INVESTIGATION ON THE MECHANICAL PROPERTIES OF VARIOUS WELDED MATERIALS BY ULTRASONIC WELDING TECHNIQUE – A REVIEW

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ABSTRACT:

The use of diverse material combinations in engineering structures is witnessing growing interest, particularly in sectors such as transportation, due to the improvements it offers in design efficiency and overall performance compared to single-component materials. Ultrasonic welding (USW) is a promising modern technique for joining thin sheets of similar and dissimilar non-ferrous metals, such as aluminum and copper, without the need for fillers. This study analyses the effect of using a zinc intermediate layer on the development of the microstructure and mechanical properties of dissimilar aluminum/copper joints resulting from ultrasonic spot welding. This study focuses on the mechanical properties of asymmetric aluminum-copper joints created using ultrasonic welding. These joints typically exhibit high strength and resistance to various mechanical loads and stresses. Recent studies have investigated the relationship between the tensile strength of welded joints and key operating parameters, such as welding pressure, welding time, and fixation period. The results show that increasing the welding pressure while extending the process time enhances the bond strength between the welded plates. Furthermore, the use of intermediate layers, particularly zinc layers, has been shown to effectively improve mechanical performance by increasing the tensile and shear strength of the joints. The shear strength of ultrasonically welded aluminium/copper joints, both with and without zinc interlayers, initially increased by 35%, while fracture energy decreased threefold during the formation of the aluminium-zinc/copper-zinc phase. However, it declined when subjected to an input energy of 1000 J. Additionally, this review article systematically examines the mechanical behaviour of ultrasonic-welded sheets, interface characteristics, performance outcomes, and the influence of system parameters applies on a selected material combination.

1. INTRODUCTION

Welding is a manufacturing process used to join two or more parts by applying heat, pressure, or a combination of both, resulting in a strong bond after the materials cool. While welding is most commonly used with metals and thermoplastics, it can also be applied to some types of wood. The final welded assembly is often called a weldment. Welding processes can be broadly categorized into three main types: Plastic (or pressure) welding: In this method, the materials are heated until they reach a plastic (semi-solid) state and are then joined by applying external pressure. This technique, belongs to the type of solid-state welding, is utilized in processes like forge welding and resistance welding. Fusion welding: Also referred to as no-pressure or liquid-state welding, this technique involves heating the materials at the joint until they melt and then allowing them to solidify to form a bond. Gas, arc and also thermit are common names that follow the fusion state of weld. Cold welding: In this approach, no heat is used. Instead, pressure is applied to cause atomic-level bonding through surface diffusion. Referred to solid-state condition, this method is especially suitable for joining non-ferrous sheet metals like aluminum and their alloys. Examples include in addition to ultrasonic welding, friction and explosive welding (Sathishkumar et al. 2023), (Gunduz et al. 2005). Figure 1 shows a type of ultrasonic welding which is directly categorized under the heading of a solid-state welding process.

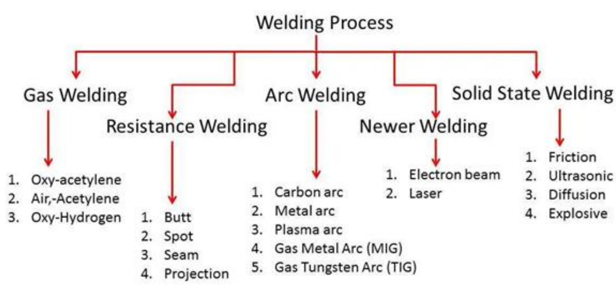

Figure 1. Classification the types of welding process

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2. GENERAL CLASSIFACTION OF ULTRASONIC WELDING

Ultrasonic welding (USW), either in metal or plastic are classified as a solid-state welding technique developed over 90 years ago, relies on the common action of both static clamping force and high-frequency ultrasonic vibrations. These vibrations induce interfacial friction and localized plastic deformation at the joint, accompanied by a slight temperature rise, enabling solid-state bonding without melting the base materials. This method offers numerous advantages, including rapid welding cycles, minimal dependence on metallurgical compatibility, high joint quality, suitability for precision applications, and low sensitivity to surface contamination. The thermal effects during the process are localized and transient, with peak temperatures remaining below the metal's recrystallization point. Consequently, this technique mitigates risks such as oxidation, thermal degradation, or melting of the joined materials. Ultrasonic welding entirely used technology for joining both metals and non-metals, in addition to thermoplastics. It operates by applying high-frequency ultrasonic vibrations, typically ranging from 20 to 100 kHz, coupled with low-amplitude displacements of 10–80 micro-meters. These vibrations generate localized heat at the material interface, promoting softening or melting, which solidifies upon cooling to form a strong, cohesive bond. The process is highly efficient and fast, with typical welding durations between 0.1 and 1.0 seconds. Beyond welding, ultrasonic energy also facilitates material deformation and the embedding of metal components into thermoplastics, enabling secure bonding of dissimilar materials (Sathishkumar et al. 2023), (Gunduz et al. 2005), (Al-Sarraf, 2013), (Feng et al. 2024).

3. PROCESS OF ULTRASONIC WELDING

The configuration of welding system by (USW) is depicted in Figure 2. As shown, the system comprises key components including an ultrasonic generator, a transducer (convertor), an optional booster, and a multi names of vibrating tool, sonotrode or horn. Additionally, the setup incorporates essential welding elements such as a fixed anvil, clamping features, and positioning fixtures to ensure proper alignment and stability during the welding process (Al-Sarraf, 2013).

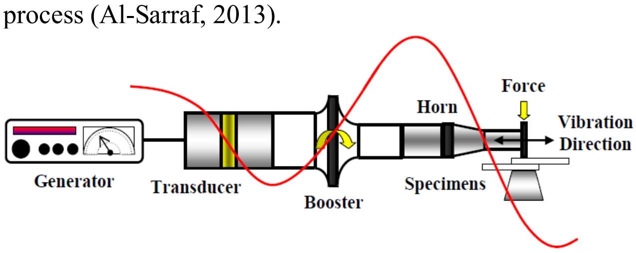


Figure 2. Typical configuration of ultrasonic system for welding materials

The range of materials and component sizes suitable for ultrasonic welding depends primarily on three factors: the power capacity of the welding device, operating parameter settings, and sonotrode design (Feng et al. 2024), (Al Sarraf Z et al. 2019). Current systems for this technology are effective in joining thin metal strips, wires, and precision components made of ductile metals such as copper, aluminum, and magnesium (Zhao et al. 2013), (Harman et al. 1977), (Pnteli et al. 201). By rapid development of high-power ultrasonic welding technology, the range of weldable materials continues to expand (Panteli et al. 2012), (Patel et al. 2012), (Venkatalaxmi et al. 2004), (Zhu et al. 2012). Recent research has revealed the possibility of successfully welding various thick metal sheets, including combinations such as aluminum-magnesium, aluminum-titanium, aluminum-steel, magnesium-copper, and magnesium-titanium. Thanks to these unique features, ultrasonic welding technology stands out as a promising solution for multiple applications in the electrical and electronics industries, aerospace, nuclear technology, advanced production of sealed components, and advanced materials manufacturing (Zhang et al. 2016), (Zhang et al. 2014), (Mirza et al. 2016). Joint performance is affected by Ultrasonic welding (USW) is critically affected by key process variables, particularly the energy intensity and amplitude of the applied vibrations. Harder metals often require increased energy input, either by raising the welding pressure or increasing the oscillation amplitude, to ensure an effective bond. It is worth noting that this technique relies on inducing local plastic deformation created at intimate surfaces between materials to be joined, under very high strain rates and in very short periods of time (Al-Sarraf. 2013), (Villegas et al. 2018).

4. MECHANISM AND PHYSICAL MEANING OF ULTRASONIC WELDING:

In process of ultrasonic welding, vibrational energy is transmitted to the weld area via a specialized tool known as a horn or sonotrode. This tool generates high-frequency vibrations that create rapid local friction between the contacting surfaces, resulting in compatible condition of the materials in the weld area. The extent of this softening depends on the amount of ultrasonic energy applied. When operating conditions are carefully controlled, thermal and mechanical effects are confined to the weld area, minimizing adverse effects on adjacent components (Deekshant et al. 2021). The hardening time required to re-solidify the softened material varies depending on the properties of the thermoplastic polymers, and hardening occurs under constant mechanical stress to ensure a strong joint. Ultrasonic welding (USW) systems employ precise control systems throughout the welding cycle to reduce variation and achieve uniform weld quality. This is often achieved by monitoring and regulating the electrical inputs to the transducer. While controlling the excitation motion of the sonotrode is useful, it does not contribute sufficient information about mechanical interactions, such as contact forces at the interface, which significantly impact joint quality. To analyze the obtaining of weld quality variations, the electrical impedance of the transformer is analyzed through equivalent electrical system modeling, which provides a more accurate representation of the system's dynamic behaviour (Tariq et al. 2014). It should be noted that the relationship between the electrical impedance at the system input and the electrical-mechanical influence of impedance at the weld interface is complex, due to the presence of several intermediate components - such as the transformer, acoustic comparators, and instruments - that affect energy transfer within the system. Therefore, relying solely on electrical input parameters is insufficient for optimal weld quality control due to the indirect and nonlinear nature of this relationship (Deekshant et al. 2021). In this context, the oscillating sonotrode tip is brought to be placed at contact condition with the specimen to be welded after being set to its resonant frequency, allowing vibration within a specified amplitude range. With the supply of ultrasonic energy from the source, the welding process begins. Local plastic deformation occurs at the area of contact, followed by a rapid increase in mechanical force to a specified level before the weld is completed. After the vibration ceases, a slight increase in force is applied to transition to the cooling phase. After cooling, the system returns to its initial state, marking the completion of the cycle. This cycle is characterized by high speed, typically lasting about one second, although this duration can vary depending on the material type and application requirements (Al-Sarraf. 2013), (Feng et al. 2014), (Al Sarraf Z et al. 2022), (Tariq et al. 2014), (Macwan et al. 2015).

In a wedge-reed ultrasonic welding system, electrical energy is initially converted into longitudinal mechanical vibrations by a transducer. These vibrations are then amplified and directed to the vane via a metal wedge attached to it, creating a transverse vibrational motion within the vane.

The necessary vertical force is applied by an air cylinder that presses against a block mounted at the upper end of the vane. In this way, the ultrasonic energy is imparted to the material to be welded through the transverse vibrations generated at the vane tip. In a side-push ultrasonic welding system, the operating unit - commonly known as the "stack" - consists of: a transducer, a booster with a mounting ring, and a horn with a sonotrode attached (see Figure 3). The transducer produces longitudinal vibrations, which are subsequently amplified by both the booster and the horn. The booster also provides a structural support for the system weld, allowing a downward-acting torque or linear pressure force to be applied to propel the sonotrode toward the workpiece.

The sonotrode is mounted perpendicular to the horn's axis of vibration and vibrates transversely, transferring ultrasonic energy to the weld zone through these transverse vibrations at the sonotrode tip (Al-Sarraf. 2013), (Li et al. 2020).

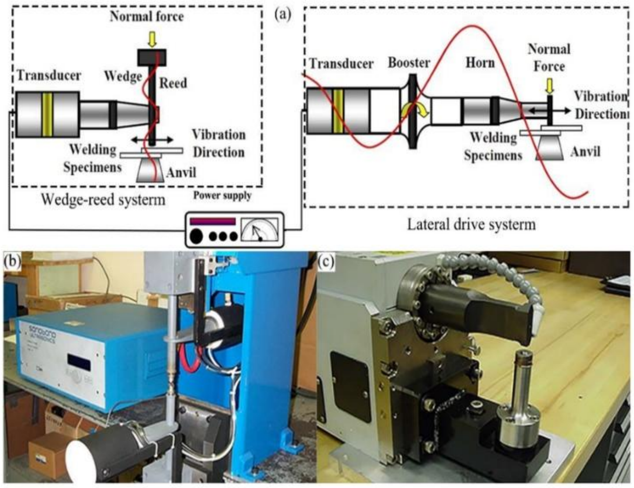


Figure 3. Two major types of ultrasonic welding process based on configuration of transverse vibration pattern (Al-Sarraf. 2013)

In ultrasonic metal welding (USMW), the parameters affecting the process can be classified into two types: system-related and material-related (see Figure 4). System-related parameters include welding cycle time, vibration amplitude, applied static pressure (clamping force), electrical power input, and operating frequency (Lin et al. 2020). Material-related parameters include surface cleanliness (such as the presence of oxides or contaminants), the crystal structure of the material, its hardness, and the geometric dimensions of the parts to be welded.

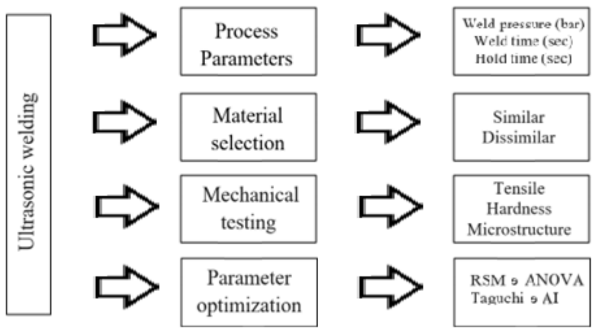


Figure 4. Main Process and Material Parameters Used in USW

5. THEORY OF BONDING MECHANISM IN USW

This technique relies on joining two metal components by exposing them to high-frequency vibrations, typically ranging from 20 to 100 kHz. These vibrations bring the internal surfaces of the materials into direct contact, generating localized frictional heat that softens or partially melts the interface. Upon cooling, a strong and secure weld joint is formed. Precise control of process parameters and material properties ensures a durable, high-quality weld. This method is considered solid-state welding, relying on acoustic vibrations rather than traditional heat to fuse components. The system is started after selecting the appropriate welding parameters from a preset table. The transducer is activated, generating the ultrasonic vibrations and transmitting them to the weld zone. This energy causes local softening or liquefaction of the interface layer - such as copper - facilitating bonding between the metal samples. At interface the friction causes heat which is generated at the faying syrface, as a result of these vibrations, is carefully controlled to enhance weld quality and ensure a strong and reliable joint (Macwan et al. 2015), (Harthoorn. 1978), (Bloss et al. 2008), (De Vries. 2004). The joints are allowed to gradually cool to a specific value of temperature that maintains and improve mechanical strength of the weld, enhancing its durability and safety in harsh environments. The metal sheets to be welded are securely clamped over the rigid anvil of the ultrasonic welding device, in a lap-joint position. This firm clamping is essential to prevent any unwanted movement caused by vibrations directed by the sonotrode during welding. After secure clamp of the specimens, high-frequency vibrations are transmitted from the sonotrode to the top of the sheet, causing local plastic deformation at the contact area, thus forming a solid metal joint. During the welding process, the sonotrode applies appropriate pressure to the clamped sheets, and this position is maintained for a specified period to enable an effective metal bond to form. According to a result, a weld bead forms at the close interface between the two materials. Upon completion of the process, a slight depression in the sheet surface due to the horn pressure is observed, providing visual evidence that the weld has been successfully welded. This process is often accompanied by the formability process of intermetallic compounds set up at weld zone, indicating the successful formation of the joint. After welding is complete, the material is removed from the anvil by removing the screws or fasteners. Figure 5 explains the following steps of welding process such as: clamping, vibration transmission, holding with applying suitable load and unloading (un clamping).

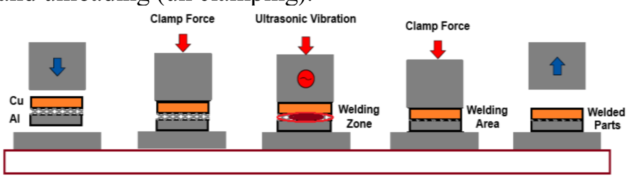


Figure 5. Steps of Welding process during operation of USW at interface of the joined materials

In the initial stage of forming, the contact surfaces of the materials are often covered with layers of oxides, lubricant residues, and absorbed moisture. These surface contaminants pose obstacles to achieving effective metal bonding when the parts are pressed together. Despite the application of a continuous clamping force that creates contact between the microscopic features of the material surfaces, these contaminants still prevent the formation of a direct metal-on-metal joint. As ultrasonic vibrations are initiated, the protrusions of the contact surfaces undergo local shear deformation. Initially, the interaction is limited to a limited number of microscopic contact points, but continued vibration gradually increases the number and area of these points. During this process, the active motion generated by the ultrasonic waves removes and breaks down the surface contaminants, enabling direct contact between the two metals. As the shear deformation process escalates, high heat is generated at the interface, leading to a gradual decrease in the material's resistance to deformation (yield strength), thus facilitating the weld zone's expansion. At ending cycle of weld, the contact area is completely filled with material that has undergone intense plastic deformation, ensuring the formation of a current and effective metallic collisions across the intimate between the two materials (Al-Sarraf. 2013), (Harthoorn. 1978), (Bloss. 2008), (De Vries. 2004).

6. THE INFLUENCE OF SELECTING PARAMETER USED IN USW PROCESS:

To achieve maximum strength in welded joints, three key operational parameters must be optimized: clamping force, welding time, and vibration amplitude. This optimization not only reduces pollutant emissions but also contributes to improved fuel efficiency in sectors such as the automotive and aerospace industries. Ultrasonic welding, which relies on high-frequency mechanical vibrations with minimal heat input, is a promising technology offering multiple advantages in diverse fields such as the automotive, aviation, home appliances, and medical industries. This study examines the effectiveness of operational parameters - such as duration time, applied force, and vibration displacement amplitude - on the weld quality and tensile strength of 0.5 mm thick copper and aluminum sheet joints. The bond was enhanced with an intermediate zinc layer. Using analysis of variance as a reliable statistical tool, it was demonstrated that welding time plays a significant role in controlling energy absorption, while both applied force and vibration amplitude had a significant impact on weld quality. The results demonstrated the remarkable effectiveness of the ultrasonic welding technique, as most of the produced joints possessed mechanical strengths exceeding those of the base material. Applying optimal welding parameters - including a period time of 1 second, a clamping force of 100 kN, with displacement amplitude of 60 µm - resulted in a joint with an extremely low gap ratio (2.5%) and a maximum peel strength of 450 N. Electron Dispersive Diffraction (EBSD) analysis was also performed to study the nature of grain boundaries and the development of the crystalline texture at contact surfaces. The results indicate that the bonding region contained a continuous crystalline texture characterized by a high level of density of large-angle grain boundaries, along with a widespread dislocation distribution and internal structural distortions. This analysis confirmed the occurrence of plastic condition for deforming set up in the bonding region, which provided the energy required for dislocation movement and microstructural state rearranged, contributing to the forming state of new interfaces between the copper plates due to start recrystallization resulting from the heat generated during welding. The study also discussed the possibility of using high-strength steel welding to join copper to aluminum using a zinc layer at varying welding energy levels, as seen in Figure 6, and sources (Sathishkumar et al. 2023), (Gunduz et al. 2006), (Bloss. 2008), (De Vries. 2004), (Li et al. 2020).

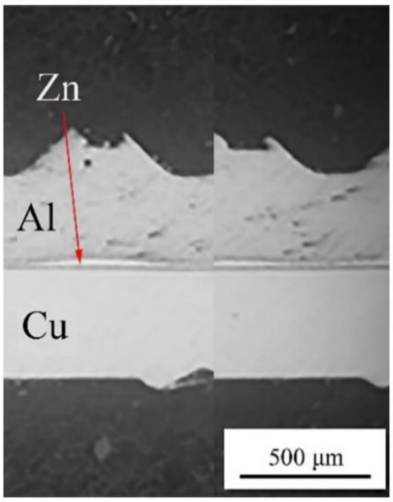
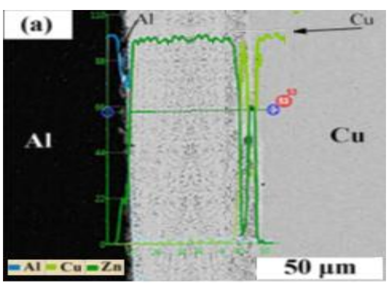


Figure 6. Enlargement of The Joint between Al-Cu having Zn Interlayer between them (Li et al. 2020)

At interface, the microstructure and the long-term stability of dissimilar welded joints were studied. The use of ultrasonic spot welding (USW) enhanced the diffusion process at the interface, resulting in the formation of a zinc (Zn)-rich layer between the aluminum and copper metals.

The thickness of this layer increased with increasing welding energy or temperature at the interface.

To better understand the bonding mechanism in USW-welded aluminum/copper (Al/Cu) joints, spectroscopic analyses using X-ray diffraction (XRD) and energy-dispersive spectroscopy (EDS) were performed on samples welded under specific operating conditions: 1000 J of energy, 100 kN of applying force, 60 µm of vibration amplitude, and a time of no more than 1 second, as shown in Figure 7. EDS line scan analysis was also applied to investigate the value of thickness of the diffusion layer at the interface and to compare the microstructure differences between joints containing and without zinc. The investigation also included an analysis of the formation mechanism of the bonding interface between aluminum and copper in these joints (Harthoorn. 1978), (Bloss. 2008), (De Vries. 2004). (Li et al. 2020).



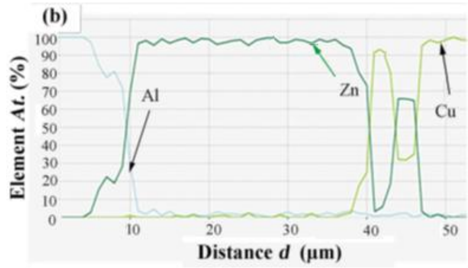


Figure 7. EDS Configuration of the Al/Cu joint result from the Zn interface under impart welding energy of 1000 J [24]

Both Al/Zn and Zn/Cu interfaces exhibited significant atomic diffusion, with the diffusion layer thickness reaching approximately 8.5 µm at the Al/Zn interface and approximately 12 µm at the Zn/Cu interface. These results indicate that despite diffusion layer initiated between aluminum and copper during the ultrasonic wave welding (USW) process, the introduction of a Zn interlayer effectively inhibits direct atomic diffusion between the two metals. X-ray diffraction (XRD) test was performed at the interfaces, both with and without a Zn interlayer, at a welding energy of 1000 J, to detect intermetallic compounds (IMCs) and determine their chemical composition. Figures 8 and 9 show a comparison of the contact areas between Al and Cu, according to (Sathishkumar. et al 2023), (De Vries. 2004), (Li et al. 2020).

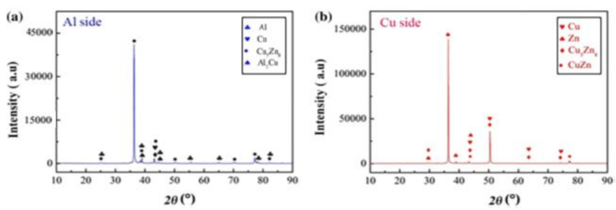


Figure 8. Results of XRD with a Zn interface: (a) XRD test close to Al; (b) XRD test close to Cu (De Vries. 2004)

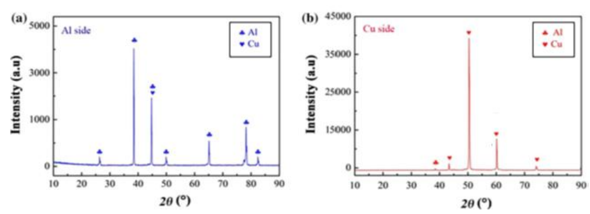


Figure 9. Results of XRD without a Zn interface: (a) XRD test close to Al; (b) XRD analysis test to Cu (De Vries. 2004), (Li et al. 2020)

X-ray diffraction (XRD) analysis of the welded joint without a zinc layer showed the appearance of five main peaks attributed to aluminum (Al) and four distinct peaks attributed to copper (Cu), indicating the absence of intermetallic compounds (IMCs) formation during the ultrasonic spot welding (USW) process in the absence of a zinc layer. This is mainly attributed to the fact that the joint formation under the influence of the applied energy is caused by the mechanical interlocking effect resulting from the vortices generated during welding, as this local interlocking plays a pivotal role in the bonding mechanism between the two materials (Sathishkumar et al 2023), (Li et al. 2020).

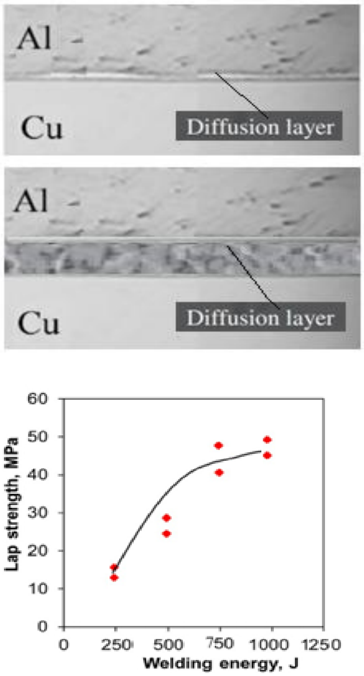


Figure 10. Images of Al/Cu joint with diffusion layer and tensile strength versus welding energy (Sathishkumar. et al 2023), ((Li et al. 2020)

The microstructure of bonding and long-term stability of dissimilar joints were studied. Ultrasonic welding (USW) promoted diffusion at the interface, lead to forming process of a diffusion layer containing a eutectic state of the structure for both aluminum and copper. The thickness of this layer was observed to gradually increase with raising in welding energy, ranging from 250 J to 1000 J, as shown in Figure 10. USW is an effective method for improving joint strength, but increasing welding energy beyond the optimal limit can lead to reduced mechanical strength during the process (Sathishkumar. et al 2023), ((Li et al. 2020).

7. MOST COMMONLY USED MATERIALS WITH ULTRASOUND TECHNOLOGY:

In process of ultrasonic welding, material selection is an unstable factor that significantly influences the efficiency and effectiveness of this process. Aluminum and copper are among the primary materials used in ultrasonic welding due to their diverse uses in fields such as welding and machining. The importance of these two metals lies in their distinct properties, such as drop in density, raise in strength-to-weight ratio, and excellent indication of vibration damping, in addition to their cost-effective manufacturing through casting processes. However, significant technical challenges arise when welding critical structural components in industrial applications, particularly when dealing with various types and series of aluminum alloys. These challenges are primarily due to the thickness of the material and the nature of the elastic vibrations during the welding process. Conversely, these difficulties are less severe when dealing with thin shapes such as foils and wires. Two major obstacles have been identified that hinder practical progress in this field: the first is the problem of unwanted adhesion between the tool and the components during welding, and the second is the instability of weld quality, even when the same machine settings are used over repeated operations (Basak et al. 2021), (Felice et al. 2020). Aluminum alloys, which rely on precipitation tempering, feature the addition of elements such as magnesium and silicon, giving them a change varied from medium to high strength, excellent weldability, and high corrosion resistance, as in the case of 6005A alloy. These alloys also exhibit good fatigue resistance and ease of cold forming, making them suitable for use in areas such as aircraft structures, marine equipment, camera housings, electrical connectors, pistons, valves, bicycles, and cosmetic applications. Copper, on the other hand, boasts high electrical and thermal conductivity, excellent ductility, and outstanding value of corrosion resistivity, providing an ideal condition for applications such as wiring (which accounts for approximately 60% of its applications), plumbing, and mechanical equipment. Various alloys, such as brass, bronze, aluminum bronze, and copper-nickel alloys, are combined with elements such as zinc, tin, aluminum, and nickel to increase the improvement of mechanical properties such as strength, corrosion resistance, and bendability. For example, aluminum bronze has high resistance to saltwater corrosion and cavitation, making it suitable for marine propeller applications, while copper-nickel alloys are widely used in heat exchangers and seawater piping (Wu et al. 2019), (Zhou et al. 2018), (Lin et al. 2020), (Youns et al. 2025), Zhao et al. 2017).

8. STEEL WITH ITS ALLOYS, TITANIUM AND MAGNESIUM FAMILIAR WITH USW:

A solid-state condition of ultrasonic weld shows promising potential for joining steel to aluminum. However, experimental research in this area is still limited. Takehiko and colleagues demonstrated the feasibility of welding A5052 aluminum alloy, rich in magnesium, with SS400 carbon steel using ultrasonic waves. Their results demonstrated that the clamping force is a critical factor in weld quality, with the optimum value being approximately 1000 N. Increasing the clamping pressure was shown to reduce interfacial friction, which negatively impacts the formation of an effective joint. Under a constant time duration of 1.0 s and varying in applying pressure to apply clamp, successful joints were achieved. Further experiments revealed that maintaining the force at 1000 N with increasing welding time improved joint strength, with the best results achieved at 2.5 s. However, extending the time to 3.0 s resulted in a decrease in the bond strength due to the formation of Fe_2Al_5 intermetallic compounds at the interface. The use of commercially pure aluminum inserts significantly enhanced weld strength, increasing weldability threefold compared to joints without inserts at the same welding time (3.0 seconds). The results indicate that three different fracture patterns occurred when ultrasonic welding aluminum with various alloys and welding conditions. While tensile strength and vibration rate had a minor effect on tensile strength, vibration duration had a significant effect, even when approaching the threshold. Welding conditions significantly influence the tensile strength of joints. For example, studies on steel-titanium welding have shown that high joint temperature enhances bond strength, often leading to fracture of the base metal. Interface composition, cracking, and crystal structure analyses have also shown that the phase transition of titanium at elevated temperatures facilitates plastic deformation and improves bond quality by filling the interfacial gaps, resulting in high-quality joints with superior mechanical performance. Among the alloys gaining particular importance in the automotive industry, titanium alloys with aluminum or copper are among the most prominent. In such welds, surface interactions play a pivotal point in controlling phenomena such as segregation with precipitation. Al-Ti and Cu-Ti joints exhibit better mechanical performance, particularly in terms of bending angles, when elements such as silicon or magnesium are present, compared to those without. During ultrasonic annealing, temperatures can reach approximately 500°C, accelerating the forming process of magnesium oxide layers on the metal surface. During the welding of Ti6Al4V to AA6111 at a dirty interface, significant accumulation of oxygen, silicon and magnesium was observed, while no significant migration of other alloying elements for example copper and also vanadium toward the joint was observed. Magnesium is one of the metals that exhibits good compatibility with USW.

Several studies have examined energy effect on various properties such as microstructure, crystal orientation, hardness, and cross-section shear strength (LSS). Recrystallization has been shown to occur in the weld zone as a result of limited slip mechanisms, reduced stacking energy defect, and the diffusion of grain boundary.

Generally, changes in the crystalline shape of the core region of magnesium alloys have also been observed, resulting from intense localized shear deformation accompanied by complex recrystallization mechanisms. Research has shown that the weldability of magnesium alloys has been evaluated using three basic methodologies: cross-section shear testing, thermal forming analysis, and microstructure characterization (Zhou et al. 2018), (Rubino et al. 2020), (Ren et al. 2017), (Anmar et al. 2024), (Patel et al. 2012), (Feng et al. 2019).

9. EFFECT OF ADDING INTERLAYER ON JOINING OF USW

In (USW), the process was used to precisely join aluminum alloys to copper, with a zinc interlayer inserted between the two contact surfaces. The presence of zinc contributed to the formation of a eutectic condition for structure in the centre of the joint, containing intermetallic compounds resulting from the interaction of aluminum with copper. These results suggest that zinc may have played a catalytic role, either through frictional effects or chemical reactions during a process of bond. Figure 11 shows an illustrative pictorial image of aluminum-copper composite joint samples.

Figure 11. Pictorial and photograph of Al /Cu lap joint sample

Microscopic examination of the aluminum-copper interfaces revealed the formation of diffusion layers on both sides, but the layer in this region was significantly thinner. It featured a thin aluminum-copper interface, along with distinctive "fork"-shaped interlocking structures. Figure 12 shows the tensile failure load curves from the overlap shear tests, along with a comparison of the overlap tensile strength at different energy input levels for stainless steel welds. Specimens welded without adding of a zinc interlayer between surface, at energies of 500 and 1000 J showed a significant difference in the tensile strength before fracture only in the weld zone. The significant improvement in overlap shear in the 1000 J weld, compared to the 500 J weld, is attributed to the increased interlocking effect resulting from active rotation within the weld zone. The overlap shear tensile strength, a conventional test measured by make divide in resulting load by the bond mass area, which was calculated for joints produced under varying welding energies, both with and without a zinc interlayer. In both cases, an upward trend in strength was observed with increasing energy input. As energy increased, higher temperatures contributed to metal softening and deformation, which enhanced the fusion process by improving interfacial diffusion. Using of a zinc interlayer substrate further enhance and increase the shear strength. The differences in values increased more markedly with increasing energy input. For example, the sample welded at 1000 J with a zinc interlayer exhibited an overlap shear tensile strength of nearly 100 MPa, a significant improvement compared to the sample without the interlayer. Despite a significant presence of brittle Al_2Cu compounds in the weld zone, the formation of a semi-cohesive compound condition for structure consisting of a eutectic Al-Zn film and $Cu\text{-}Zn_5$ compounds dispersed around the weld perimeter contributed to enhanced joint cohesion and significantly increased the cross-linking shear strength (Balasundaram et al. 2014), (Zhao et al. 2013), (Sarraf. 2023), (Gu et al. 2019).

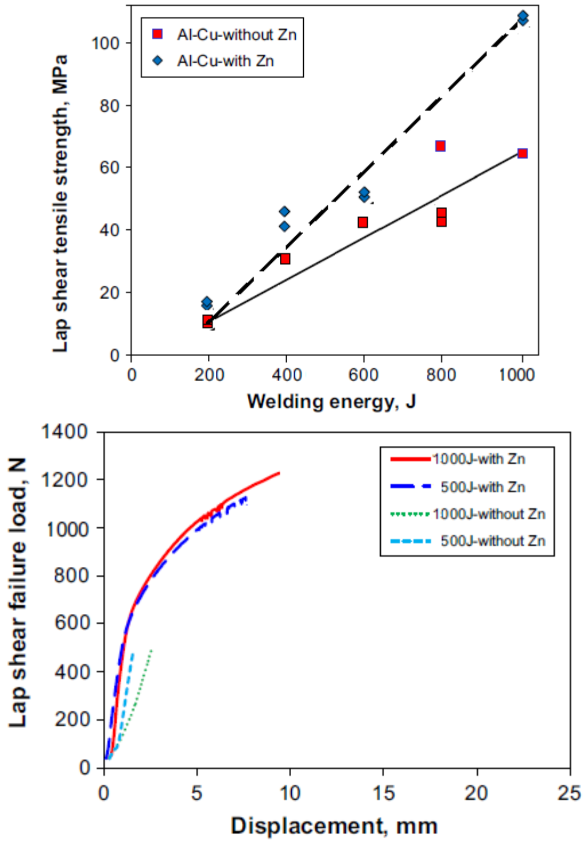


Figure 12. Relation between lap shear failure load vs displacement (to left), and lap shear tensile strength vs. different energy inputs (to right) (Balasundaram et al. 2014), (Zhao et al. 2013), (Sarraf. 2023)

10. CONCLUSIONS

The progressive development of uncoated zinc (USW) welding methodologies and equipment contributes to the improvement of process parameters, including performance metrics, reliability indicators, and cost-benefit ratios. Systematic investigation of the underlying mechanisms allows for improved applications, which in turn improves qualitative and quantitative output parameters. Uncoated zinc (USW) welding warrants extensive research through its multi-functional advantages, including the capability to join any two dissimilar Al/Cu materials, improve weldability efficiency, and reduce consumption of energy requirements. The joining mechanism was analyzed with the addition of a zinc interlayer and then compared with the absence of a zinc interlayer, as follows: The extent of plastic deformation shows a direct correlation with welding energy input, exhibiting a gradual densification across different zinc interlayer thicknesses. This relationship suggests that higher energy deposition induces more aggressive material flow characteristics, with the zinc interlayer thickness acting as a critical moderating variable in deformation behaviour. At the aluminium/copper interface, two types of intermediate metal compounds (IMCs) were identified to form Cu-Zn and Al-Cu eutectic structures. However, no evidence of these compounds was observed at the aluminium/copper interface in the joint when no zinc interlayer was added. Zinc interlayers in USW aluminium/copper joints improved the cross-linked shear strength by 35% and the fracture energy by threefold through the formation of an aluminium/zinc/copper/zinc phase. While the primary joints failed at the interface, zinc-modified joints failed in the copper base metal above 1000 J, confirming the bond strength.

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