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Understanding the Trends in Welding of Copper and Steel

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Abstract
Copper-steel welded joints are now used widely in heat exchangers, piping and power generation industries. Owing to their different thermal characteristics, sound welding of the pair is a challenging task. Extensive research is carried out to achieve successful welding of copper and steel. This article presents an insight into the works done on the joining of copper and steel by various techniques. The microstructural modifications in different approaches are critically presented. Mechanical properties of joints obtained through different techniques are compared.

Author Keywords. Copper. Steel. Dissimilar Welding. Microstructure. Microhardness. Tensile Strength.

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1. Introduction

Owing to good thermal conductivity, excellent corrosion resistance and high ductility, copper alloys are widely used as a thermal conductive material in chemical and metallurgy industries. However, the low strength and high thermal expansion of copper limits its uses in different industrial applications. Therefore, the joining of copper with high-strength alloys such as steel is of great attention to researchers. The bi-metallic joint of copper steel is extensively used in heat exchangers in nuclear and power generation industries. Both fusion weldings and solid-state weldings were used by researchers to obtain copper-steel joining.

The major difficulty in fusion welding of copper and steel is the huge difference in their thermal properties. The higher thermal conductivity of copper results in the dissipation of heat from the weld zone. Also, the difference in thermal expansion coefficient results in difference in shrinkage during cooling. This leads to the generation of residual stress and consequently leads to crack generation in the weldment. Therefore, special attention is required to control the heating and cooling of the fusion joint to achieve defect-free joining. Moreover, the differences in the metallurgical aspects of the two materials are concerning aspects of achieving successful joining between them. Due to the metallurgical differences, in the liquid phase, the materials tend to get separated, which leads to copper inclusion and hot cracking. Besides laser welding and electron beam welding, TIG and other arc welding processes also were used for the welding of copper and steel. The Fe-Cu phase diagram (Figure 1) suggests that solid-state copper-steel bonding can be achieved at elevated temperatures. Therefore, several solid-state techniques such as explosive welding, friction welding, diffusion bonding, etc., were attempted for the successful fabrication of copper-steel joints.

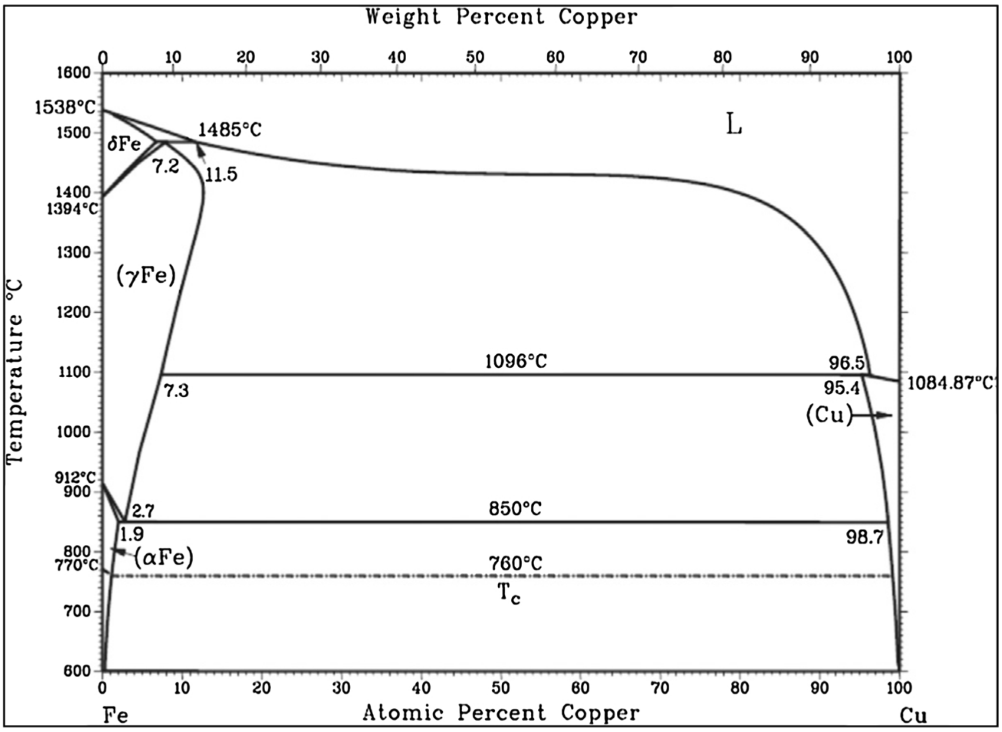

Figure 1: Fe-Cu phase diagram (Mai and Spowage 2004)

In this article, the state-of-the-art of welding of copper and steel is presented. Different approaches adopted for achieving successful joining of them are analyzed. The joint microstructure and mechanical properties of the joints are critically discussed. Finally, the article is summarized with some suggestions for future research.

1.1. Different welding techniques

1.1.1. Laser welding

Laser welding is one of the most used fusion welding techniques for dissimilar welding. Laser welding of copper and steel is usually performed by offsetting the laser beam on the steel side (Figure 2), as the melting temperature of steel is much higher than copper.

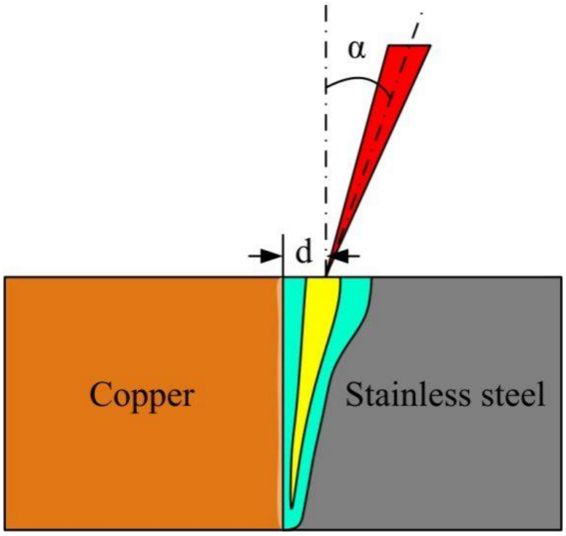

Figure 2: Schema of laser welding of copper and steel (Chen et al. 2015)

Mai and Spowage (2004) used Nd-YAG laser as the heat source focusing on the steel side to weld copper and tool steel. They observed that due to the low heating of copper, a very thin interface zone (~70µm) with the presence of micro-pores was formed. Chen et al. (2015)

adopted two different techniques of welding, such as fusion mode and welding-brazing mode, by changing the laser beam offset and compared the joints obtained by those approaches. They observed liquid phase separation in fusion mode and consequent reduction in interface hardness as compared to welding-brazing joint. Also, the high melting of copper in fusion mode resulted in the deterioration of joint toughness. Further microstructural analysis revealed Scraggy morphology in the welding-brazing joint due to the cooling of molten steel by cold copper. However, micro-cracks were evident in fusion joining which were eventually filled by molten copper (Chen et al. 2013). Yao et al. (2009) welded copper and E235A steel of different thicknesses by CO_2 laser. They used different process parameters such as laser power, offset in steel, weld geometry, etc., and evaluated the amount of copper at the fusion zone. The high ratio of copper at the stir zone resulted in a thick fusion zone, but a significant amount of porosity was also evident. However, low dilution of copper resulted in a pore-free fusion zone (Figure 3).

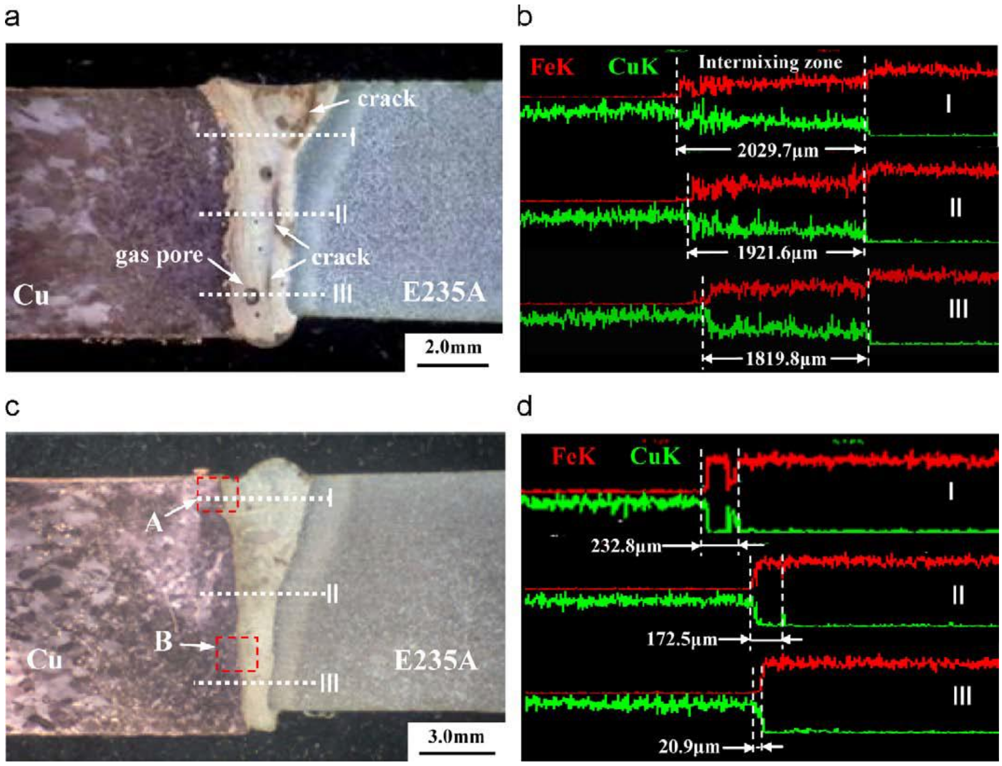

Figure 3: (a, c) Microstructure and (b, d) corresponding elemental distribution of laser welded copper and steel, (a, b) thinner plate, (c, d) thicker plate (Yao et al. 2009)

Weigl and Schmidt (2010) used pulsed Nd:YAG laser with a moving heat source for spot welding of copper and stainless steel. Although symmetric weld morphology was achieved, porosity at the weld zone was inevitable. By using a continuous CO_2 laser to weld copper and pure iron, Phanikumar et al. (2005) observed different microstructural modifications on both sides of the weld. Jagged microstructure of weld zone, iron-rich banded rings at copper indicated convective material flow leading to mixing of iron and copper. Kuryntsev, Morushkin, and Gilmutdinov (2017) used fiber laser to weld copper and austenitic stainless steel and observed that porosity, micro-cracks and copper penetration were evident in the joints. The defect-free joint yielded moderate electrical conductivity as compared to copper and steel. Mannucci et al. (2018), during laser (Yb:YAG laser) welding of copper and 316L stainless steel, observed that high laser power led to hot cracking at the weld zone. They also concluded that the level of copper penetration significantly reduced the corrosion resistance of the welded joints Copper penetration at the weld zone was also observed by Moharana et al. (2020) during laser welding of copper and AISI 304 stainless steel.

1.1.2. Electron beam welding (EBW)

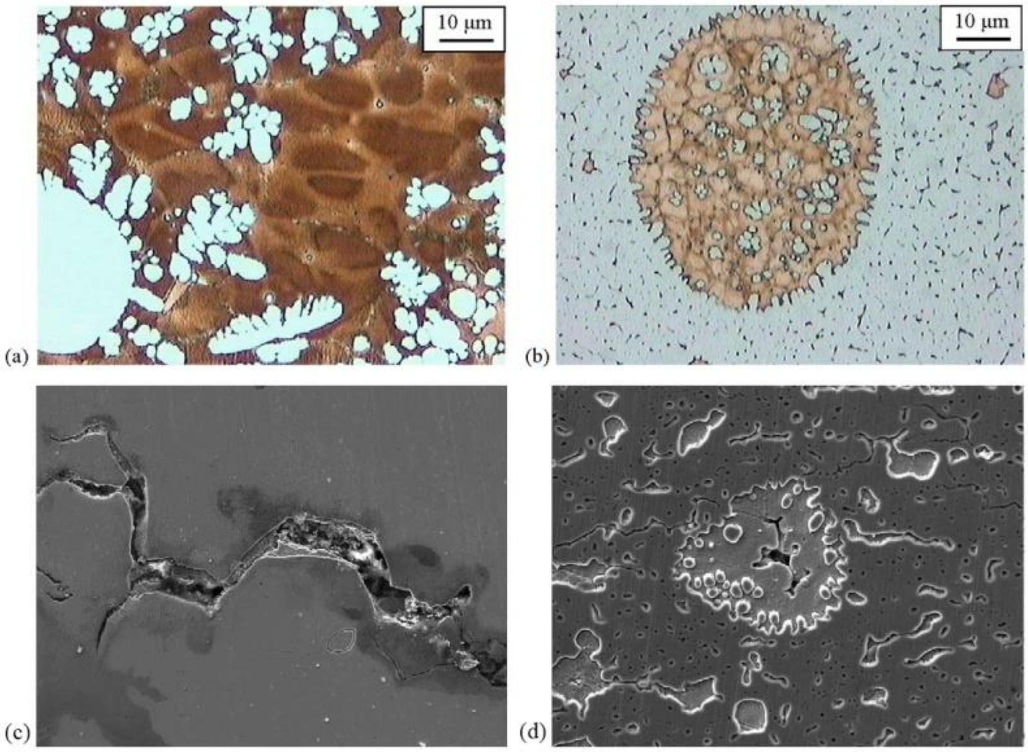

Figure 4: (a, b) Globules of steel and copper in weld zone, (c, d) microcracks and porosity (Magnabosco et al. 2006)

Tosto et al. (2003) attempted EBW of copper and 304L and observed non-equilibrium phases at the weld zone, which made the overall welding unstable. Magnabosco et al. (2006) also observed poor weld zone during EBW of copper and austenitic stainless steel. They observed porosity and microfissures along with solidification cracks at the fusion zone. Also, globules of copper and steel were observed in a separate state from the steel and copper matrix, respectively (Figure 4). Guo et al. (2016) also observed globular phase separation during EBW of copper and 304 stainless steel with an offset focus of electron beam on the copper side. However, other defects, such as cracks and porosity, were minimized with low beam offset, and the joint resulted in high strength.

Kar et al. (2018) and Kar, Roy, and Roy (2016) observed that with proper beam oscillation parameters, the globular phase separation, cracks, and pores were significantly reduced in EBW of copper-304 stainless steel joints. The size and number of pores were decreased, and high strength joint was achieved. Zhang et al. (2015), during EBW of QCr 0.8 copper alloy and 304 stainless steel, observed that the addition of copper filler at the weld interface reduced the residual stress on either side of the joint.

1.1.3. Tungsten inert gas welding (TIG)

TIG welding is the most used conventional fusion welding technique for welding copper and steel. Munitz (1995) joined copper and stainless-steel pipes through the TIG welding technique and observed the phase separation of copper and steel in the molten pool and their solidification of them as distinct phases. The high cooling rate associated with TIG welding process resulted in phase separation. Soysal et al. (2016) also observed phase separation in TIG weld zone of copper and low carbon steel. They also observed horizontal layers in the weld zone formed during the cooling of thick plate. Chang et al. (2017) welded stainless steel with copper and copper alloy by TIG welding process and observed that the major alloying elements of steel, such as Fe and Cr were mixed with copper. Therefore, clusters of grains containing Fe and Cr were visible in the copper matrix. Several researchers used filler material to achieve successful welding of copper and steel. Shiri et al. (2012) used different filler materials for TIG welding of copper and 304 stainless steel. They concluded that the use of copper filler yielded defect-free welding with high joint strength, whereas the use of 304 stainless steel filler and Ni-Cu-Fe filler resulted in a crack at the weld zone. Saranarayanan, Lakshminarayanan, and Venkatraman (2019) used ErNiCu-7 as filler material to join copper and 304 stainless steel. They concluded that the cooling was majorly influenced by the filler, and therefore different solidification mechanisms occurred at different portions of the fusion zone. As a result, different grain structures such as globular Fe, and dendritic Fe grains were visible (Figure 5).

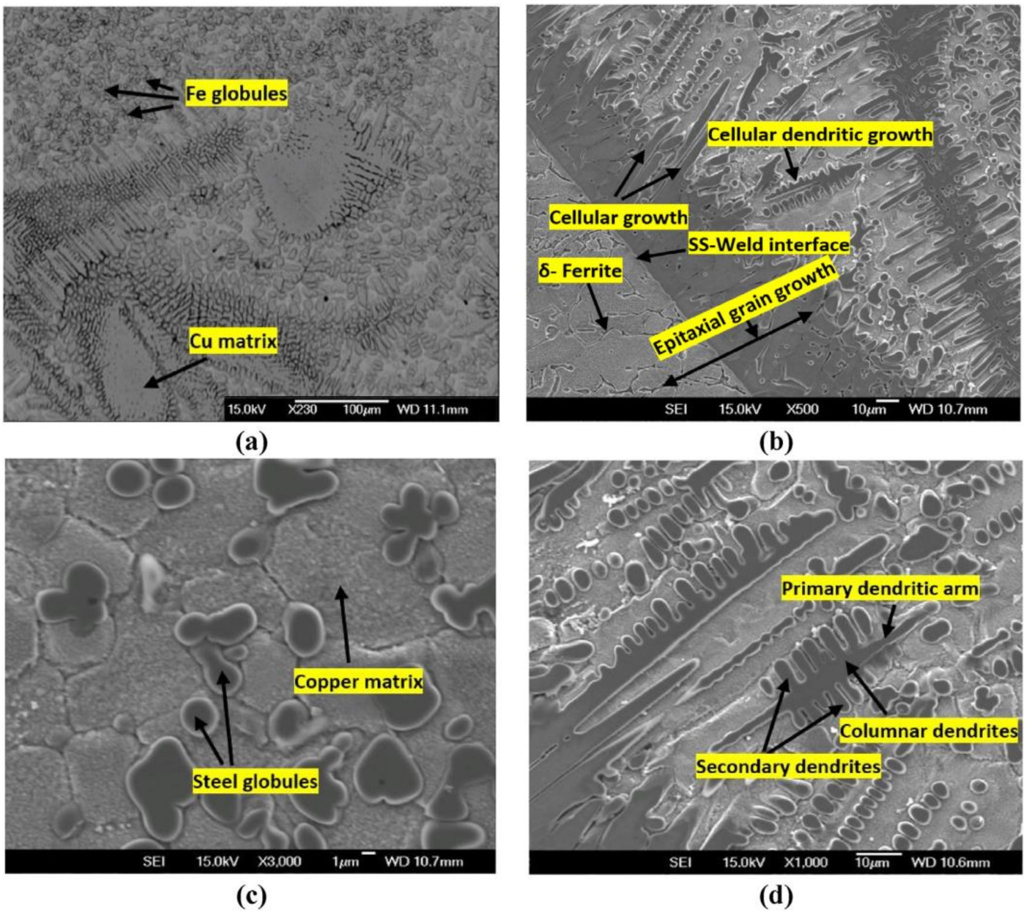

Figure 5: Different grain modifications at various regions of fusion zone in TIG welded copper-stainless steel joint
(Saranarayanan, Lakshminarayanan, and Venkatraman 2019)

1.1.4. Other fusion welding techniques

Velu and Bhat (2013) observed that for Metal Inert Gas (MIG) welding of copper and EN31 steel, nickel-based filler resulted good joining of them, whereas bronze-based filler resulted in porosity and cracks at the weld zone. In the nickel-based joint, intermetallic diffusion was also evident, indicating excelled joining between the weld materials. Asai et al. (2012) adopted a hybrid MIG and plasma welding technique to join copper and steel (Figure 6). They suggested that the hybrid process was a feasible welding technique for the dissimilar pair. Cheng et al. (2019) used ERCuSi-A filler for double-side MIG-TIG hybrid welding of copper and stainless steel (Figure 7). They observed that welding in fusion mode resulted in scraggy interface with significant strength reduction at HAZ. The welding-brazing mode yielded defect-free joining with diffusion of weld material in each other.

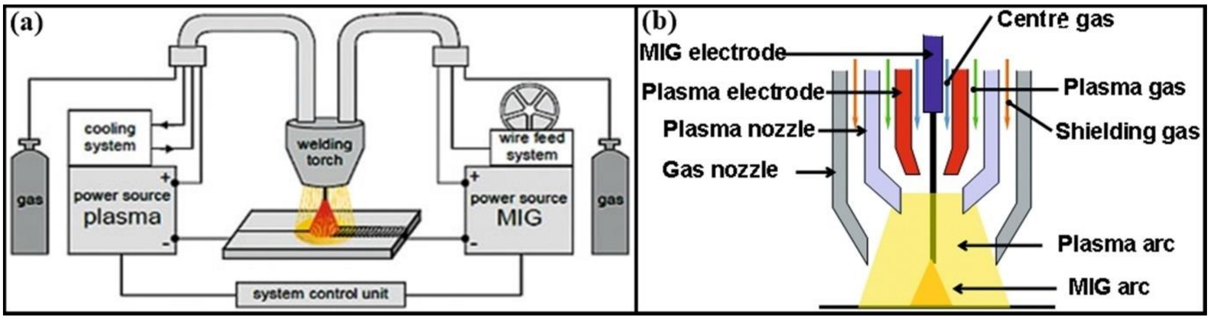

Figure 6: (a) Plasma-MIG hybrid welding setup, (b) nozzle configuration for the welding (Asai et al. 2012)

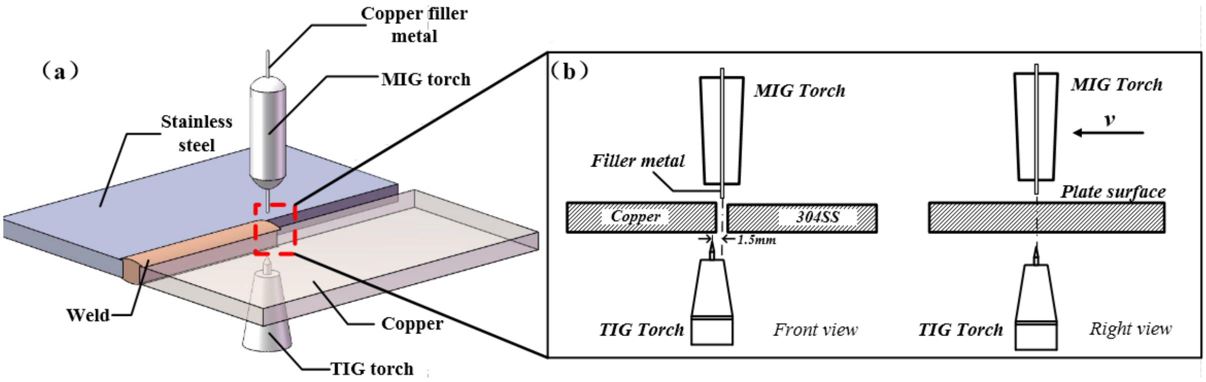

Figure 7: Schema of TIG-MIG double side welding (Cheng et al. 2019)

1.1.5. Explosive welding

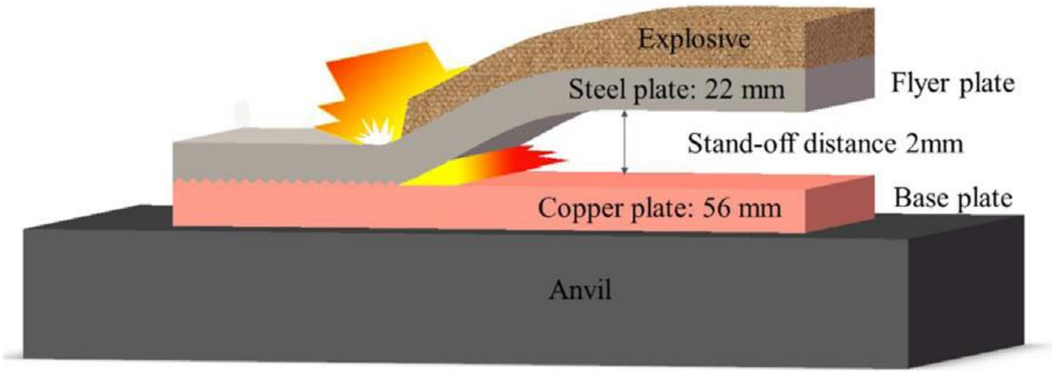

Figure 8: Schema of copper-steel explosive welding (Zhang et al. 2018)

In explosive welding of copper and steel, generally, copper is used as the base plate, and steel is used as the flyer plate, as shown in Figure 8. Durgutlu, Gülenç, and Findik (2005) welded copper and steel plates by explosive welding and observed a wavy interface with a high explosive ratio and high stand-off-distance as compared to flat interface for low parameters. They also concluded that the wavy interface exhibited higher mechanical strength. A similar observation was made by Bina, Dehghani, and Salimi (2013) while welding copper and 304L stainless steel. However, they analyzed the joint interface and concluded that diffusion of weld materials did not occur in the explosive welding of copper and steel and the joint failed in brittle manner in a tensile test. Therefore, to strengthen the bonding, they annealed the weld, resulting in the formation of a thick diffusion zone at the interface (Figure 9). Also, the annealed joint fractured in ductile manner. Zhang et al. (2018) examined the explosive welded and annealed copper-steel joint and observed two different features at the wavy joint interface. A thinner (~5µm) solid state joint and a wider (~50µm) vortex flow was evident at the interface. During the tensile test, crack propagated in the copper, indicating the wavy interlayer's excelled property.

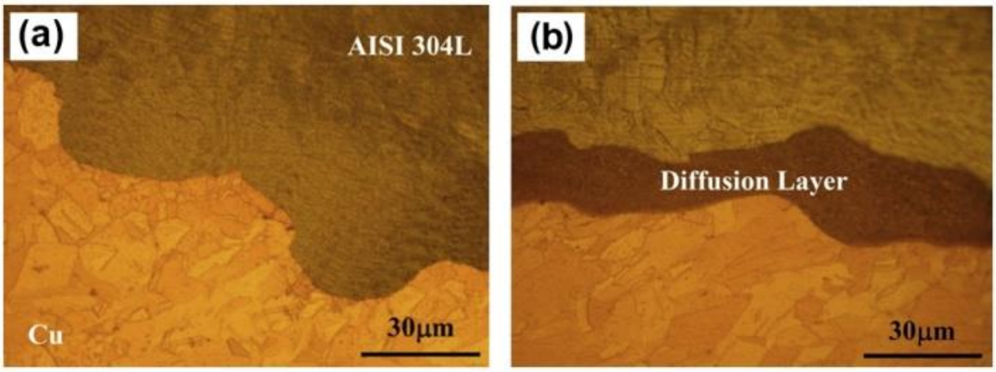

Figure 9: Copper-steel explosive welded interface, (a) as-welded, (b) after annealing (Bina, Dehghani, and Salimi 2013)

1.1.6. Friction welding

Friction welding is also proven to be efficient for copper and steel welding. Luo et al. (2012) observed intermetallic diffusion during radial friction welding of brass and high carbon steel. However, the extent of Fe diffusion in copper was higher than the copper diffusion in Fe (Figure 10). A smooth interface was formed with some 'furrow-shaped' holes due to reduced friction in brass at semi-solid state. Wang et al. (2013) also observed elemental diffusion and consequent formation of Cu_9Si and $FeCu_4$ during radial friction welding of T3 copper and steel. Although the intermetallic phases were not distinctly visible in the micrograph, the XRD analysis indicated the formation of the intermetallic compounds (Figure 11a). The formation of the intermetallic resulted in strong metallurgical bonding between the weld materials. They also observed that recrystallization hardening did not occur at the weld interface due to plastic deformation during welding. Sahin, Çıl, and Misirli (2013) also observed the formation of $FeCu_4$ along with Cu_2NiZn at the weld interface of friction welded 304 stainless steel and copper (Figure 11b). However, they observed that the Fe diffusion was limited only to the interface zone. The breaking of the copper oxide layer at the interface led to the formation of 'dirt repellent surfaces' (Sahin, Çıl, and Misirli 2013).

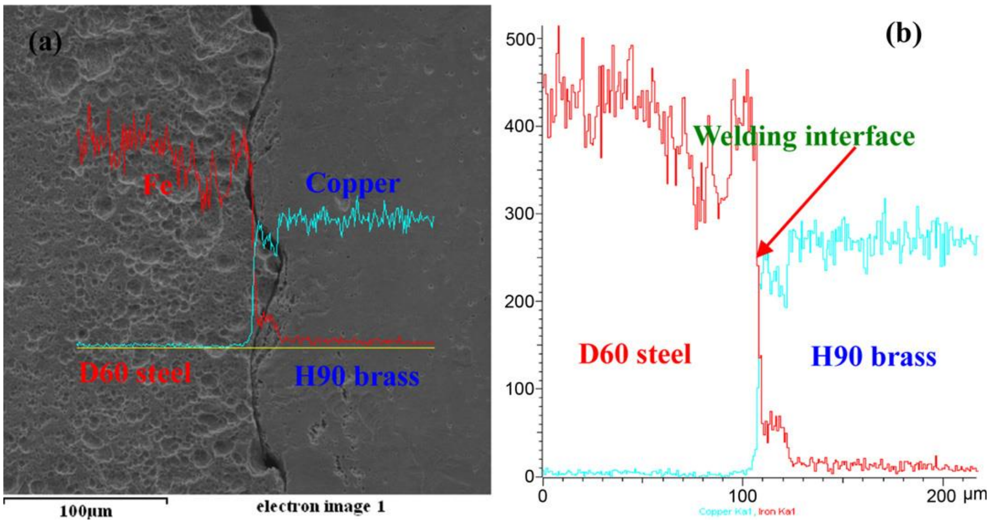

Figure 10: Radial friction welded brass-steel joint and corresponding elemental distribution (Luo et al. 2012)

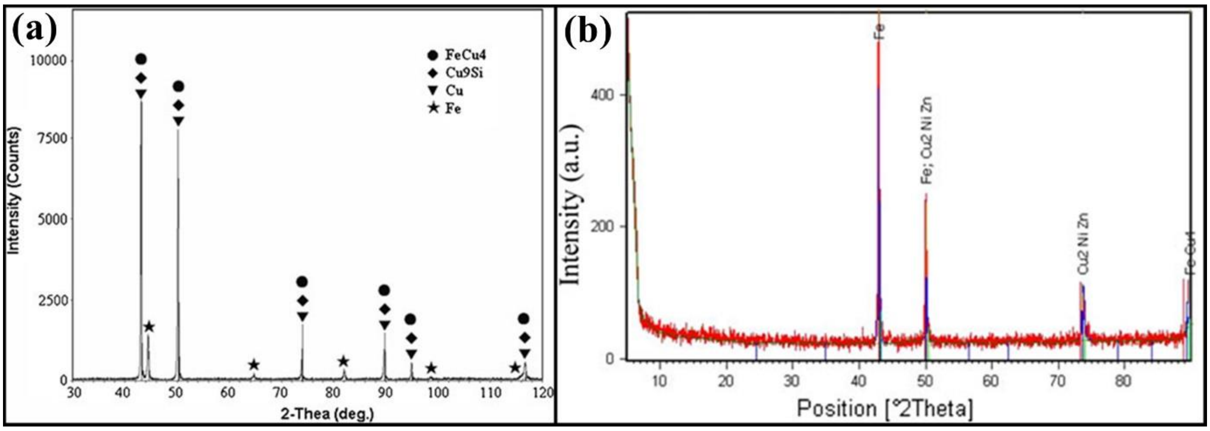

Figure 11: XRD analysis of friction welded copper-steel joints
(Wang et al. 2013; Sahin, Çıl, and Misirli 2013)

1.1.7. Other solid-state welding techniques

Yilmaz and Çelik (2003) adopted diffusion bonding to join copper and 304 stainless steel and observed good thermal and electrical conductivity in the welded structure. However, the interface consisting of intermetallic alloy exhibited superior electrical conductivity and modified thermal conductivity. The detailed analysis of the interface suggested that the intrinsic diffusion coefficient of copper was higher than steel. Therefore, the intersection of elements shifted towards copper from the original interface. Pure copper and low carbon steel were welded by He et al. (2016) using the ballistic impact welding technique. The frictional heat associated with the impact welding resulted in the annealing of copper near the joint interface and a wavy interface was formed. The elemental analysis revealed that diffusion of elements was restricted only in the vicinity of the interface and the interface was free of intermetallic compounds (He et al. 2016). Kore et al. (2011) employed electromagnetic impact welding to join copper and stainless steel and observed grain compression near the interface. Also, due to the entrapment of oxide, voids were observed away from the coil. The vacuum brazing technique was adopted for joining pure copper and 304L stainless steel by Choudhary, Laik, and Mish (2017) while using silver-based filler and an additional Ni coating on stainless steel. They observed that at low brazing temperatures, Ni coating led to defect-free joining with layered interface. However, high-temperature brazing led to crack formation at the interface due to differences in elemental diffusivity and thermal stress. Friction stir welding was also successfully used to weld copper and stainless steel by Jafari et al. (2017). Grain refinement at the interface and grain coarsening at the HAZ was evident in the welded joints. Also, diffusion of Ni from steel to copper was detected from the elemental analysis (Jafari et al. 2017). Bhogendro Meitei et al. (2018, 2020) used induction welding to weld copper with different steels and observed diffusion of copper and iron on either side of the interface. Owing to the diffusion, intermetallic compounds, as well as different oxides, were formed at the interface. However, a few micro-voids and micro-cracks were also evident.

1.2. Comparison of different techniques

The mechanical behavior of copper-steel welded joints fabricated by different methods is compared to understand the effect of different welding techniques. The typical microhardness distribution of laser welded copper and steel joints (Figure 12a) suggests negligible distortion in both steel and copper HAZ as the hardness of HAZs is almost similar to the respective un-welded materials. The interface microhardness is intermediate to the copper and steel microhardness and hardness gradient from the steel side to the copper side is also observed (Chen et al. 2015; Weigl et al. 2010; Kuryntsev, Morushkin, and Gilmutdinov 2017; Moharana et al. 2020). However, an enhancement in the microhardness of steel and copper due to induced residual stress may also occur (Mai and Spowage 2004). The microhardness gradient at the weld interface largely depends on copper melting and can be omitted by performing welding-brazing join (Chen et al. 2015). EBW of copper and steel also yields similar microhardness distribution profile with gradient in the weld zone (Figure 12b), which can be minimized by offsetting the electron beam. However, unlike laser welding, a significant reduction in microhardness at HAZ of copper is evident in the EBWed joints (Kar, Roy, and Roy 2016; Magnabosco et al. 2006; Guo et al. 2016). TIG welding of copper and steel leads to softening at HAZ in both copper and steel (Figure 12c) (Chang et al. 2017; Saranarayanan, Lakshminarayanan, and Venkatraman 2019). However, the selection of proper filler may eliminate the softening effect (Shiri et al. 2012). The fusion zone of the TIG welded joints exhibits a nearly homogeneous distribution of microhardness (Shiri et al. 2012; Saranarayanan, Lakshminarayanan, and Venkatraman 2019; Chang et al. 2017). Other fusion welding processes, such as for double side MIG-TIG hybrid welding and MIG welding, result in uniform microhardness distribution in the fusion zone. However, the hybrid welding yields softening of copper up to 15 mm away from the weld zone, whereas (Figure 12d) MIG welding with Ni filler enhanced hardness in steel HAZ (Cheng et al. 2019; Velu et al. 2013). Explosive welding of copper-steel pair leads to enhancement of hardness in the weld materials due to strain hardening imposed during the collision (Figure 12e). Owing to the strain hardening, the interface of an explosive welded joint may exhibit higher hardness than the weld materials' hardness, depending on the amount of copper diffusion (Zhang et al. 2018; Bina, Dehghani, and Salimi 2013). Enhancement of microhardness in the vicinity of the weld interface by work hardening is also evident in the induction welding of copper and steel (Figure 12f) (Bhogendro Meitei et al. 2018; Bhogendro Meitei et al. 2020). In friction stir welding, the interface microhardness is observed to be higher than the un-welded materials due to intense grain refining (Figure 12g) (Jafari et al. 2017). However, other solid-state processes, such as friction welding and impact welding, result in no significant change in the weld material microhardness and a sharp transition of hardness from steel to copper side is observed (Figure 12h) (He et al. 2016; Kore et al. 2011; Sahin, Çıl, and Misirli 2013).

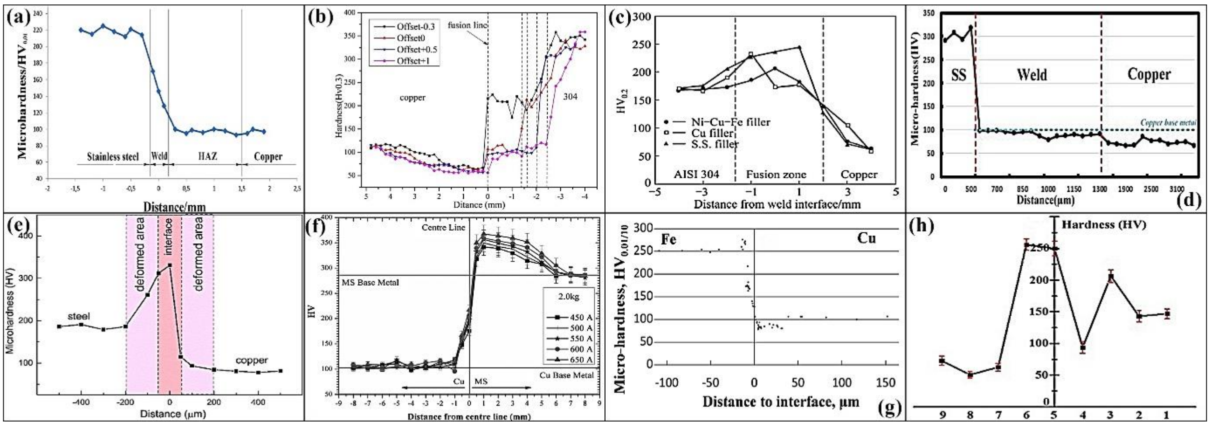

Figure 12: Comparison of microhardness distribution in copper-steel joints obtained by different processes (a) laser welding, (b) electron beam welding, (c) TIG welding, (d) MIG-TIG hybrid welding, (e) explosive welding, (f) induction welding, (g) friction stir welding, (h) ballistic impact welding (Zhang et al. 2018; Shiri et al. 2012; Kuryntsev, Morushkin, and Gilmutdinov 2017; Jafari et al. 2017; He et al. 2016; Guo et al. 2016; Cheng et al. 2019; Bhogendro Meitei et al. 2018)

The tensile strength of the laser welded copper-steel joints depends on the process parameters and laser beam offset. Depending on the amount of heat input, the fracture of laser welded copper-steel joints occurs at weld zone or HAZ of copper (Chen et al. 2015; Yao et al. 2009; Kuryntsev, Morushkin, and Gilmutdinov 2017; Mannucci et al. 2018; Moharana et al. 2020). As high as 93% of copper tensile strength may be achieved by laser welding of the pair (Kuryntsev, Morushkin, and Gilmutdinov 2017). In EBWed copper-steel joints, ductile fracture takes place at HAZ of copper or in the fusion zone, depending on the mode of joining. The EBWed copper-steel joint can exhibit a maximum of 97% of the tensile strength of copper (Guo et al. 2016; Kar, Roy, and Roy 2016). In the case of TIG welded joints, during tensile loading, fracture takes place at the HAZ of copper and a maximum of 96% of copper strength can be achieved (Shiri et al. 2012; Saranarayanan, Lakshminarayanan, and Venkatraman 2019). For double-side MIG-TIG hybrid welding of copper and steel, 84% joint strength can be achieved, whereas MIG welding of the pair results in 79% joint strength (Velu et al. 2013; Cheng et al. 2019). In defect-free explosive welded joints, fractures occur on the copper side away from the weld interface, and due to the strain hardening effect strength of the joints may be even higher than in unwelded copper (Bina, Dehghani, and Salimi 2013). Among other solid-state welding techniques, friction stir welding results in nearly 80% joint strength, whereas induction welding may exhibit almost 100% joint strength (Bhogendro Meitei et al. 2020; Jafari et al. 2017).

1.3. Corrosion behavior of welded joints

The corrosion resistance of steel, especially stainless steel, derives from the passivation layer generated by chromium; copper is a corrosion resistive material in the chemical environment and in the atmosphere. However, in the copper-steel welded structure, the different nature of the metals creates a galvanic couple which results in localized corrosion. Mannucci et al. (2018) observed that in laser welded copper-steel structure, the amount of copper in the weld zone determined the corrosion behavior of the joint in salt water. They also found that in copper-rich zones, severe intergranular corrosion occurred. Xu et al. (2021) also found similar severity of corrosion in the copper-rich zone for TIG welded copper-steel joint in $CuSO_4$ and H_2SO_4 solution. They observed that in the welded structure, corrosion resistance was higher in steel and lowest in copper, whereas the welded zone yielded intermediate corrosion resistance. In the welded zone, the γ-Fe rich phase acted as cathode and ε-Cu rich phase acted as anode, which created micro-galvanic couples in corrosive medium. Due to the galvanic couples, the anodic copper was dissolved rapidly and formed corrosion pits.

2. Summary and Future Research Directions

Several welding techniques adopted for copper-steel joining are discussed in this article. The microstructural features achieved by different processes are critically analyzed.

Laser welding of copper and steel requires precise offsetting to achieve defect-free joining, whereas copper dilution controls the weld bead appearance. Liquid phase separation is one important aspect of the electron beam welding process, which must be controlled with proper parameter selection to achieve sound welding. TIG and other fusion welding processes can also produce defect-free joints with proper filler material. Solid state processes such as explosive welding, friction welding, etc. also yield good joining of copper and steel by diffusion of alloying elements. Owing to the diffusion of elements in solid state welding processes, a few intermetallic compounds, such as $FeCu_4$, Cu_9Si, and Cu_2NiZn, formed in the joint interface. The compounds aid in achieving good metallurgical bonding between the weld materials.

The microhardness distributions of the joints obtained by different processes suggest softening of copper at HAZ in fusion welding processes such as laser welding, electron beam welding, TIG welding, etc. The weld zones of fusion welded joints exhibit intermediate microhardness of copper and steel with a gradient from the steel side to the copper side. However, the softening of copper is not evident in solid-state weldings except in friction welding. Also, a sharp decrease from interface microhardness to copper microhardness is evident in solid-state welded joints. Among fusion welding processes, electron beam welded copper-steel joints exhibit higher tensile strength, whereas, among solid-state weldings, explosive welding of the pair may result in achieving tensile strength even higher than unwelded copper.

The majority of the available literature is focused on the welding of copper with stainless steel and the mechanical performance of the joints. Emphasis of further research may be given to welding of other engineering steels and different copper alloys. Also, more in-depth microstructural characterization such as grain orientations, residual stress, etc. may be analyzed thoroughly to understand the joints performance in detail. The formation of intermetallic compounds in the weld interface and their consequent effects on weld properties, especially in solid-state welding, may be analyzed. In addition, other performance measures, such as corrosion resistance, high-temperature performance, etc., may be evaluated in detail.

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