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REVIEW ARTICLE

Latest Developments in Welding of Common Dissimilar Metals: A Literature Review

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Abstract: In the domain of industrial building and production technology, the welding of dissimilar materials finds a wide range of applications. Unique properties of different materials are utilized to produce addition and cost effectiveness of the product for intended applications. For determining the feasibility of welding of dissimilar metals together to create a strong joint, a number of factors need to be taken into account. This paper discusses critical factors and conditions for welding of dissimilar metals and touches upon the practical challenges arising from different physical and chemical properties of the metals. It presents the latest and pertinent literature dealing with the details about the current fusion and non-fusion processes employed for welding common dissimilar metal combinations. The results suggest that research and development in the field of dissimilar metal welding is still needed, especially in light of the growing need for customized materials in contemporary engineering and industrial applications.

Keywords: Laser welding, dissimilar metals, fusion welding, friction, heat, alloy.

1. INTRODUCTION

"Fusion and non-fusion welding are the two main types of welding processes. Fusion welding involves heating two or more materials to their melting point to fuse or combine them in a liquid state, with or without the use of filler material. Non-fusion welding applies pressure to heat the materials to a semi-molten or plastic state without supplying external heat.

Welding dissimilar metals presents metallurgical challenges. Researchers have been investigating methods for welding dissimilar metals, such as steel, aluminum alloys, copper, tin, and magnesium alloys. However, welding these metals together is challenging due to their intrinsic differences in characteristics. The primary barrier to the quality of dissimilar weld joints is the development of brittle, crack--sensitive, and corrosion-prone intermetallic phases at the interface of the metals. Additionally, differences in thermal conductivities, melting points, and coefficients of thermal expansion result in uneven heating and cooling rates during the welding process, leading to the development of residual stresses and tension that affect the joint's performance. Different metals also possess different mechanical properties,-such as hardness, ductility, and yield strength, causing uneven load distribution and stress concentrations.

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Furthermore, the electrochemical potential difference between different metals leads to galvanic corrosion when the weld joint is exposed to an electrolyte such as atmospheric moisture. Consequently, the dissimilar weld joint becomes weaker when in service due to localized corrosion, leading to a shorter lifespan. The integrity and long-term durability of the dissimilar weld joint are compromised due to the rapid deterioration of the weld interface. Various researchers have attempted different techniques to improve the performance and lifespan of dissimilar weld joints [1-2]. This paper discusses critical factors and conditions for welding dissimilar metals and addresses the practical challenges arising from the different physical and chemical properties of the metals. It presents the latest literature dealing with the fusion and non-fusion processes employed for welding common dissimilar metal combinations".

2. DISSIMILAR METALS WELDING PROCESSES

As discussed earlier, fusion and non-fusion welding are two general processes that encompass a range of techniques for welding dissimilar metal pairings like steel-Al alloy, Al Alloy-Mg alloy, Copper-Steel alloy, steel-Mg alloy, *etc.* The schematic of various techniques for welding dissimilar metals is presented in Fig. (**1**) [1]. According to this, dissimilar metals can also be joined by low-dilution welding and mechanical methods. However, fusion and non-fusion welding processes remain favorites for dissimilar metal joining.

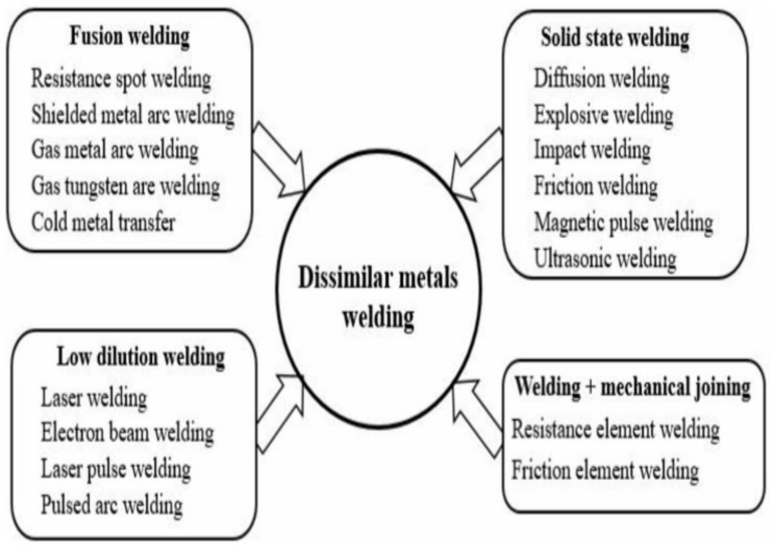

Fig. (1). Various processes for dissimilar metal welding. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

2.1. Steel-Aluminum Welding

2.1.1. Fusion

The most common metals utilized in the production of automobile bodies are steel and aluminum alloys. They are the highly researched dissimilar material combination due to the special combination of aluminum alloys, formability and lightweight properties, and exceptional strength and toughness of steels [3]. Research on laser welding of butt joints made of aluminum and steel was performed by Sun *et al.* [4]. According to their study, butt joints can be used to link aluminum alloy to steel if the steel groove face is previously hot-dip galvanized. This improves the weld properties when appropriate welding parameters are used. The joints are dual-purpose, with the aluminum side being a brazing junction and the steel side being a welded joint. Pengfei Wang *et al.* [5] reviewed laser welding for joining steel-aluminum. However, they found a number of issues associated with laser welding due to the variations in thermal, physical, and chemical properties of steel and aluminum.

2.1.2. b Non-Fusion

Analysis of the resistance spot welding process for Al-steel, using a fully linked multiphysics simulation model, was carried out by Jing Wang *et al.* [6]. This model solves the equations simultaneously by directly coupling the thermal, electrical, and mechanical fields. The model offers insightful data on the process's dynamic current flow, heat production and transfer, nugget growth,, and mechanical deformation. The parabolic kinetics mode of growth and the temperature history at the Al-steel contact interface were used to compute the Al-steel intermetallic compound (IMC) thickness, which is crucial to the weld strength. Compared to earlier methods of numerical calculation in predicting welding process parameters like electrode geometry and weld schedule before expensive physical testing, this fully coupled process simulation model offers a significant improvement in economy and acts as a powerful tool for understanding the fundamental physics involved during the Al-steel resistance spot welding. Chen *et al*. [7] examined the effects of production parameters on the microstructural and mechanical characteristics of resistance Al-steel spot welds, including gaps between the sheet, metal, angles between the sheet metal and welding electrode, and variations in current and cap length. Identification of the intermetallic compounds at the Al-steel resistance spot weld contacts was undertaken by Wan *et al.* [8]. They analyzed two types of IMC layers developing at the interface. The first type, which occupied the center of the interface, was made up of FeAl3 that was serrated to Al with tongue-like Fe_2Al_5 formation next to the steel; the second type, which was the mixture of $FeAl_3$ and Al, was positioned on the joint interface periphery. When sufficiently high welding duration was used, a bimodal IMC thickness distribution was discovered. After about 200 ms of welding, it was found that the distribution is related to the lower interfacial temperature at the core of the Al-steel interface than what was in the surrounding area because of the substantial cooling impact of the electrode. Sadiq Aziz Hussein *et al.* [9] studied features of friction stir welded aluminum-steel junction. Because steel and aluminum have different mechanical and thermal characteristics, friction stir welding uses its solid-state process behavior to fuse the two metals. But slight melting and re-solidification phases were found to evoke harmful responses.

2.2. Copper-steel Welding

2.2.1. Fusion

The impact of beam offset on the properties of electron beam welded copper-304 stainless steel was investigated by Guo *et al.* [10]. The influence of beam offset on the joint strength was thoroughly examined by determining the phase structure and distribution of the weld zone, the bonding interface of the fusion zone, the breadth and grain size of the heat-affected zone, the diffusion behavior of Fe/Cu, the cooling rate and the fracture behavior. Based on the data, it was concluded that the beam offset is flexible that can vary between -0.2 and 1 mm. The narrow heat-affected zone (HAZ) and a small fault weld zone contributed to the joint's good performance when there was a modest beam offset. The electron beam welding machine is shown in Fig. (**3**).

By adjusting the welding power and speed, as well as the offset and inclination angle of the laser beam facing stainless steel, the microstructures and mechanical characteristics of the stainless steel-copper laser welded joint were examined by Chen *et al.* [11]. Depending on the applied process settings, the joint showed three common forms of fracture: at the interface, in the heat-affected zone (HAZ), and the fusion zone. Although the melting of copper caused the joint hardness to decrease, it had no significant effect on the tensile strength of the joint.

2.2.2. Non-Fusion

Heng Zhang *et al.* [12] conducted a study on the mechanical characterization and microstructural analysis of an explosive welded copper-steel composite. The interface revealed a periodic wavy bonding structure with a solid-solid bonding area and a vortex zone. Analysis of the copper matrix texture and orientation showed typical annealed twin structures. The iron matrix exhibited Adiabatic Shear Bands (ASBs) filled with much smaller equiaxed grains with orientation differences in various locations. A transition layer consisting of 60 nm-sized nanoparticles was found between the copper-copper and steel plates. Tensile tests confirmed the high-quality bonding, as cracks extended into the copper matrix rather than along the interface wave structure. Additionally, Kore *et al.* [13] demonstrated the use of the non-fusion electromagnetic (EM) impact technique for fusing copper sheets to stainless steel sheets (SS), with the electromagnetic welding machine structure depicted in Fig. (**2**).

They observed that Cu-SS sheet welding is made easier with the use of electromagnetic welding techniques than with traditional methods. It shows promise as a welding method for many types of industrial components that need joints of different sheet metals. The Cu-SS EM weld joint was found to be stronger than the parent metal from tensile shear strength tests. The weld interface's metallographic analysis revealed metal continuity. Because of the grain compression close to the weld contact, the hardness values were found to be higher than in the base metal. The mechanical characteristics and microstructure of sandwich copper-steel composites created using explosive welding were studied by S.V. Gladkovsky *et al.* [14]. The effect of plate-contact collision was found to be responsible for the wavy interfaces in three-layered copper-steel-copper composites. An alternative method for hardening the welded sandwich composites was cold rolling. It was discovered that a wave profile was acquired following cold rolling. The development of dynamic polygonization and recrystallization processes led to grain refinement in copper and steel layers. Tensile test findings showed that the sandwich composite strength values were 1.8–3.5 times greater than that of the original copper. The ductile copper layers and fracture energy dissipation at the price of crack deviation while crossing the interfaces were attributed to the sandwich composites high impact strength values. Zhang H. *et al*. [15] examined the interface properties of explosive-welded copper-steel composite by experimental and computational methods. They developed the procedure to create a unique copper-steel composite stave. Their findings showed that, in comparison to copper cooling staves, the copper-steel composite cooling stave had higher anti-deforming performance and a comparable cooling capacity.

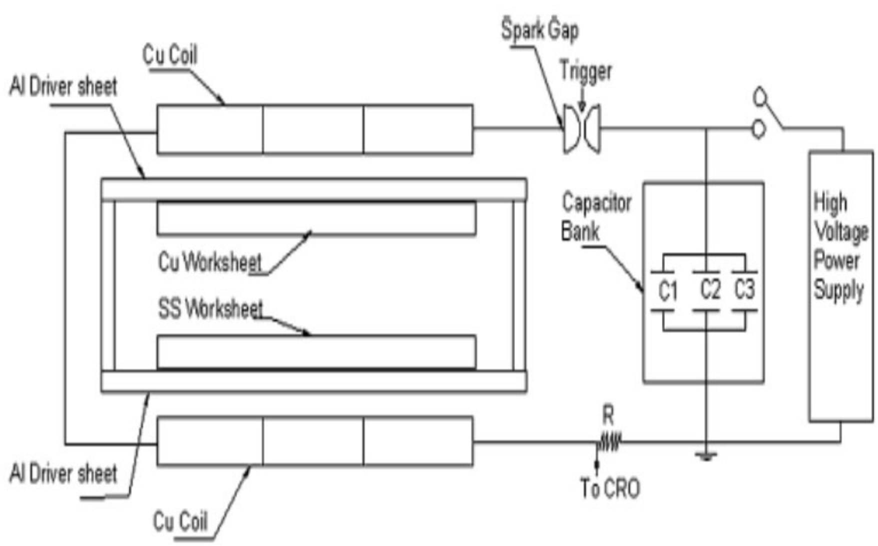

Fig. (2). The electromagnetic welding machine structure. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

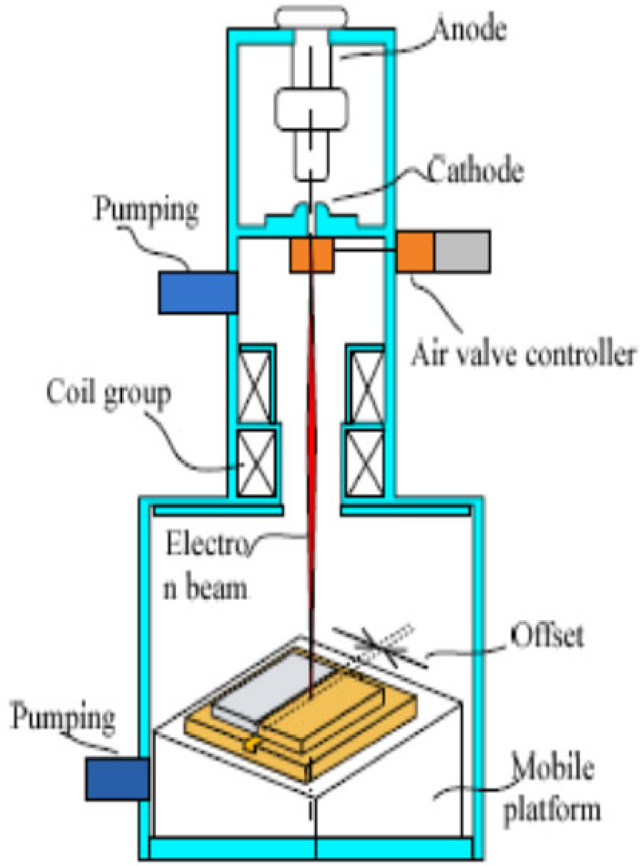

Fig. (3). Electron beam welding equipment. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

2.3. Titanium-steel welding

2.3.1. Fusion

Shuhai Chen *et al.* [16] examined microstructures and mechanical characteristics of a dissimilar joint of a titanium alloy laser but welded to stainless steel. It was found that a more robust junction was produced when the laser beam was shifted in the direction of the stainless steel side. Wang *et al.* [17] focused on the effects of various filler metals on titanium alloy electron beam welded to stainless steel. According to them, Ti-Fe intermetallic were effectively restrained using suitable filler metals. Solid solution and interfacial intermetallic were present in all welds involving various filler metals. The metallurgical interactions between the filler metals and base metals determined the type of solid solution and interfacial intermetallic for each type of filler metal. Fe_2Ti+Ni3Ti+NiTi2, Ti-Fe, and $Cu_2Ti^{+}Cu^{-}Ti^{+}CuTi_2$ were the interfacial intermetallic in the joints welded with Ni, V, and Cu filler metals. The hardness of interfacial intermetallic influenced the tensile strength of the joints. The joint welded with Ag filler metal exhibited the highest strength of around 310 MPa. The comparison of each intermetallic layer's average microhardness is available in Fig. (**4**).

2.3.2. Non-Fusion

Changes in structure during explosive welding of High--strength titanium and alloy steel were studied by Lazurenko *et al*. [18]. They investigated the features of the structure of layered materials of tool roller steel and high-strength titanium alloy with an intermediate layer of structural low-carbon steel. Additionally, the billets of structural steel and titanium alloy were fused by diffusion welding to understand the characteristics of structural alterations caused by extended heating. It was seen that a continuous layer of stable, brittle intermetallic compounds formed throughout the whole interface between the materials. The intermetallic phases in explosively welded joints were localized, which resulted in a reduced embrittlement impact property. The microstructure and mechanical behavior of titanium-steel interfaces formed by explosive welding were investigated experimentally and numerically by Qiaoling Chu *et al.* [19] wherein the structure and mechanical behavior of Ti/Fe explosive-bonded contacts were systematically explored. The method of Smoothed Particle Hydrodynamics (SPH) numerical simulation was utilized to replicate the fluid-like transient behavior in the bonding zone. A wave shape that emerged from significant plastic deformation during the welding process characterized the nature of the contact. Around the molten zone, created by confined jetting, were heavily deformed bulk materials. Fe-Ti intermetallic generated in the joint were confirmed to be brittle with the help of nanoindentation experiments and fracture observations. Extreme heat buildup close to the interface caused the distorted grains to recover and recrystallize, allowing the contact to withstand comparatively high strain. Cheepu *et al*. [20] presented a novel method for applying the interlayer in titanium-stainless steel friction welding process. Electrodeposited nickel coating on one of the substrates (stainless steel) as an interlayer was used in the study. Energy dispersive spectroscopy, optical microscopy, and scanning electron microscopy were employed to study the bonding interface of the joint. The nickel interlayer junctions exhibited a greater tensile strength in comparison with the direct joints. The improved performance with the interlayer approach was attributed to the lack of brittle Fe–Ti intermetallic compounds at the interface. Conversely, the presence of Ti-Ni phases, which were more malleable than Fe–Ti intermetallic compounds, were found to characterize the interface. Fig. (**5**) shows the joint interface microstructure for a 70 Lm thick interlayer with the production of thick intermetallic compounds for the upset pressure in P6 welds.

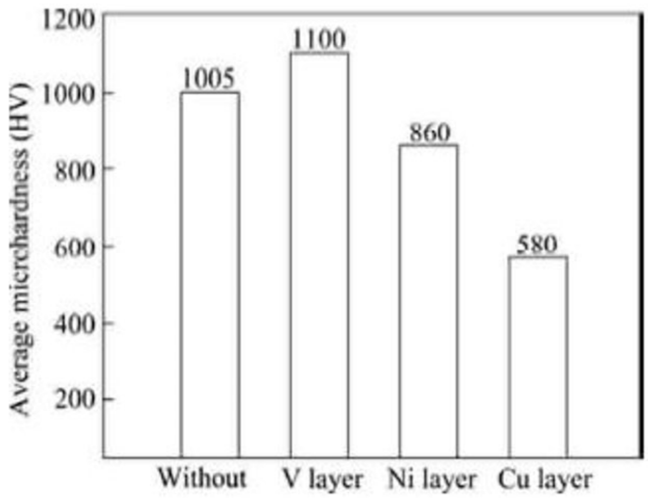

Fig. (4). A comparison of each intermetallic layer's average microhardness. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

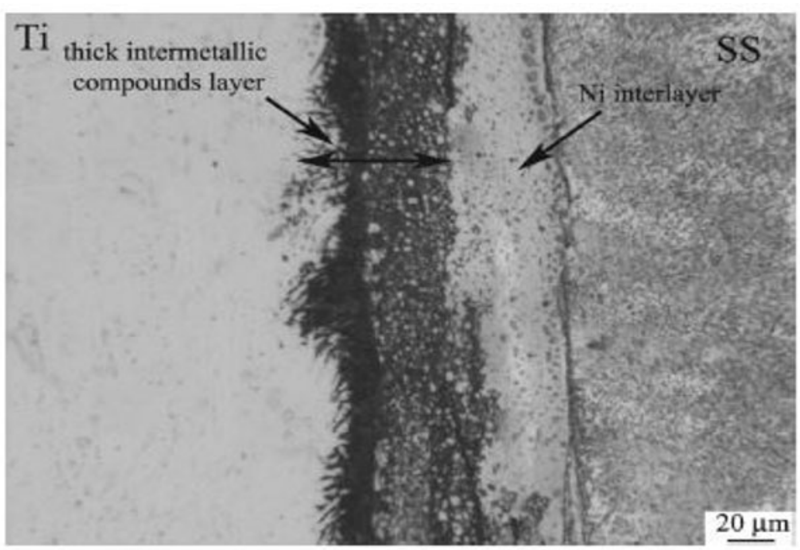

Fig. (5). The joint interface's microstructure at the 70 Lm thick interlayer demonstrates the production of thick intermetallic compounds for the upset pressure P6 welds. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

2.4. Magnesium-steel welding

2.4.1. Fusion

According to Liqun Li *et al.* [21], magnesium-based filler was used in the development of a laser welding brazing (LWB) technology that joins magnesium alloy to mild steel and magnesium alloy to stainless steel in lap configurations. The Mg/mild steel interface was found to have no discernible reaction layer, leading to the confirmation of the interface contributing to the mechanical bonding. On the other hand, the Mg/stainless steel interface revealed an ultra-thin reaction layer with a continuous and uniform morphology, suggesting metallurgical bonding. Transmission electron microscopy (TEM) in conjunction with energy dispersive spectroscopy (EDS) allowed the identification of the newly developed interfacial layer of the Fe-Al phase. Casalino *et al.* [22] performed AZ31B magnesium alloy laser offset welding on 316 stainless steel. They investigated whether it would be possible to connect incompatible metals with a fiber laser. The butt configuration of 316 stainless steel and AZ31B magnesium was autogenously bonded. The beam was directed onto the magnesium plate's upper surface, offset from the interface by a predetermined amount, and without the need for interlayer or groove preparation. This technique is known as laser offset welding (LOW). The ultimate tensile strength was greater than 100 MPa because the fusion zone contained a thin, resistant coating of strong intermetallic compounds. The break failure zone was found well away from the centerline on the magnesium side. The fusion zone's metallurgy proved the efficiency of phase coalescence without liquid-state mixing. It was shown that LOW is a potential method for joining dissimilar metal welds since it can result in a strong connection with good tensile strength. Fig. (**6**) presents a diagrammatic representation of the LOW technique workflow.

2.4.2. Non-Fusion

Liu *et al.* [23] presented work on resistance spot type welding (RSW) for joining magnesium to steel. An innovative technique was developed, resulting in the joint strength that could reach up to 95% of that of the magnesium to magnesium connection. Mechanical testing and metallurgical analysis using energy-dispersive X-ray spectroscopy, X-ray diffraction, and scanning electron microscopy were used to examine the mechanics of dissimilar joining. The findings suggested that braze welding, solid-state bonding, and soldering are the connecting mechanisms involved in the RSW of magnesium alloy to Zn-coated steel. A preliminary investigation of friction stir lap welding (FSW) of magnesium alloy to steel was carried out by Jana *et al.* [24]. The investigation was conducted to assess the viability of utilizing friction stir welding to fuse a magnesium alloy AZ31 sheets to a galvanized steel sheets in a lap arrangement. For comparing the dissimilar joint potential, two distinct automotive sheet steels were used: A 1.5 mm thick hot-dipped galvanized (HDG) high-strength, low-alloy (HSLA) steel and 0.8 mm thick electro-galvanized (EG) mild steel. These steels were attached to the AZ31B magnesium sheet, which had a thickness of 2.33 mm. For both dissimilar welds, a single FSW tool design was employed while the process parameters remained unchanged.

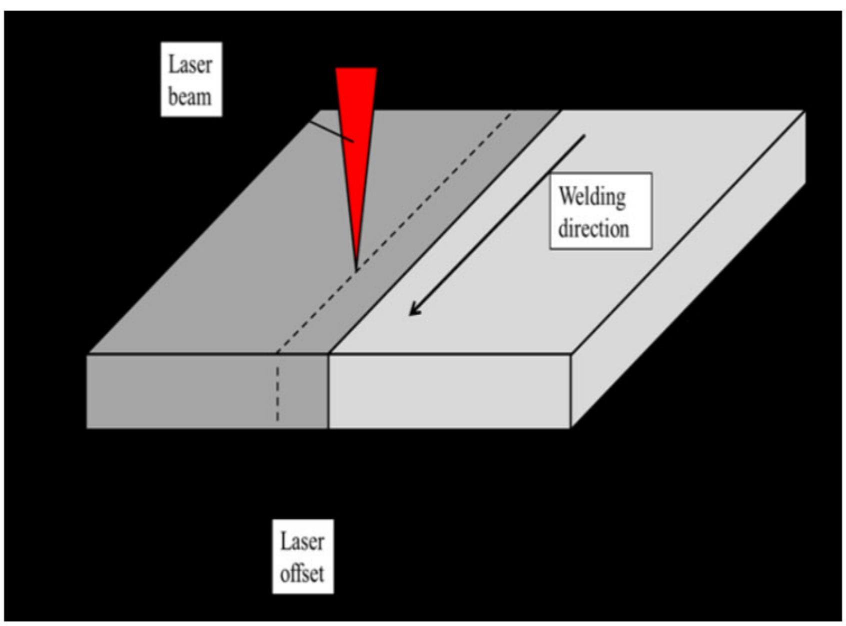

Fig. (6). Diagrammatic representation of the LOW technique workflow. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

2.5. Copper-Titanium welding

2.5.1. Fusion

Xie *et al.* [25] reported the influence of nickel interlayer on copper-titanium joints obtained by laser welding. Cu/Ti dissimilar joints offer a wide range of possible uses in the nuclear and aerospace industries. To accomplish a strong bond between titanium (TA2) and copper (T2), nickel was used as an intermediary layer. The investigation was undertaken over the effects of the intermediate layer of nickel on the formation of joints, microstructure, mechanical characteristics, melting, and element diffusion behavior. The characteristics and microstructure of Cu/Ti laser-welded joints were explained by Zhao *et. al*. [26]. According to them, a link between titanium and copper could be made possible by laser welding. The tensile strength of the butt joint reached 151 MPa, or 61% of the tensile strength of the copper base metal, with the laser beam offset of 0.45 mm from the copper side. At the IMCs, the quasi-cleavage fracture occurred.

2.5.2. Non-Fusion

Kemal Aydın *et al*. [27] conducted experiments on Copper-Titanium welding using diffusion bonding process. Titanium was bonded to copper at 3 different temperatures for 3 different durations. During bonding, a 3MPa uniaxial load was applied. The joints' interface quality was evaluated using a micro hardness and heat testing apparatus. Additionally, energy dispersive spectroscopy, optical microscopy, and scanning electron microscopy were employed to analyze the bonding interfaces. Diffusion bonding was also used to accomplish the welding of $Ti^{-6}Al^{-4}V$ to Cu. Diffusion welding equipment is shown in Fig. (**7**).

The properties and microstructures of lap-welded titanium–copper metals were studied by R. Cao *et al.* [28]. Using one of the non-fusion type of welding processes, *i.e.,* cold metal transfer (CMT) welding, dissimilar metals were successfully welded. The findings showed that the CMT welding process could produce good lapped junctions between commercially produced pure copper TA2 and titanium T2. Wang *et al.* [29] investigated the interaction between titanium and copper during explosive welding under various welding conditions. According to their findings, the performance of the explosive welded clad plate's interface sealing was impacted by vortex holes at the welding interface; hence, it was important to select the right manufacturing settings to prevent the creation of these holes. The interface ripple morphological change law and vortex hole production at the interface of the welded clad plate under various stand-off distances were studied using the step technique. According to the experimental results, there is a positive correlation between the stand-off distance and the welding interface's shear strength as well as the ripple's wavelength and amplitude. Hardness was found to increase with proximity to the contact; dislodged metal blocks in the melt zone did not significantly affect the hardness.

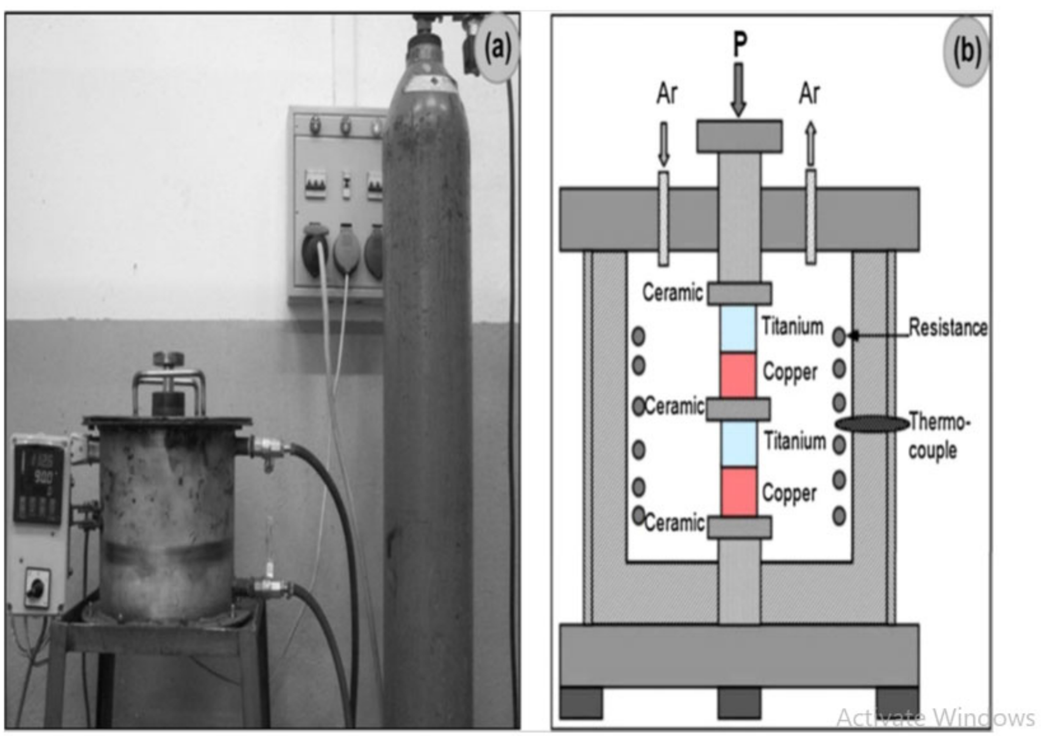

Fig. (7). Diffusion welding Instrument for Cu-Ti welding **a**) Photograph and **b**) Schematic. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

3. DISCUSSION

Dissimilar welding is the process of joining components made of dissimilar metals and their alloys. Before deciding the optimal method for joining dissimilar metals, the filler material and microstructure of both metals must be assessed. Although fusion welding is a widely used technique, certain dissimilar metal combinations may not lend themselves well to it. Sometimes a welder has to figure out another way to fuse dissimilar metals together. The welder must take into account the following factors for each of these joining types:

(a) What makes up the intermetallic layer
(b) The area of basic material known as the unmixed zone (UMZ) that does not merge with the intermetallic layer, and
(c) The zone affected by heat (HAZ). A proper and reliable connection between dissimilar metals requires the welder to minimize the effect of the material variations on the intermetallic layer and the extent of HAZ and UMZ.

Problems that arise in dissimilar metal fusion welding processes like arc welding, laser welding, electron beam welding, *etc.* are as follows: - Welding becomes more difficult with increase in the range of melting points of dissimilar metals. Metal with the higher melting point stays solid while the metal with the lower melting point achieves its melting condition. This is the stage at which the molten material can readily enter into the overheated zone's grain boundary, resulting in the loss of low melting point metal followed by its burning or evaporation. The higher the difference in thermal expansion rates of dissimilar metals, the greater the shrinkage during cooling and the higher are the welding residual stress generated when the molten pool crystallizes. There is considerable deformation of the joint as a result of the residual stresses. Owing to the varying residual stress levels in the materials on either side of the weld, it is easy for cracks to appear in the heat-affected zone and weld, and the stresses may even cause the base metal and weld metal to peel apart. The variation in the material's specific heat capacity and thermal conductivity can also severely coarsen the grain structure and adversely affect the weld metal's crystallization. Because of this, it's crucial to select a robust heat source for welding and to place it such that it faces the side of the base metal that has the best thermal conductivity. The more materials' electromagnetic characteristics differ from each other; the higher is the instability of the welding arc, thereby generating a lower-quality weld. Intermetallic compounds can lead to the formation of cracks or even cause fractures in the weld zone due to their brittleness. Changes in the metallographic structure or the creation of new structures in the welding zone leads to the decline in the performance of the welded joint. It is also challenging for the weld and the two dissimilar base metals to achieve the criteria of equivalent strength.

Non-fusion joining of dissimilar metals includes processes such as friction welding, diffusion bonding, explosion welding,, *etc.* Friction welding only melts a small bit from one of the base surfaces. Because the welder discards the molten portion, the mixed metal zone, and the intermetallic area are reduced. By heating only one side, the HAZ is also reduced. Explosion welding uses less heat to eliminate the HAZ and intermetallic layers. Non-fusion welding works well when joining the following pairs of dissimilar metals:-

- Steel and aluminum
- Steel and copper alloys
- Stainless steel and nickel alloys

Finally, one of the emerging requirements for industry is the joining of different metals. One has to try various approaches that can minimize the stated problems associated with dissimilar metal fusion and non-fusion welding processes. In the current work, welding of dissimilar metal combinations of Steel-Al, Copper-steel, Steel-Titanium, Steel-Magnesium, and Copper-Titanium has been studied because Fe, Cu, Mg, and Ti are the most commonly used metals in alloyed form in crucial engineering applications. Many factors need to be considered when assessing whether it is possible to weld different metals together for producing a robust weld connection.

CONCLUSION

A variety of welding procedures are covered by two broad categories, namely, fusion welding and non-fusion solid-state welding. Researchers have examined the various parameters that govern the welding of dissimilar metals. Several inventive techniques have been developed or adopted for dissimilar metal welding that are beneficial to the manufacturing industry. Among all welding methods, laser welding appears to be a versatile approach to welding dissimilar metals. The crucial parameters in laser beam welding are the welding power and speed and the offset and inclination angle of the laser beam. Some other welding approaches like explosive welding, electron beam welding, friction welding, resistance spot welding, diffusion welding, electromagnetic welding,, and cold metal transfer welding have also been tried out to weld dissimilar metals. In certain cases, numerical analysis is performed by using simulation techniques. Numerical simulation techniques have reached a level of maturity where they can accurately forecast the welding outcomes.

LIST OF ABBREVIATIONS

Al	=	Aluminum
Mg	=	Magnesium
Cu	=	Copper
Ti	=	Titanium
Mg	=	Magnesium
Ni	=	Nickel
Ebsd	=	Electron Backscatter Diffraction
IMC	=	Intermetallic Compound

HAZ	=	Heat Affected Zone
Fsw	=	Friction Stir Welding
HDG	=	Hot-Dipped Galvanized
HSLA	=	High-Strength Low-Alloy
EG	=	Electro-Galvanized
EM	=	Electro-magnetic
LOW	=	Laser Offset Welding
ASB	=	Adiabatic Shear Band
RSW	=	Resistance Spot Welding
SPH	=	Smoothed Particle Hydrodynamics
LWB	=	Laser Welding-Brazing
TEM	=	Transmission Electron Microscopy
EDS	=	Energy Dispersive Spectroscopy
CMT	=	Cold Metal Transfer
UMZ	=	Unmixed Zone

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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