. Representative micrographs taken from the left and right sides of the stir zone, as well as from the entire stirred region, are shown in Fig. 4a-c.

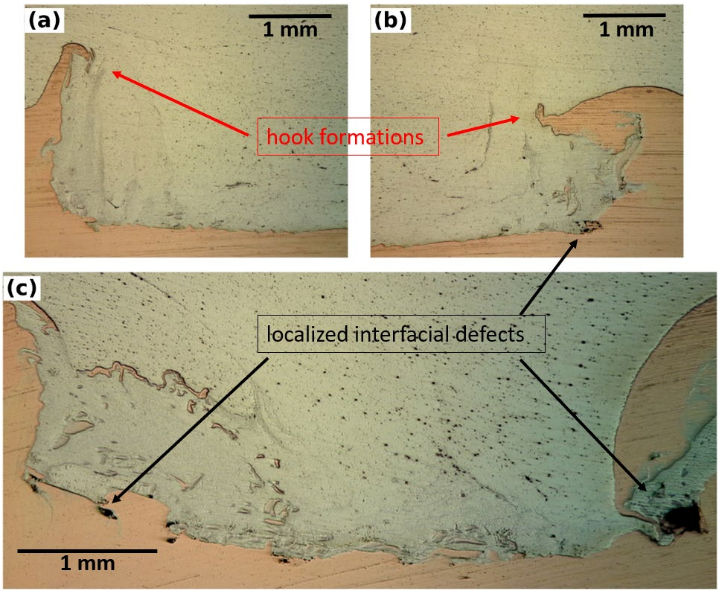

Fig. 4. Optical micrographs of the stir zone showing hook structures and interfacial morphology: (a) left side of the stir zone, (b) right side of the stir zone, and (c) overall stir zone. Pronounced hook structures extending into the aluminum layer are observed, contributing to mechanical interlocking and metallurgical bonding. Localized interfacial defects are occasionally present at the base of the hook structures.

In all cases, pronounced hook structures are observed to initiate at the Al–Cu interface and extend upward into the aluminum layer. The consistent upward growth of the hooks indicates intense plastic flow of copper into the aluminum during FSW, driven by the combined effects of tool rotation, traverse motion, and elevated temperature. The presence of well-developed hooks on both sides of the stir zone confirms the stability and repeatability of the material flow during welding.

Within the stir zone, the microstructure is dominated by an aluminum-rich matrix containing a significant population of copper-rich particles. These particles originate from the mechanical fragmentation and transport of copper into the aluminum during stirring. Their non-uniform but widespread distribution suggests efficient mechanical mixing, while also indicating the potential formation of Al–Cu intermetallic phases.

Localized defects, such as microcracks or small void-like features, are occasionally observed near the base of the hook structures. These regions are subjected to high strain localization and thermal exposure, making them susceptible to the formation and cracking of brittle phases. Importantly, these defects are isolated and discontinuous, and they do not form a continuous damage path along the interface. These localized interfacial defects are highlighted in Fig. 4 and remain spatially confined to limited regions near the hook roots, without extending along the interface or compromising the overall structural continuity of the bimetallic sheet.

Interfacial microstructure and metallurgical bonding

Detailed examination of the Al–Cu interface was carried out using scanning electron microscopy combined with energy-dispersive X-ray spectroscopy. Figure 5 presents the SEM micrograph of the Al–Cu interface at high magnification, where a chemically and morphologically complex interfacial region is clearly observed.

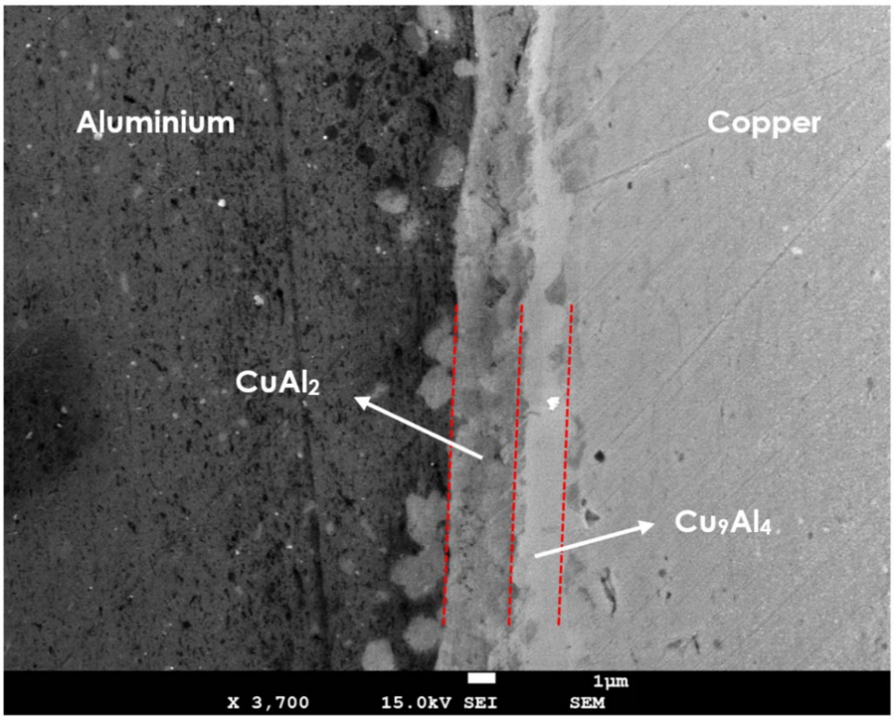

Fig. 5. SEM micrograph of the Al–Cu interface showing the formation of two distinct interfacial layers between the aluminum and copper substrates, attributed to aluminum-rich ($CuAl_2$) and copper-rich (Cu_9Al_4) intermetallic compounds.

As shown in Fig. 5, two distinct interfacial layers can be identified between the aluminum and copper substrates. The layer adjacent to the aluminum side exhibits a morphology consistent with aluminum-rich intermetallic compounds, while the layer adjacent to the copper side is enriched in copper. Based on their location, morphology, and contrast, these layers can be reasonably attributed to the θ-phase ($CuAl_2$) near the aluminum side and the γ_1-phase (Cu_9Al_4) near the copper side. The formation of these phases is consistent with diffusion-controlled reactions promoted by severe plastic deformation and elevated temperature during friction stir welding.

To further investigate the chemical transition across the interface, an EDS line scan analysis was performed, as shown in Fig. 6. The line scan reveals a gradual decrease in aluminum concentration accompanied by a corresponding increase in copper concentration across the interfacial region. This compositional gradient confirms that the interface is not abrupt, but instead consists of a diffusion-driven transition zone.

The presence of two chemically distinct regions within the interfacial zone, highlighted in Fig. 6, provides additional evidence for the formation of layered Al–Cu intermetallic compounds. Such a configuration agrees well with previous reports on Al–Cu friction stir welded joints, where $CuAl_2$ and Cu_9Al_4 layers are typically observed on the aluminum and copper sides, respectively [1,7]. Although these intermetallic compounds are inherently brittle, their thickness remain limited.

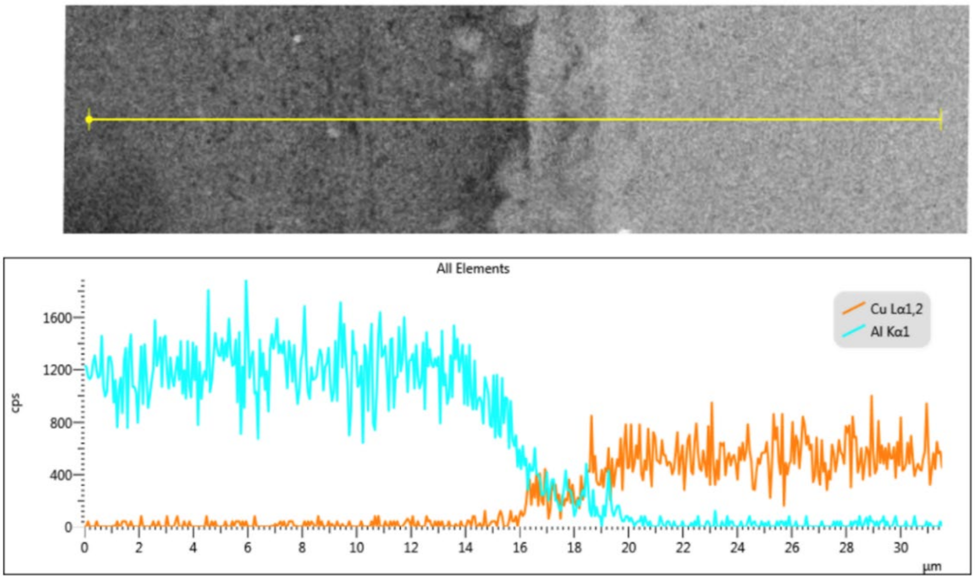

Fig. 6. EDS line scan across the Al–Cu interface, illustrating the gradual transition from aluminum-rich to copper-rich regions and the presence of two chemically distinct interfacial layers formed by diffusion during friction stir welding.

Interfacial integrity of the Al–Cu bimetallic sheet under cold rolling

The mechanical integrity of the Al–Cu bimetallic sheet was further evaluated through successive cold rolling passes. Cold rolling imposes severe through-thickness plastic deformation and interfacial shear stresses, making it a stringent and widely accepted method for assessing the structural integrity and bonding quality of bimetallic materials. In insufficiently bonded systems, rolling typically promotes interfacial delamination or sliding between layers due to incompatible plastic flow and weak interfacial cohesion. Figure 7 presents the macroscopic appearance of the specimen after the 1st, 3rd, and 6th rolling passes, illustrating the progressive deformation imposed on the material.

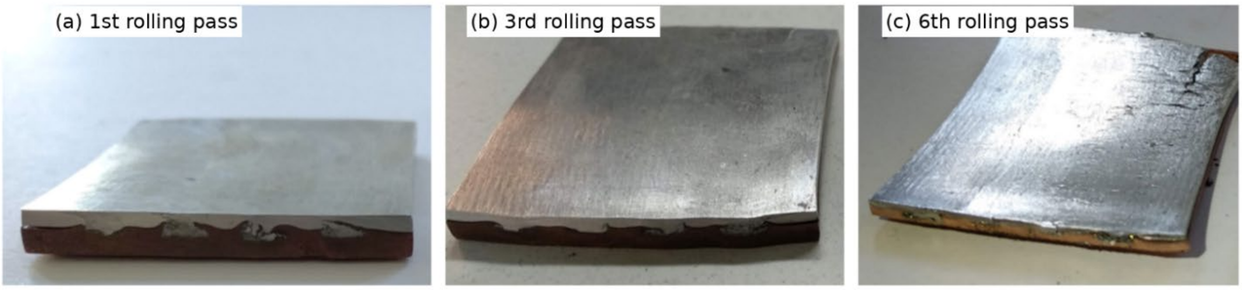

Fig. 7. Macroscopic evolution of the Al–Cu bimetallic sheet during cold rolling: (a) after the 1st rolling pass, (b) after the 3rd rolling pass, and (c) after the 6th rolling pass, demonstrating progressive deformation without macroscopic delamination of the Al–Cu interface.

As shown in Fig. 7, the bimetallic sheet undergoes increasing levels of deformation with each rolling pass. Despite the severe plastic deformation introduced during rolling, no macroscopic delamination or separation between the aluminum and copper layers is observed, even after the 6th rolling pass. This behavior indicates that the Al–Cu interface remains mechanically stable under substantial through-thickness strain.

The evolution of the average rolling force as a function of pass number, shown in Fig. 8, further supports this observation. The rolling force increases progressively with increasing deformation, reaching values above 150 kN in the final pass. The rolling force was continuously recorded during each rolling pass, and the values presented in Fig. 8 correspond to the average force calculated from these continuous measurements. Importantly, no abrupt drops or instabilities were observed in the force evolution during rolling, which would otherwise indicate interfacial failure or sliding between the bonded layers. The smooth and continuous evolution of rolling force suggests effective load transfer across the Al–Cu interface and confirms that the bimetallic sheet behaves as a single structural entity during deformation.

The rolling force generally increases with successive passes due to strain hardening and the associated increase in deformation resistance, as well as the slight increase in specimen width during rolling, which increases the effective contact area. The force values recorded for passes 3 to 5 are very close, indicating a relatively stable mechanical response. The slight decrease observed in passes 4 and 5 may be attributed to localized fracture and redistribution of brittle intermetallic phases within the stir zone, which can locally reduce deformation resistance. However, the overall trend of increasing rolling force confirms progressive work hardening and effective load transfer across the Al–Cu interface.

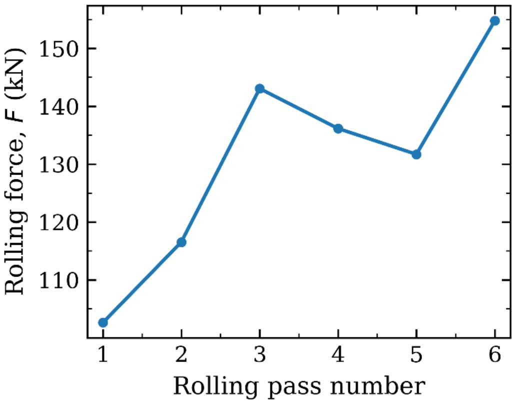

Fig. 8. Average rolling force versus rolling pass number for the Al–Cu bimetallic sheet, indicating stable load transfer during successive deformation passes without interfacial failure.

The absence of macroscopic delamination during rolling can be directly attributed to the hybrid bonding mechanism developed during friction stir welding. The pronounced hook structures generated at the Al–Cu interface provide strong mechanical interlocking, which resists interfacial sliding and separation under compressive stresses. At the same time, metallurgical bonding and localized intermetallic compound formation enhance interfacial cohesion, contributing to the overall stability of the joint.

Although localized cracking of brittle intermetallic phases was observed at the microscale, these features do not propagate into continuous interfacial damage under rolling. Instead, the mechanical interlocking mechanism dominates the macroscopic deformation response, ensuring the preservation of interfacial integrity throughout successive rolling passes.

Overall, the rolling experiments demonstrate that the fabricated Al–Cu bimetallic sheet exhibits high resistance to interfacial failure under severe plastic deformation. This behavior confirms the effectiveness of the proposed joining strategy for the production of mechanically robust bimetallic sheets suitable for subsequent forming operations.

Conclusion

In this work, a hybrid joining strategy was employed for the fabrication of Al–Cu bimetallic sheets using friction stir welding. Instead of suppressing hook formation, controlled heat input and tool penetration were deliberately selected to promote the development of large stir zones and pronounced hook geometries, leading to mechanical interlocking combined with metallurgical bonding at the Al–Cu interface.

Macroscopic and microscopic analyses confirmed the successful formation of large-scale bimetallic materials through multiple parallel FSW passes. Optical and SEM observations revealed extensive hook structures extending into the aluminum layer, accompanied by localized diffusion-driven intermetallic compound formation at the interface. These microstructural features were shown to be mechanically effective, as confirmed by cold rolling experiments used as a stringent validation of interfacial integrity. The bimetallic sheets withstood severe plastic deformation without macroscopic delamination, even after multiple rolling passes. The progressive increase in rolling force and the absence of load instabilities further confirmed effective load transfer across the Al–Cu interface and the structural coherence of the bimetallic sheet.

Overall, the results demonstrate that exploiting mechanical interlocking in combination with metallurgical bonding provides an effective and scalable route for producing mechanically robust Al–Cu bimetallic sheets. The proposed strategy demonstrates a high tolerance to severe plastic deformation, maintaining interfacial integrity without complete delamination despite localized fracture of brittle intermetallic phases. Such damage-tolerant Al–Cu bimetallic systems are particularly relevant for structural and functional applications where resistance to catastrophic delamination under severe deformation or impact-like loading is required, rather than preservation of intermetallic integrity.

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