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Review

Brazing of high-strength steels: Recent developments and challenges

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ABSTRACT

Zinc-coated high-strength steels (HSS) and advanced high-strength steels (AHSSs) are widely employed in automobile body manufacturing owing to their impressive metallurgical and mechanical characteristics. However, acquiring defect-free and mechanically sound welding joints is still quite challenging due to the formation of various defects, namely porosity, loss of coating, and the evolution of undesired microstructural phases in both the heat-affected zone and the fusion zone. The higher heat input during conventional fusion welding processes tends to exacerbate these challenges. Brazing, sometimes referred to as weld-brazing, is a comparatively new joining process that offers the ability to join thin and zinc-coated steel sheets with a significantly lower heat input using a compatible lower melting temperature filler wire, has been proposed as an alternative to fusion-based joining techniques. However, under-matching, i.e., mechanically weaker brazing filler than that of the base metal, limits the widespread application of brazing. In this regard, several developments have been reported to overcome under-matching by changing the filler composition, coating composition, and joining methodology. This comprehensive review highlights the key challenges associated with steel-to-steel brazing, while offering a detailed survey of various methods that can be used to improve the performance of brazed joints.

1. Introduction

To meet current economic and environmental demands, automobile manufacturers are adopting strategies such as lightweight design and hybrid/multi-material construction of automotive structures [1–3]. These approaches, although quite challenging, allow for more efficient utilization of resources. While materials like aluminium [4], magnesium [5], and fibre-reinforced composites offer desirable traits such as corrosion resistance and high specific strength, there are certain limitations to their use in the automobile industries. Steel remains the most widely used material in vehicle structures due to its superior mechanical properties which enhance crashworthiness and improve passenger safety [6]. High-strength steels (HSS) and advanced high-strength steels (AHSS) provide an attractive balance of sufficient weight reduction and better mechanical properties in structural components, making them one of the more efficient alternatives for improving fuel efficiency of the automobiles [7,8]. According to Reisgen et al. [9], HSS with reduced sheet metal thickness constitute a possibility for lightweighting while simultaneously improving the strength of automobile structures. HSSs such as complex phase (CP), dual phase (DP), and Transformation Induced Plasticity (TRIP) variants are composed of specific microstructural phases which need to be systematically controlled during the production and subsequent manufacturing processes. The systematic manipulation of microstructural phases is crucial for ensuring the desired material characteristics, highlighting the importance of precision and consistency in the production and processing of these advanced high-strength steels.

Since the specific microstructures of high-strength steels require systematic processing, the key challenge for conventional joining methods is to preserve these microstructural features to obtain mechanically and metallurgically sound welded joints. Given the high thermal impact of traditional fusion welding processes, the fusion zone, and its surrounding heat-affected zone (HAZ) suffer from undesired microstructural evolutions [10,11]. Zinc-coated AHSSs have satisfied the current needs of the automobile industry as they provide an interesting combination of good mechanical strength, low stretchability, good corrosion resistance and weldability [3,12,13]. Although, other types of coatings do exist, like Al—Si coatings, which are widely

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employed in hot-stamping applications [14–18], different compositions of Zn-based coatings continue to dominate in the automobile industries [14–18]. Welding zinc-coated sheet metal using conventional welding methods (i.e., arc and laser) presents considerable difficulties due to vaporization of Zn at relatively low temperatures, resulting in welding defects like porosity in fusion zone, undesired bead geometry, spatter, loss of corrosion protection in the vicinity of the joint, and hardness variations in both the weld and HAZ [19,20]. All these defects ultimately affect the integrity of the joint and therefore, lead to lower productivity, and the need for more rework, as well as increased post-weld processing [21].

Resistance spot welding (RSW) is a commonly employed process in industries for joining coated and uncoated steel sheets. However, the formation of brittle and hard intermetallic phases at the tip of the copper electrodes has been reported during the joining of Zn-coated sheets. This occurs due to the interaction with the zinc coating, which deteriorates the electrode and, consequently, limits its widespread application for joining zinc-coated steel sheets [22]. Excessive wear of the electrode affects the productivity as well as cost of the automotive welding assembly lines in an adverse manner due to poor weld quality, robustness, and reliability [23]. Emre and Kaçar [24] investigated the effect of different coatings during RSW of steel and reported that tip of the copper electrode is susceptible to the formation of brittle and hard intermetallics because of its interaction with the Zn coating, resulting in sticking of electrode caused by local bonding with the workpiece. William and Parker [25] and Parker et al. [26] reported that failure of these localized bonds, composed of brittle intermetallics, eroded the surface of copper electrodes, leading to an enlargement of diameter of electrode tip and, ultimately, the failure of the copper electrode. Frequent replacement of electrodes during RSW leads to higher production costs and quality issues. Therefore, the current emphasis in the automobile sector is on the development and exploration of alternative joining processes that minimize thermal impact on zinc-coated high-strength steel sheets, aiming to achieve better joint properties.

As an alternative to conventional welding processes, brazing/weld-brazing, which is a relatively novel and low heat input process, has been proposed. This process combines the features of traditional welding heat sources (i.e., high welding speed, simple automation, and high deposition rate) with those of conventional brazing processes (i.e., low heat input and negligible melting of the base metal) [27]. There are several types of brazing processes, depending on the category of welding heat source used, i.e., arc, laser, or laser-arc hybrid. In the case of the gas metal arc brazing (GMAB), the same experimental setup can be employed as for conventional GMA welding; the only difference is the composition of the filler wire [28]. Arc brazing processes ensure comparatively lower heat input as well as the ability to join thin zinc-coated sheets without creating a large HAZ or significant warpage in the brazed components [29–31]. Generally, copper-based fillers are employed for brazing high-strength steels due to their advantageous characteristics, which include good metallurgical compatibility with steels, high thermal conductivity, excellent fluidity and wettability, high corrosion resistance, and good ductility. Moreover, copper exhibits favourable metallurgical compatibility with multiple alloying elements like aluminium, silicon, and manganese, ultimately enhancing the strength of the brazed joints [32]. Way et al. [33] reported that Cu is a common constituent of many filler wires for brazing owing to its good wettability. The choice of filler material primarily depends on the materials being joined, the application of the joint, and the desired properties of the joint. Despite the benefits of copper-based fillers while joining steels, alternative filler materials can also be considered based on factors such as wettability, availability, cost, brazing process, brazing temperature, filler metal form, and compatibility with steel. In addition to GMA brazing, laser brazing is a well-established technique for joining coated steels in automobile industries [34–38] but it has certain limitations such as lower stability, spatter, and formation of wavy edges at higher joining speeds which may affect the productivity, as well as the quality of brazed joints [39–42].

During GMAB, joining takes place via the inter-diffusion of atoms, without any noticeable melting of the base material, preventing considerable damage to the coating and mechanical behaviour of steels. Both, GMAB and its extension, cold metal transfer brazing (CMTB), have drawn significant attention from automobile industries for joining thin Zn-coated steel sheets. The low thermal impact, i.e., heat input, and the high joining speed, achieved by using non-ferrous (Cu-based) filler materials with a melting point significantly lesser than that of steel, are some of the attractive features of GMAB and CMTB processes. These characteristics allow them to be efficient solutions for joining heat-sensitive materials in the automobile industry. In practice, brazing procedures may vary as per the joining requirement. Therefore, it is essential to investigate the integrity of brazed/weld-brazed joints under different loading/service conditions which will be useful in identifying the most appropriate joining parameters required for a particular joining application. The configuration of the joint is a crucial factor to consider during brazing. Lap brazing is preferred over butt brazing for several reasons, including the larger surface area available for bonding between the filler and steel in the lap configuration. This, in turn, results in faster heat dissipation from the joint, satisfactory strength, and ensures a leakproof joint. Additionally, lap joints exhibit lower sensitivity to fit-up variations and gaps. On the other hand, butt joints have limited surface area and are more sensitive to fit-up variations and gaps, making it challenging to achieve a leakproof joint.

Given the recency of the development of the joining process and the lack of existing standards on the use and regulation of brazing technologies, this review offers a critical look at the state-of-the-art regarding the use of brazing in the automotive industries to deliver vital insights into the influence of several processing parameters on the metallurgical and mechanical characteristics of brazed joints. Different cutting-edge and novel methods and techniques being used to improve the joint strength and performance of brazed joints have been reviewed and recommendations have been made regarding the scope for further developments within the field based on the research gaps that have been identified as part of this work.

2. Significance of arc brazing in automotive industries for joining high-strength steels

High-strength steels offer significant versatility as they exhibit specific microstructural features depending on variations in chemical composition and processing conditions. For example, DP steels are characterized by hard martensitic islands in a ductile ferrite matrix [18,19], while TRIP steels consist of the following microstructural phases: bainite and retained austenite within a soft ferrite matrix [43]. The fraction and nature of these microstructural phases can be significantly affected by the thermal cycle experienced during a given joining process, leading to potentially detrimental changes in the joint properties. Traditional joining methods such as gas tungsten arc welding (GTAW) [44], gas metal arc welding (GMAW) [45], and laser welding [46,47] may encounter issues related to unexpected microstructural evolution within the joints. These problems include blowholes, porosity, lack of fusion, undercut, spatter, unacceptable bead shape, thermal distortion, as well as a loss of corrosion resistance and increased hardness in the HAZ and fusion zone [10]. These challenges can significantly degrade the overall joint properties when welding high-strength steels.

Ahsan et al. [48] investigated the formation of porosity (pits and blowholes) during CMT welding of galvannealed steel sheets, as depicted in Fig. 1. The authors observed that as the heat input increased, the proportion of pores in the joints initially increased and then decreased. This phenomenon could be attributed to the lower temperature of the molten pool at medium heat inputs, causing increased resistance i.e. longer travel time for zinc vapors to reach the molten pool surface due to the higher viscosity of the molten filler metal. Consequently, the solidification of the deposited molten filler occurred before the escape of the

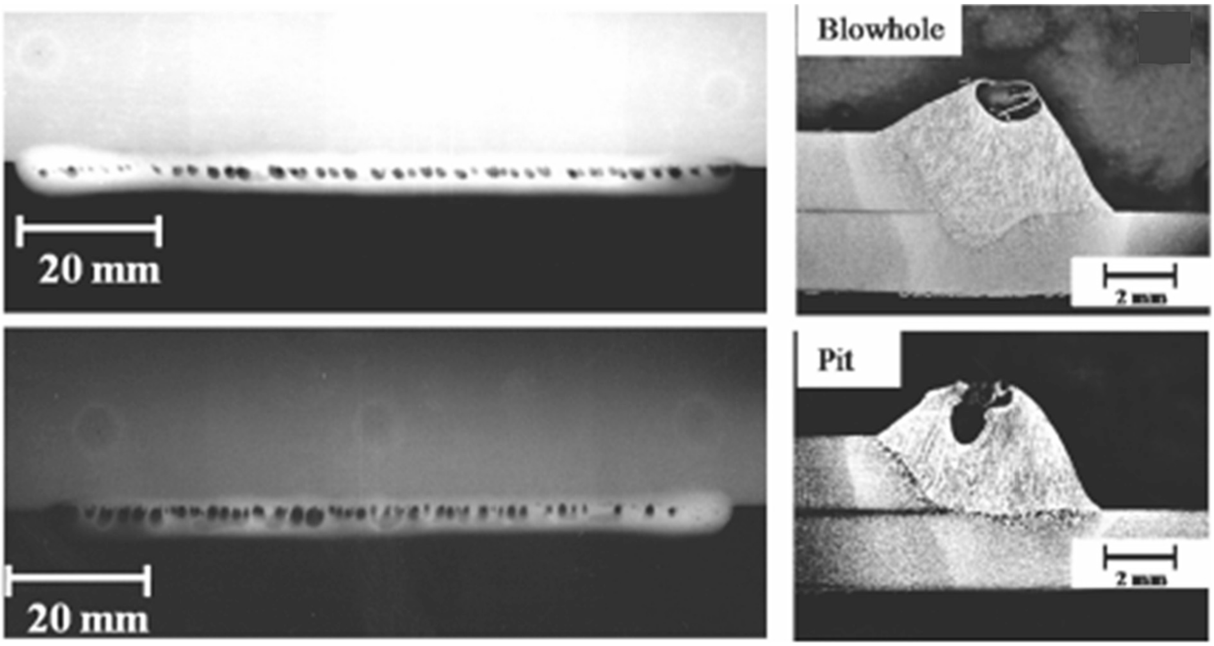


Fig. 1. Formation of porosity (blowhole and pit) in the joints during CMT welding [48].

zinc vapors, leading to pore formation. In some instances, irregular or partial escape of zinc vapors resulted in blowholes (i.e., pores open to the surface). Similar porosity issues have been reported by Yu and Kim [49] in CMT-welded joints, primarily due to the melting and vaporization of the zinc coating from the steel surface.

Kashani et al. [50] further investigated the joining of zinc-coated steels using laser welding, which exhibited porosity, spatter, and crater defects in the joints due to the inevitable vaporization of zinc caused by its low boiling point (871 °C). Notably, porosity formation and spatter are common issues encountered in conventional welding of zinc-coated steels, adversely affecting the integrity of the weld joints [51,52]. Therefore, to preserve the properties of high-strength steels, low heat input joining processes have been recommended to control undesired microstructural evolutions, especially in the HAZ. Additionally, the use of low heat input during welding helps suppress excessive melting and vaporization of the zinc coating from the steel surface.

An alternative process to join zinc-coated steels is brazing [27], which employs a copper-based filler wire with a comparably low melting point. The brazing process operates at lower temperatures, which reduces corrosion in joints, spatter, and zinc coating loss. It has also been reported that brazed joints experience reduced distortion compared to welded joints [28]. Fig. 2 provides a comparison of cross-sections of lap joints fabricated using welding and brazing processes. The images reveal several cracks and severe melting of base metal sheets in the case of welding, attributed to the higher thermal impact compared to brazing. Conversely, nearly flat interfaces in the brazed joints exhibit negligible melting of base metal [53].

Recent advancements in joining equipment have introduced variations of the GMAW process, such as GMA brazing, CMT brazing, cold arc brazing, and Surface Tension Transfer (STT) brazing, offering advanced low heat input joining methods [2,54]. Singh et al. [2] highlighted the STT method, developed by Lincoln™, which enables independent adjustment of short circuiting without varying wire feed rate (WFR) and voltage, allowing precise control of heat input by altering welding current only. Additionally, KEMPPI™ developed a unique power source-based control of material deposition to modify short-circuiting transfer [54]. The power source control regulates short-circuiting phenomenon and facilitates precise duration for the molten filler drop transportation from the tip of filler wire into the weld pool. Furthermore, EWM introduced the cold Arc technique to reduce heat input during the short-circuit phase. The main difference between cold Arc and CMT lies in the process of heat input reduction during short-circuiting. In CMT, it is mechanically controlled by the backward motion of the filler wire, while cold Arc uses electronic control. Kah et al. [54] also emphasized that the primary goals in the development of these joining processes were to suppress spatter, reduce heat input, and enhance process flexibility.

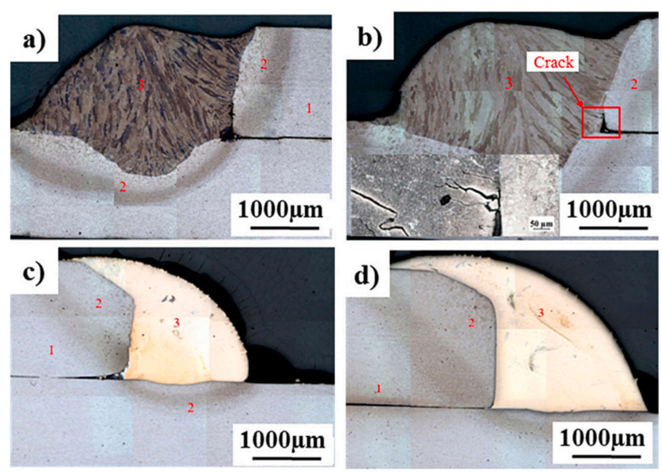


Fig. 2. Comparison of macrostructural features welding and brazing processes [53].

Despite extensive research on the joining of zinc-coated steels using low heat input processes, the challenge of porosity formation during arc brazing continue to persist. Sharma et al. [31] elucidated the porosity formation mechanism in brazed joints through a schematic diagram (refer to Fig. 3). The lower melting point of the zinc coating caused its melting as soon as the brazing arc made contact with the steel surface. Consequently, zinc vapors/fumes were generated, which adversely disturbed the brazing arc. The attempt of these zinc fumes to escape from the joint area was impeded by the deposition of the molten filler, leading to their entrapment and, subsequently, the formation of porosity in the deposited bead upon solidification. However, the lap configuration offered favourable conditions for joining zinc-coated sheets, as it provided an easy escape path for zinc fumes through the gap between

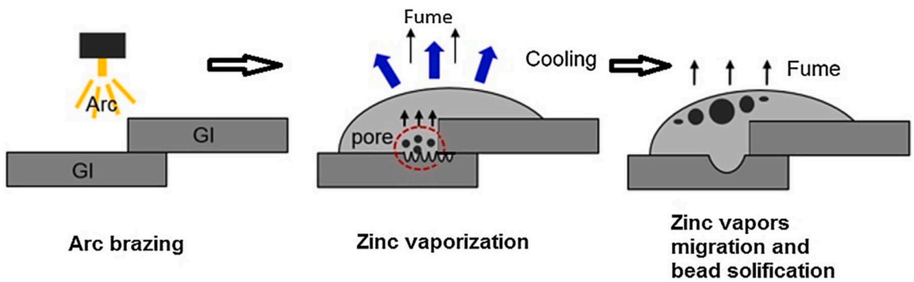


Fig. 3. Schematic showing formation mechanism of porosity in brazed joints [31].

faying surfaces [56]. To promote the efficient escape of zinc vapors, Akhter et al. [57] suggested incorporating a gap between the coated sheets in the lap configuration. Nevertheless, maintaining a precise gap during actual production proved to be a challenging task.

Arc brazing stands as a novel joining technology with relatively low thermal impact on the base metal, which helps to restrict undesired microstructural evolutions. Additionally, arc brazing exhibits advantages such as low component distortion and high corrosion resistance [58]. However, the automotive industry critically views the issue of under-matching, wherein a brazing filler of lower strength is utilized to join high-strength steel sheets. In addition, the penetration of copper along the grain boundaries of coated steels, poses a common challenge during the arc brazing of steels. Traditionally, brazed joints are supposed to be resistant to this phenomenon [59,60] but several researchers including Khan et al. [61], Singh et al. [32], and Shajan et al. [62] reported the penetration of Cu into the steel grain boundaries. It can further lead to a reduction in the ductility of the brazed joint, a phenomenon known as liquid metal embrittlement (LME) [61]. Cu penetration typically occurs due to limited mutual solubility between the liquid filler and steel, the absence of intermetallic phase formation at the interface, and the influence of internal or external stress. The steel microstructure also plays a crucial role in this phenomenon. Copper tends to wet ferritic steel less effectively than steels containing pearlite, austenite, or martensite, making the ferrite microstructure least susceptible to penetration of Cu [32,62–64]. Consequently, the industrial application of arc brazing is currently limited. The lack of an available database for mechanical properties, particularly achievable joint strengths, serves as a primary deterrent to the adoption of the brazing process in production.

Over the years, various research efforts have been made to efficiently join the high-strength steel sheets using various brazing process variants, such as laser brazing, GTAW brazing, and GMA brazing, in combination with various Cu-based filler wires, including Cu-Al-Ni, Cu-Si-Mn, Cu-Mn-Al [65], Cu—Si [66], and Cu—Al [32,67–69]. However, the challenge of under-matching, where the brazing filler exhibits lower strength compared to the high-strength base metal, remains a prominent concern during brazing. Chovet and Guiheux [65] successfully acquired 95 % joint efficiency using Cu based Al—Ni and Mn—Al enriched fillers during GMA brazing of DP600 steel. Additionally, they were able to achieve 100 % joint efficiency in case of 0.9 mm thick DP600 steel using 1.2 mm CuAl8 filler wire at 135 J/mm heat input. The composition of the filler wire was found to have a positive impact on the strength of the brazed joints. Basak et al. [21] reported a joint efficiency of 98 % during GMA brazing of DP600 steel (1.2 mm thick) using CuAl8 filler (1.2 mm diameter) at a heat input of 204 J/mm. The joint efficiency achieved in previous studies is summarized in Table 1. There are three possible brazing combinations: undermatching (filler strength < base metal strength), matching (filler strength ≈ base metal strength), and overmatching (filler strength > base metal strength), depending on the difference between the strength of the filler and the base metal used. Reisgen et al. [9] and Singh et al. [69] were able to achieve 100 % joint efficiency in cases of under-matching by using a filler strip between the overlapped steel sheets to be brazed. However, this insertion had a negative influence on the strength of lap joints, as it created gaps between the sheets and resulted in excessive bending of the samples during loading. Furthermore, the gap between the sheets had negligible impact on the wettability of the joints. Consequently, additional efforts are required to address the under-matching issue without compromising the integrity of brazed joints.

Table 1
Summary of the joint efficiency achieved by several authors during brazing of steels.

Authors	Grade of steel	Filler wire	Condition	Joint efficiency
Basak et al. [21]	DP600 (600 MPa)	CuAl8	Under-matching	98 %
Chovet and Guiheux [65]	DP600 and TRIP700 (600 and 700 MPa)	CuAl8, CuAlNi6, CuMn13Al7	Under-matching	DP600 (100, 95, 97 %) and TRIP700 (95, 60, 75 %)
		Mecufil 214Al	Overmatching	DP600 (100 %) and TRIP700 (90 %)
Makwana et al. [66]	IF steel (302 & 316 MPa)	CuSi3	Overmatching	100 %
Makwana et al. [66]	HIF steel (353 MPa)	CuSi3	Matching	80-90 %
Reisgen et al. [9]	HCT780XD (780-900 MPa)	CuAl8	Under-matching	100 % using iron filler strip
Basak et al. [70]	IF steel (~300 MPa)	CuAl8	Overmatching	100 %
Singh et al. [69]	DP780 (780 MPa)	CuAl10Fe	Under-matching	82 % without filler strip and 100 % with filler strip at184 J/mm
Singh et al. [68]	C-Mn-440 (440 MPa)	CuAl8	Matching	100 %
Singh et al. [32]	DP780 (780 MPa)	CuAl10Fe	Under-matching	100 % (by increasing the heat input to 266 J/mm)
Cho et al. [28]	GA-coated DP600 (600 MPa)	CuSi3Mn1	Under-matching	100 %
Khan et al. [30,73]	Zn-coated DP600 (600 MPa)	CuSi3Mn1	Under-matching	100 % for GA-coated DP600 70-80 % for GI-coated DP600

3. Influence of the geometrical and microstructural features on the integrity of brazed joints

The quality of a brazed joint is significantly influenced by the processing parameters and the wetting characteristics, along with the microstructural evolutions that occur when a molten braze/filler metal wets the steel surface [74,75]. To comprehend the influential parameters affecting the quality of brazed joints, a cause-and-effect diagram is depicted in Fig. 4.

While brazing may produce weaker joints compared to other welding processes, the strength of brazed joints can be enhanced through a thorough understanding of different influential factors such as geometrical features of the joint and microstructure. Geometrical parameters, including wetting length, bead width, bead height, and wetting angle, play a crucial role in determining the interfacial and cross-sectional area of lap brazed joints, thereby enhancing their resistance against deformation under loading. Similarly, the microstructure of the interface and the deposited bead significantly impact the failure load of the brazed joints. Both the geometrical and microstructural features are directly influenced by process parameters, such as feeding rate of filler wire, brazing speed, and position of torch, among others. In the subsequent discussion, the effects of various geometrical and microstructural features on the performance of brazed joints are expounded upon.

3.1. Shape/geometry of deposited bead

The shape and geometry of brazed joints are critical factors influencing the performance of steel-steel brazed joints. Several bead parameters, such as bead width (W), height (H), wetting length (L), wetting angle (θ), and cross-sectional area (A) (shown in Fig. 5), significantly impact the strength of lap brazed joints. The wetting or bonding length denotes the effective joining area between the deposited filler bead and the base metal sheet. The contact or wetting angle represents the angle formed between the surfaces of the solid substrate (steel) and the deposited liquid (molten filler) at the interface [76–78]. To achieve satisfactory lap joint strength, it is desirable to have a high wetting/bonding length and a low wetting/contact angle. Inadequate wetting length can lead to joint failure from the interface of the deposited bead and steel, as it reduces the interface area available to resist shearing during tensile testing. Conversely, a high or steep wetting angle can cause stress concentration at the bead's toe, potentially leading to a sudden deterioration in joint strength under loading conditions. Therefore, a wetting/contact angle of $<90^\circ$ is recommended to achieve satisfactory joint strength. However, too low of a wetting angle could influence the joint strength negatively, as excessively spreading filler with a smaller wetting angle can reduce the effective cross-sectional area. Thus, the wetting angle at the toe of lap brazed joints needs to be optimized carefully. It should not be too low but should not exceed 90° to acquire satisfactory static and dynamic strength.

The bead shape and geometry of brazed lap joints can be varied by changing the heat input during GMA brazing. The heat input depends not only on the feeding rate of filler wire and brazing speed but also on the position of brazing torch, which plays an important role in determining the heat transfer to the base metal sheet. Increasing the WFR (by raising welding current and voltage) or decreasing welding speed leads to both an increase in energy transfer to the base metal (i.e., heat input) and an increase in the deposition rate. Researchers have reported that higher welding currents can lead to increased flowability of the molten filler, resulting in wider beads with lower wetting angles [31]. On the other hand, steep wetting angles have been found to be unfavourable for cyclic loading because they result in stress concentration at the toe of brazed joints. To increase the wettability of the overlapped brazed joints, it has been suggested to increase the heat input. For instance, during GMA brazing of interstitial-free (IF) steel with CuSi3 filler, a rise

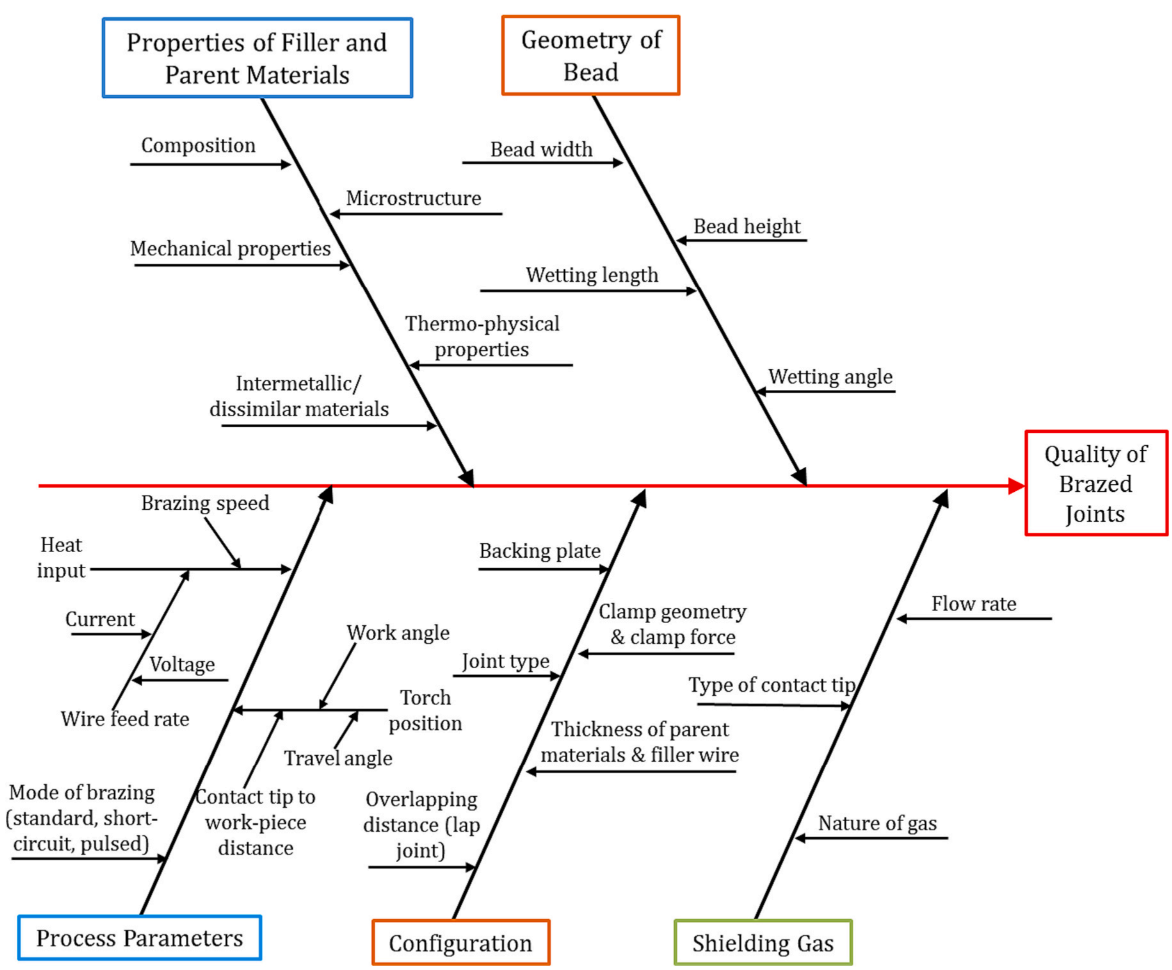


Fig. 4. Cause and effect diagram for brazing process.

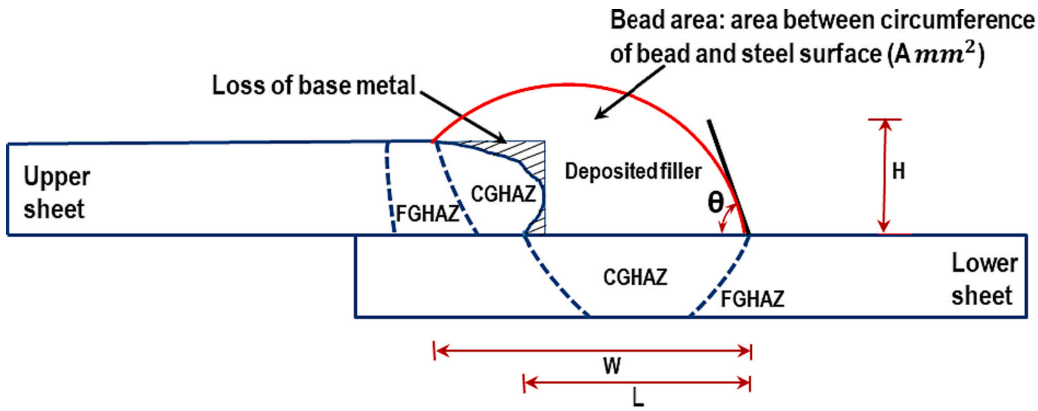


Fig. 5. Schematic representation of cross-section of steel-steel brazed/weld-brazed lap joint [68].

in heat input (108 to 234 J/mm) resulted in a significant increase in wettability, as observed by an increase in wetting/bonding length from 2.72 to 4.02 mm and a decrease in wetting/contact angle from 83 to 64° (Fig. 6).

Reisgen et al. [9] reported that a very steep wetting angle, >90^0, is unfavourable for the fatigue strength of CMT brazed joints. To address this, researchers have introduced a pre-setting gap between the sheets with the aim of enhancing wettability by filling the gap with molten filler [9,69]. However, joints with predefined gaps may fracture from the bead with the lowest strength due to increased bending torque during fatigue testing, leading to enhanced strain in the brazed seam [9]. Nevertheless, the insertion of filler strips between the sheets to be brazed, aimed at creating a pre-set gap, resulted in a significant improvement in the shear-tensile testing of lap brazed joints due to dispersion strengthening of beads [9,21,69]. To achieve satisfactory joint performance, the German welding society recommends a wetting angle of <90° even for static loading [9]. However, there is limited literature focusing on the correlation between shape of bead and mechanical strength of brazed joints. Furthermore, the wetting/bonding length also significantly influences the fracture location in lap-brazed joints during shear-tensile loading. Joints with low wettability are susceptible to failure along the bead-steel interface because of the limited joining or bonding area between the deposited braze/filler metal and the base metal sheet [77,79].

On increasing the heat input, Singh et al. [69] observed a significant improvement in the wetting/bonding length at the interface, causing the failure mode/location to shift from the lower interface (mode 1) to the deposited filler bead (mode 2), and eventually to the vertical interface (mode 3) (Fig. 7). For instance, Basak et al. [21] found that increment in heat input improved the strength of lap brazed joints due to a corresponding increase in the deposited bead cross-sectional area. Furthermore, the location of failure shifted from the interface to the fusion zone (FZ) and then to the HAZ/BM because bead geometry/shape influenced the propagation of the crack. Samples with low wetting/bonding length fractured from the interface, while those with higher wetting length fractured from the HAZ and exhibited the highest shear-tensile strength. Similarly, Makwana et al. [66] reported that joints brazed at a heat input of 108 J/mm fractured from the interface of the base metal sheet and deposited braze bead. In contrast, increasing the heat input to 142 J/mm resulted in fracture occurring in the base metal sheet due to a significant rise in wetting/bonding length and the thickness of the intermetallic layer.

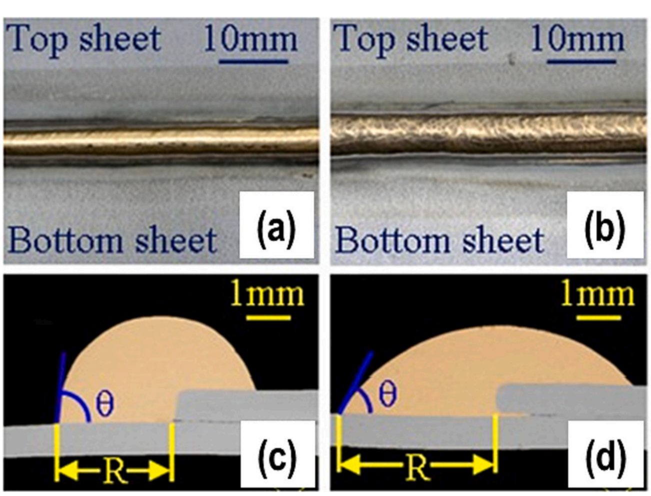


Fig. 6. Bead shape of the brazed joints at different heat inputs (a) & (c) 108 and (b) & (d) 234 J/mm [66].

3.2. Volumetric fraction of intermetallic compounds in the deposited braze metal

Brazing, which is a surface phenomenon involving the inter-diffusion of atoms at the steel-filler interface, is expected to occur without any noticeable fusion of the base metal [30]. However, during lap brazing, an intriguing observation emerged: a part/edge of the upper steel sheet melted and dissolved in the molten filler bead due to the influence of strong arc forces near the high-temperature arc zone. The German Steel Institute has reported that up to 10 % of the height/thickness of the steel sheet at the bottom may be melted and dissolved during the arc brazing of steel in the lap configuration [9]. This phenomenon led to an increase in the loss of base material as the heat input was raised, as illustrated in Fig. 8. The presence of alloying elements, such as Si and Al, in copper-based filler metal prompted a reaction with the dissolved iron atoms in the deposited braze bead. This reaction, limited by the solubility of Fe in Al, resulted in the formation of uniformly distributed dendritic intermetallic compounds in the deposited braze bead (Fig. 9a).

Beyond the bead's shape and geometry, previous studies have highlighted the significance of the volumetric fraction intermetallic compounds in the deposited filler bead, influencing the mechanical performance of lap brazed/weld-brazed joints. Kai et al. [80] found that dispersive intermetallic compounds/phases can significantly strengthen the deposited braze filler, consequently improving the mechanical characteristics of the brazed/weld-brazed joints. In addition, Varol et al. [67] were able to successfully increase the failure load during tensile testing of GMA brazed/weld/brazed lap joints of TRIP 800 steel by enhancing the volumetric share of dispersive CuAlFe intermetallics in the deposited CuAl8 braze metal (i.e., bead) through increased heat input. Basak et al. [21] reported an increase in iron dendrite concentration with higher heat input, as the top corner of the upper plate experienced more heat and extended growth time. They observed that

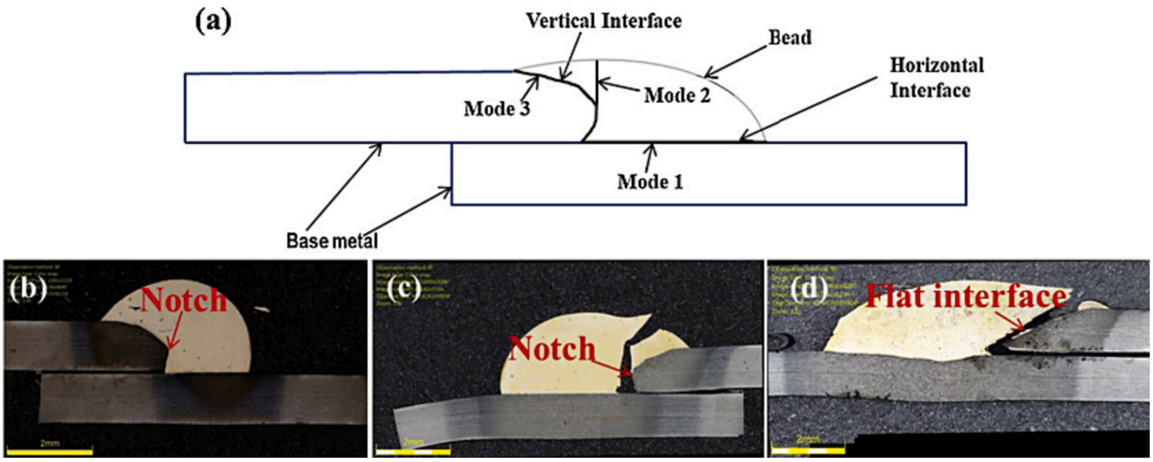


Fig. 7. Different failure locations (interface, bead, and base metal) of GMA brazed joints during shear-tensile loading (a) top view and (b) cross-section [69].

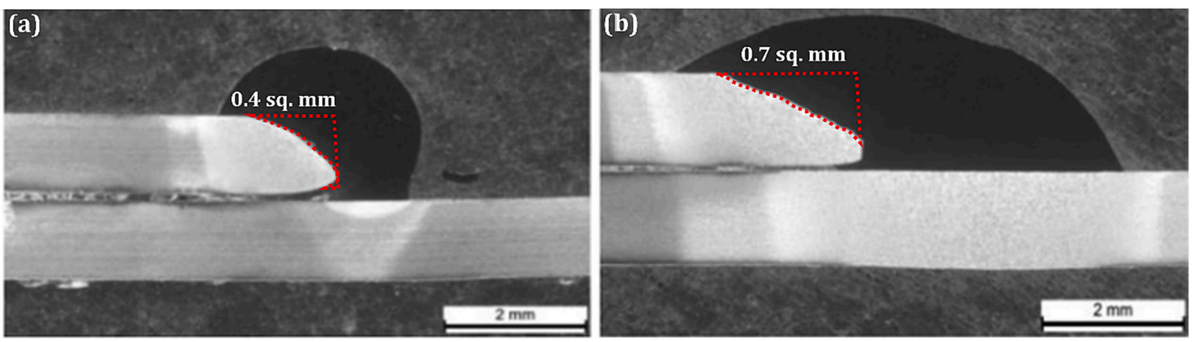


Fig. 8. Cross-sectional macrographs of the deposited bead showing loss of base metal (a) 52 and (b) 123 J/mm [69].

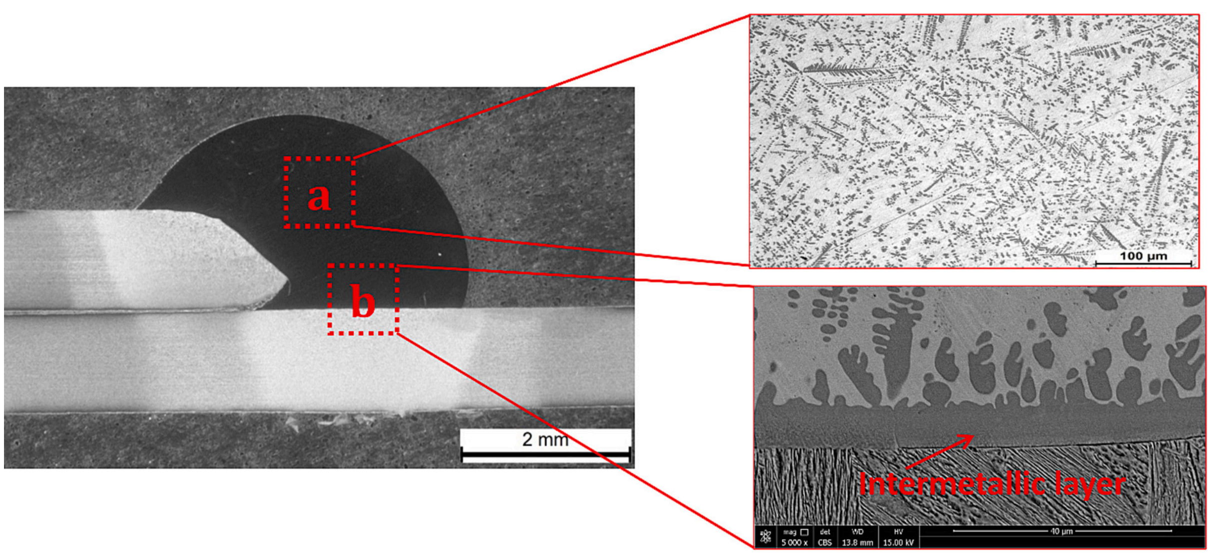


Fig. 9. Micrographs showing the evolution of intermetallic phases at the interface and inside deposited Cu based Al enriched filler [1].

the deposited Cu—Al filler exhibited a hardness around 110 HV. However, due to the presence of Fe dendrites and an Fe-enriched Cu matrix, the hardness of the fusion zone (deposited bead) increased up to 180 HV, a phenomenon referred to as dispersion hardening.

Reisgen et al. [9] achieved a rise in the fraction/amount of dispersive intermetallics (Fe3AlyCuz) in the bead by putting a filler steel strip of thickness 0.1 mm between the overlapped DP780 steel sheets (1.2 mm thick) during CMT brazing, resulting in 100 % joint efficiency at 285 J/mm heat input using CuAl8 filler. They found that increasing the heat input (3452 J/mm) led to a higher amount of dendrites inside the bead, but also required a higher level of base metal melting. Joints with a higher amount of intermetallic phases experienced failure from the heat-affected zone (base metal) and confirmed the positive impact of intermetallic phase fraction on tensile strength. However, the amount of dispersive phase fraction was found to be ineffective during fatigue testing. Initially, shear-tensile strength of brazed lap joints increased with the volumetric fraction/amount of dispersive intermetallic compounds, but this strength eventually reached a constant value, as further increases in heat input caused embrittlement in the heat-affected zone. Samples with a phase fraction >8.5 % fractured in the base material sheet at almost the same or lower failure loads.

3.3. Intermetallic compound layer at steel-filler interface

A brittle and hard layer composed of Fe-Al-Cu intermetallics formed at the interface (steel-filler) due to solubility limitations of iron in aluminium (Fig. 9b). The evolution of this intermetallic layer is governed by the inter-diffusion of iron and aluminium atoms across the interface. In addition, availability of reacting atoms also influences the outcome of the interfacial reaction. The aluminium available in the molten filler wire diffused into the solid steel surface generating Al-enriched, Fe-based intermetallic phases that formed the interfacial region. Alloying elements in the filler wire such as Al and Si have poor solubility in Fe and therefore, lead to the evolution of intermetallics at the interface in the form of a continuous layer as shown in Fig. 9b. The higher diffusion coefficient of iron into aluminium enables the diffusion of Fe atoms for a range of temperature from 730 to 1400 °C. For this temperature range, the coefficient of diffusion of aluminium into iron $\left(1.8 \times 10^{-4} exp\left(\frac{-228.2\times10^3}{RT}\right)\right)$ is comparatively lower than that of aluminium into iron $\left(53 \times 10^{-4} exp\left(\frac{183\times10^3}{RT}\right)\right)$ [32,81,82]. Makwana et al. [66] reported that increment in the availability of reacting atoms (Fe, Cu and Si) near the interface resulted in thickening of IMC layer. They observed a significant thickening of the IMC layer, ranging from 1.52 to 3.43 μm, with an increase in heat input from 108 to 170 J/mm, as illustrated in Fig. 10. Furthermore, a subsequent increase in heat input to 234 J/mm resulted in an even thicker IMC layer, measuring 7.72 μm. Both Singh et al. [69] and Makwana et al. [83] reported significant improvement in the strength of lap brazed joints with an increment in intermetallic layer thickness at the steel-filler interface.

On the other hand, the evolution of a continuous intermetallic layer at the interface prevents the penetration of Cu along the grain boundaries of steel, a phenomenon commonly observed when brazing steel with Cu-based fillers. It occurs because of molten filler metal penetrating along the grain boundaries of the solid phase, i.e., steel, which may reduce the ductility of the brazed/weld-brazed joints (Fig. 11). Singh et al. [32] observed that the issue of Cu penetration is more common in the case of pure copper filler whereas formation of intermetallic layer in case of alloyed fillers prevented it. This phenomenon generally occurs when there is minimal mutual solubility between the solid metal and the molten filler, and no intermetallic formation at the interface.

The microstructure of steel also plays a key role in the penetration of Cu. Ferrite microstructures are found to be least susceptible to this problem compared to pearlite, austenite and martensite because copper does not wet ferrite microstructures properly [62]. Several efforts have been reported to prevent this phenomenon by modifying the composition of either filler wire or steel as it directly controls the atomic reaction at the interface. Ishida et al. [84] observed that silver addition to the copper filler successfully suppressed the penetration of molten filler along the grain boundaries. In another study, Chen et al. [85] investigated the influence of Si addition to the brazing alloy during CMT welding-brazing of dissimilar materials copper and steel and observed that formation of ferrite band along the interface of steel and deposited Cu—Si brazing alloy prevented the intergranular liquid copper penetration of solid steel. Lee et al. [86] observed that formation of a diffusion inhibition layer composed of brittle and hard Fe_2Al_5 intermetallic phase successfully suppressed the Zn-induced LME of TWIP steel. Shajan et al. [62] reported that boron added steels (>30 ppm) exhibited higher resistance to Cu penetration during brazing using Cu—Zn filler as it suppressed the diffusion of liquid filler metal along the grain boundaries of steel. Lepisto et al. [87] achieved better fatigue strength for MIG brazed joints compared to welding but suggested further investigations to explore the effect the penetration of Cu along the grain boundaries of steel. Research has clearly shown that the type of Zn coating can also have a significant effect on Cu-penetration into grain boundaries [61] or on LME susceptibility of the steel [60]. Hence, it can be inferred that the intermetallic layer at the interface provides numerous benefits in steel-steel brazing. These advantages include preventing Cu penetration into the grain boundaries of steel and enhancing the strength of the brazed joints. However, it is crucial to carefully optimize the thickness of this layer because Fe—Al intermetallics are inherently brittle and hard in nature.

4. Fatigue/dynamic strength of brazed lap joints

The fatigue/dynamic/cyclic performance of GMA-brazed joints plays a crucial role in ensuring the reliability of automotive structures during service. GMA brazing has been recognized as a promising technique to enhance fatigue strength by allowing better control over joint geometrical and microstructural features. However, the lack of sufficient published data has hindered the validation of its efficacy. Brazed joints introduce microstructural and structural discontinuities that can adversely degrade the overall fatigue strength of the structure [88]. In lap brazed steel-steel joints, the steepness of the toe, commonly referred to as the wetting angle, significantly influences the fatigue strength due to stress accumulation at this point. The site with the highest stress concentration becomes the weakest area, as stress concentration is a well-known structural discontinuity in a brazed joint [89]. Additionally, the presence of metallurgical discontinuities arising from the compositional gradient between the deposited filler and base metal can also impact the mechanical behaviour of the brazed joints. The nature of the intermetallic compound layer at the interface plays a key role in this degradation process [90]. However, existing literature on lap joints demonstrates that stress concentrations resulting from the bead's

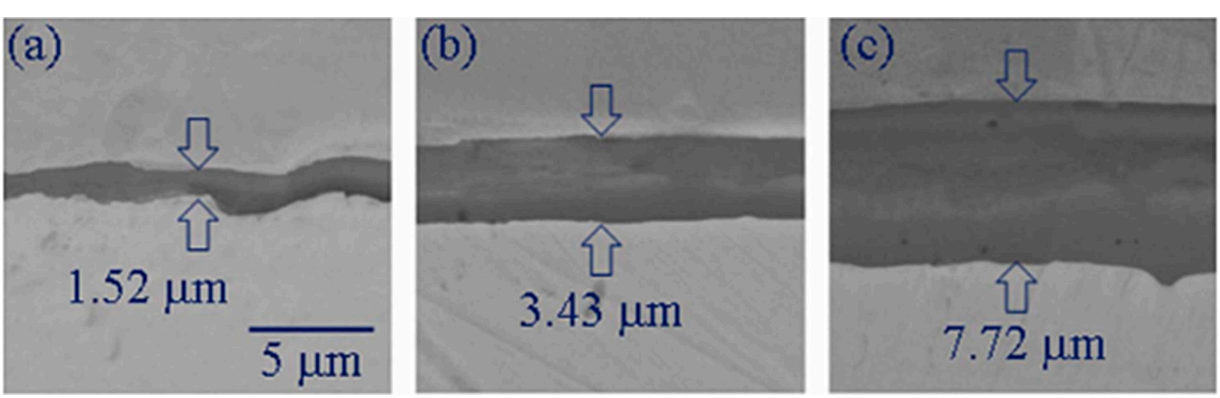


Fig. 10. Micrographs showing variation of IMC layer thickness at different heat inputs (a) 108, (b) 170 and (c) 234 J/mm [66].

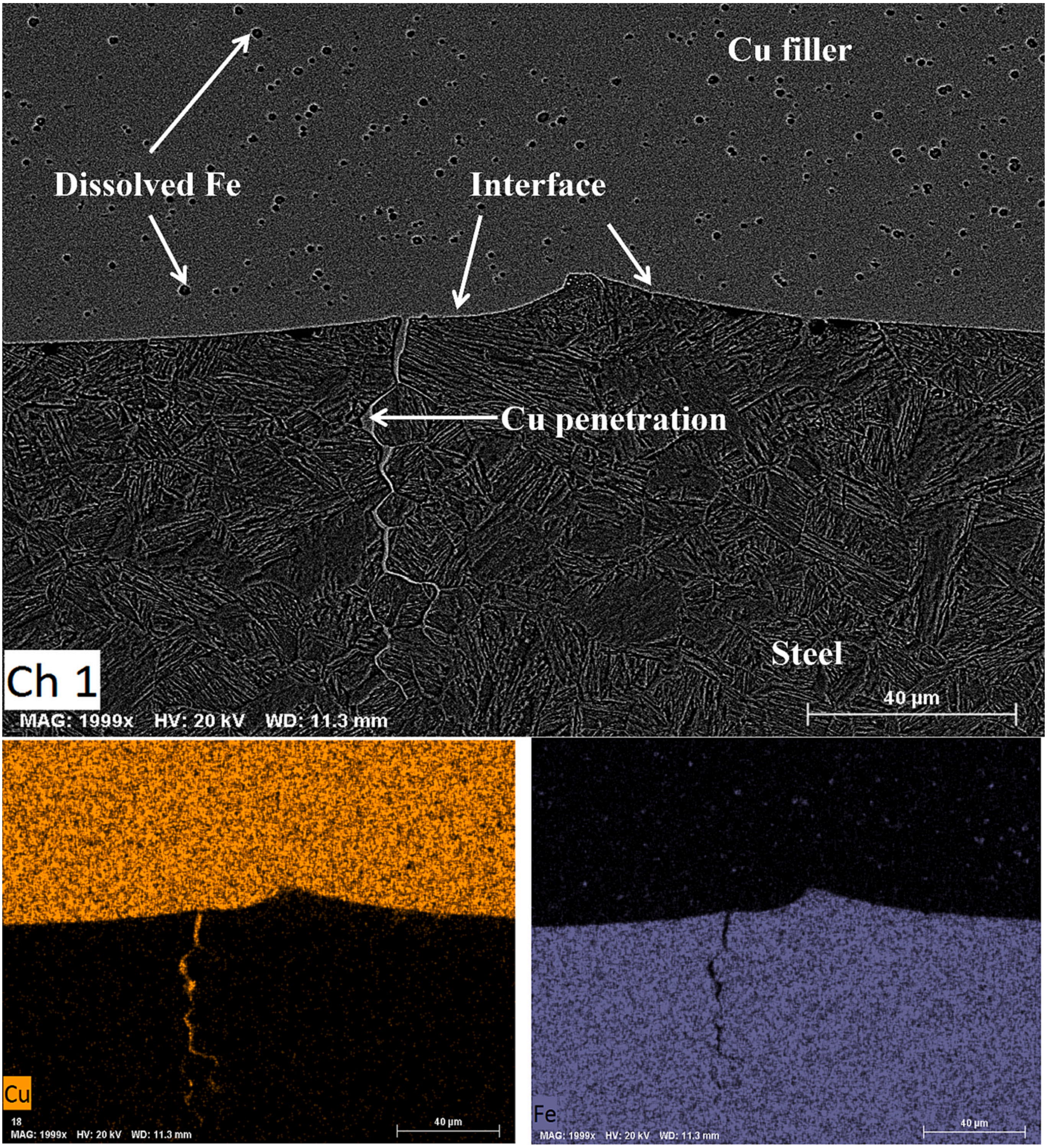


Fig. 11. Penetration of copper along the grain boundaries of DP780 steel during cold metal transfer brazing using pure Cu filler [1,32]

geometry are a predominant factor in assessing the fatigue strength of brazed lap joints [73].

Numerous studies have examined the fatigue behaviour of brazed joints, with bead shape emerging as a crucial determinant in both the failure location and the number of cycles before failure. Reisgen et al. [9] reported that during fatigue testing of CMT brazed joints, failure often occurred in the vicinity of the brazing seam. The failure modes were categorized as follows: (i) failure from the geometrical notch in the upper sheet, (ii) failure within the brazing seam, and (iii) failure from the base metal-brazing seam interface. Surprisingly, no significant correlation was found between the number of cycles/cyclical loading and failure location. Furthermore, Reisgen et al. [9] observed that despite achieving the highest shear-tensile strength in samples with a predefined gap between the sheets, a lower strength and failure were observed from the braze seam. This phenomenon was attributed to the enhanced strain on the seam caused by an increased induced bending torque. In lap joint configurations, the eccentricity of the applied load path during both tensile and fatigue testing leads to joint rotation during loading, resulting in a combination of tensile and shear loads [73,91]. Nordberg [92] initially reported that the rotation rarely exceeded 3° in most cases, although higher degrees of rotation have been observed and reported in more recent literature.

To investigate the effect of different input parameters on the fatigue strength of brazed joints, systematic and extensive research has been carried out in the field of GMAW/CMT brazing of high-strength steels by Reisgen et al. [9], Basak et al. [21], and Singh et al. [68]. Basak et al. [21] explored the impact of brazing mode on the fatigue life of GMA brazed joints. They found that samples brazed in push mode (named DP3 samples) exhibited better fatigue properties, attributed to the presence of flatter beads in this mode. On the contrary, Singh et al. [68] observed that joints brazed in pull mode displayed superior fatigue strength compared to push mode due to a higher wetting length and a smaller toe angle (Fig. 12a). In a similar study, Reisgen et al. [9] reported that joints with a higher intermetallic phase fraction in the braze seam demonstrated better fatigue strength, while joints brazed with a predefined gap showed relatively lower fatigue strength due to additional bending of the samples (Fig. 12b). Singh et al. [68] attributed the improved fatigue strength of pull-mode samples to several factors: a greater volume fraction of dispersive intermetallics within the bead, higher wettability, and a smaller toe angle. These factors collectively result in lower stress concentration at the edge of the joint.

In a lap joint configuration, the toe and root of the joints are recognized as two sensitive locations that are more prone to failure. This increased susceptibility to failure at these two locations is attributed to the higher stress concentration resulting from the abrupt change in the cross-sectional area of the joint [73]. Fig. 13 illustrates different failure locations of brazed joints under fatigue loading, with cracks initiating either from the root or the toe for the abovementioned reasons. During fatigue testing of brazed lap joints of steels, three modes of failure are observed: base metal, bead, and interface failures [21,68]. In each of these failure modes, cracks initiate either from the toe or the root of the deposited filler bead. This initiation is influenced by the shape of the bead as the shape controls the stress distribution under loading. When a crack originates from the root, it propagates in two directions: along the interface and across the bead. Ultimately, the brazed lap joint failed from the weaker steel-filler interface which is attributed to the insufficient metallurgical connection and shorter wetting lengths at the steel-filler (Fig. 13a). In cases where the metallurgical bonding at the interface is strong enough to resist crack propagation, the joints fail from the deposited bead (Fig. 13b). Furthermore, when the crack originates from the toe, it results in failure occurring at the same location, with no discernible deformation at the root of the joint (Fig. 13c). This occurs primarily under high amplitude loading conditions, attributed to significantly faster rate of crack propagation at higher amplitudes, leaving less duration for even the initiation of the crack at joint's root. In conclusion, the location and reasons for these failures suggest that the shape of the toe is more crucial than that of the root, as it can significantly degrade joint performance especially at high amplitude loading if not properly optimized.

5. Different strategies for improving the mechanical performance of brazed lap joints

This section explores various strategies that should be carefully considered to enhance the performance of brazed joints in service. The load-bearing capacity of steel-steel brazed joints can be improved either by increasing wettability or by increasing the intermetallic fraction in the bead. Both wettability and intermetallic fraction can be adjusted by manipulating several factors, including heat input, filler wire composition, torch position, presetting gap, root geometry, type of coating, and hybridization of joining processes, among others. All these strategies are discussed in detail in the subsequent subsections.

5.1. Increasing heat input

Processing of heat sensitive materials such as Copper, Aluminium, Magnesium and Titanium require very controlled adjustment of processing parameters. To improve the stability of the joining process, power sources are nowadays being incorporated with special synergy programs. In synergic program, both welding voltage and current vary on changing the rate of wire feeding (WFR) in order to balance the feed rate and burn off rate of the filler wire. In addition, there is also a provision to change the voltage, current or any other characteristic parameter at a constant WFR as per the joining requirements. On increasing the WFR (welding current and voltage) or decreasing welding speed, both thermal energy transfer to base metal i.e. heat input and the deposition rate increase. In this regard, Basak et al. [21] reported that with increasing welding current, increase in flowability of molten filler dominated over the increased deposition rate and resulted in wider bead with low wetting angle. Reisgen et al. [9] reported that higher stress concentration at the toe caused by steep wetting angle is unfavourable for cyclic loading of the brazed lap joints. The wettability of molten braze filler can be enhanced by increasing the heat input. During the GMA brazing of interstitial free (IF) steel with $CuSi_3$ filler, Makwana

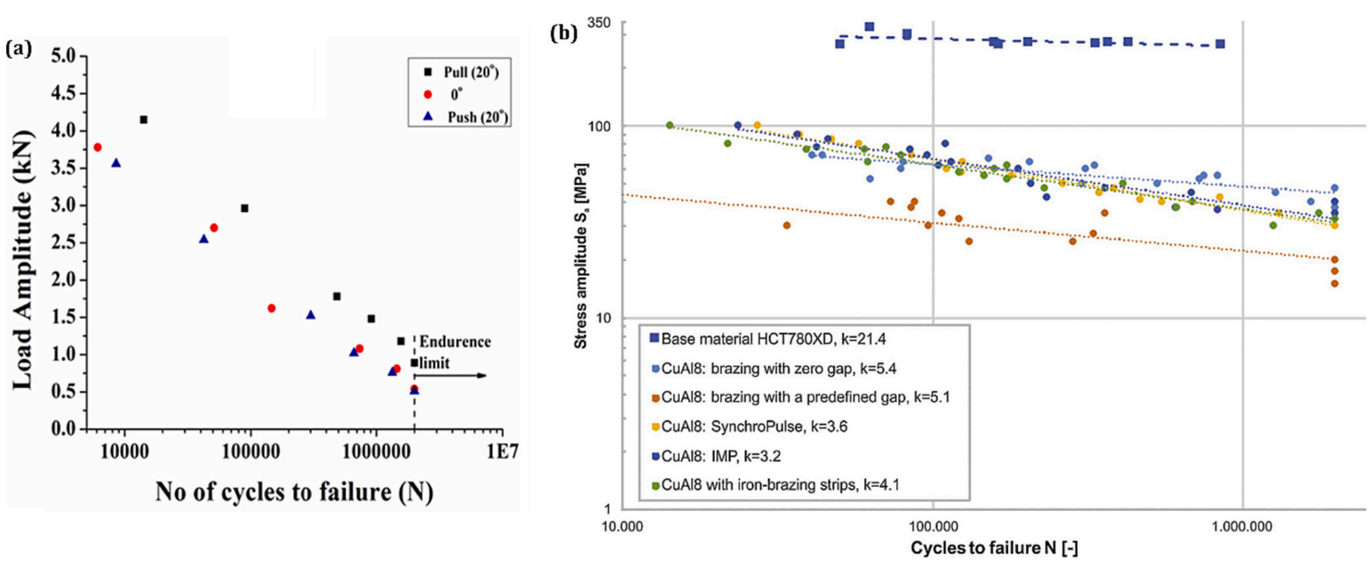


Fig. 12. Variation of fatigue strength with different process parameters including heat input, mode of operation, and predefined gap [9,68].

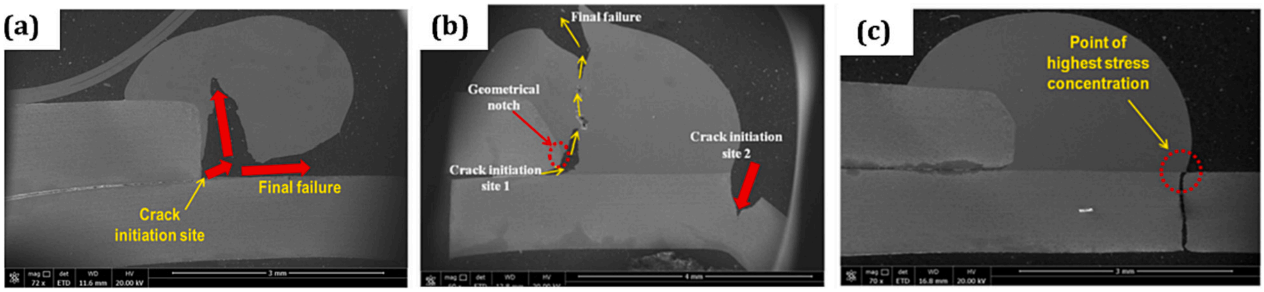


Fig. 13. Three different failure locations of brazed joints during cyclic loading: the interface (a), bead (b), and base metal (c). These failures are caused by insufficient wetting length, weaker deposition, and higher stress accumulation at the toe, respectively [68].

et al. [66] found an increase in the wettability of the joints (wetting/bonding length increased from 2.72 to 4.02 mm and wetting/contact angle decreased from 83 to 64°) on rising the heat input from 108 to 234 J/mm. In addition, Singh et al. [69] reported that the fraction of dispersive intermetallic phases/compounds in the deposited braze bead also increased on increasing the heat input due to a parallel rise in the amount of loss of base material. They reported an increase in the fraction of dispersive intermetallics from 7.3 to 16.6 % on increasing the heat input from 62 to184 J/mm as shown in Fig. 14.

In a similar research work, Reisgen et al. [9] reported that to increase the fraction of dispersive dendrites in the deposited filler bead, higher melting of the base metal is required which was achieved by increasing the heat input (3452 J/mm). They observed that the tensile strength of the CMT brazed joints increased effectively up to a dendritic fraction of 8.5 % and then strength was found to be constant because further increase in heat input caused embrittlement of the joint in the HAZ due to excessive formation of martensite and thus samples with intermetallic phase fraction >8.5 % failed from base material exhibiting similar or lower strength. Basak et al. [21] also achieved the best shear-tensile strength for the samples brazed at highest heat input 204 J/mm and observed a shift in the failure mode from interface to bead and base metal on increasing the heat input. On the other hand, higher heat input leads to the evaporation of zinc coating in the joint vicinity especially on the back side which may degrade the stability of brazed joints in corrosive environments. Therefore, it is not feasible to increase the heat input beyond a certain limit. The interaction between the galvanized coating and brazing parameters is the important in establishing optimum brazing conditions. If arc brazing is to be used as a replacement for conventional welding, it is essential to determine the resistance to corrosion and electro-chemical behaviour of the steel-steel brazed lap joints. In this regard, optimal brazing parameters would assure acquiring the desired corrosion resistance as well as mechanical properties [58].

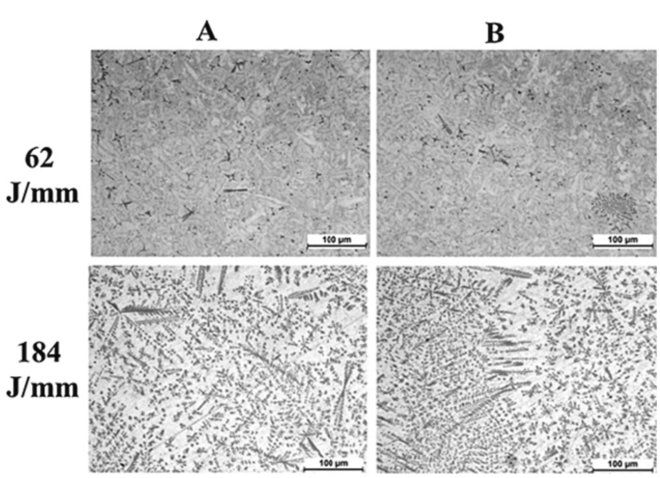


Fig. 14. Microstructure of the deposited bead at two different heat input. The fraction of dispersive intermetallics increased from 7.3 to 16.6 % on rising the heat input from 62 to 184 J/mm which significantly improved the strength [69].

5.2. *Filler wire composition*

The chemical composition of the filler wire influences its fluidity in the molten state which ultimately controls the wettability of brazed joints. Wetting is the ability of a liquid filler to keep contact with a solid steel surface, resulting from inter-molecular interactions (inter-diffusion) when the two are brought together. Singh et al. [32] observed that alloying Cu-based filler wires with elements like Al and Fe significantly influenced the wettability of steel-steel brazed joints. Addition of Al and Fe to Cu-based filler resulted in poor wettability of the brazed joints as shown in Fig. 16. However, the volumetric fraction of dispersive intermetallic dendrites in the deposited filler bead and the thickness of the formed intermetallic layer were significantly higher in case of alloyed wires, i.e. CuAl8 and CuAl10Fe (refer to Fig. 15), which in turn contributed to the strength of brazed joints.

It can be seen from Fig. 16 that joints brazed using CuAl10Fe filler exhibited higher strength compared to those obtained using pure Cu and CuAl8 fillers in spite of having lowest wettability. This can be attributed to strengthening of the bead and interface due to higher phase fraction and thicker intermetallic layer respectively. In addition, Singh et al. [32] were able to achieve 100 % joint efficiency (joint strength equals to that of the base metal) at a heat input of 266 J/mm using CuAl10Fe filler wire during CMT brazing of DP780 steel. However, a geometrical characteristic, L/θ, was observed to be influential for individual filler wires as can be seen in Fig. 16b. Shear-tensile strength, i.e. failure load, increased linearly with L/θ for each filler wire. To date, very limited work is reported on the influence of filler composition on joint properties and additional efforts are required on the same.

5.3. *Position of brazing torch*

Heat input during brazing/welding is not only controlled by the brazing speed and the wire feed rate (WFR) but also by the orientation of the brazing torch which controls the net heat transfer between the substrate and the arc. It is important in the region where the heat input and brazing arc are focused on the substrate. Basak et al. [21] studied the effect of torch position (i.e., travel angle) on shear-tensile and fatigue strength of gas metal arc brazed joints, observing that the mode of operation (travel angle: push/pull) significantly effected bead shape/geometry and mechanical properties (both static and dynamic strength) of GMA brazed joints. Brazing in push mode tends to exhibit comparatively flatter beads with better mechanical performance than joints produced using pull mode for a given level of heat input. In addition, Singh et al. [69] investigated the influence of the work angle on bead geometry/shape, microstructure, and strength of CMT brazed lap joints. They reported that changing the work angle from 0, 20 and 40°, resulted

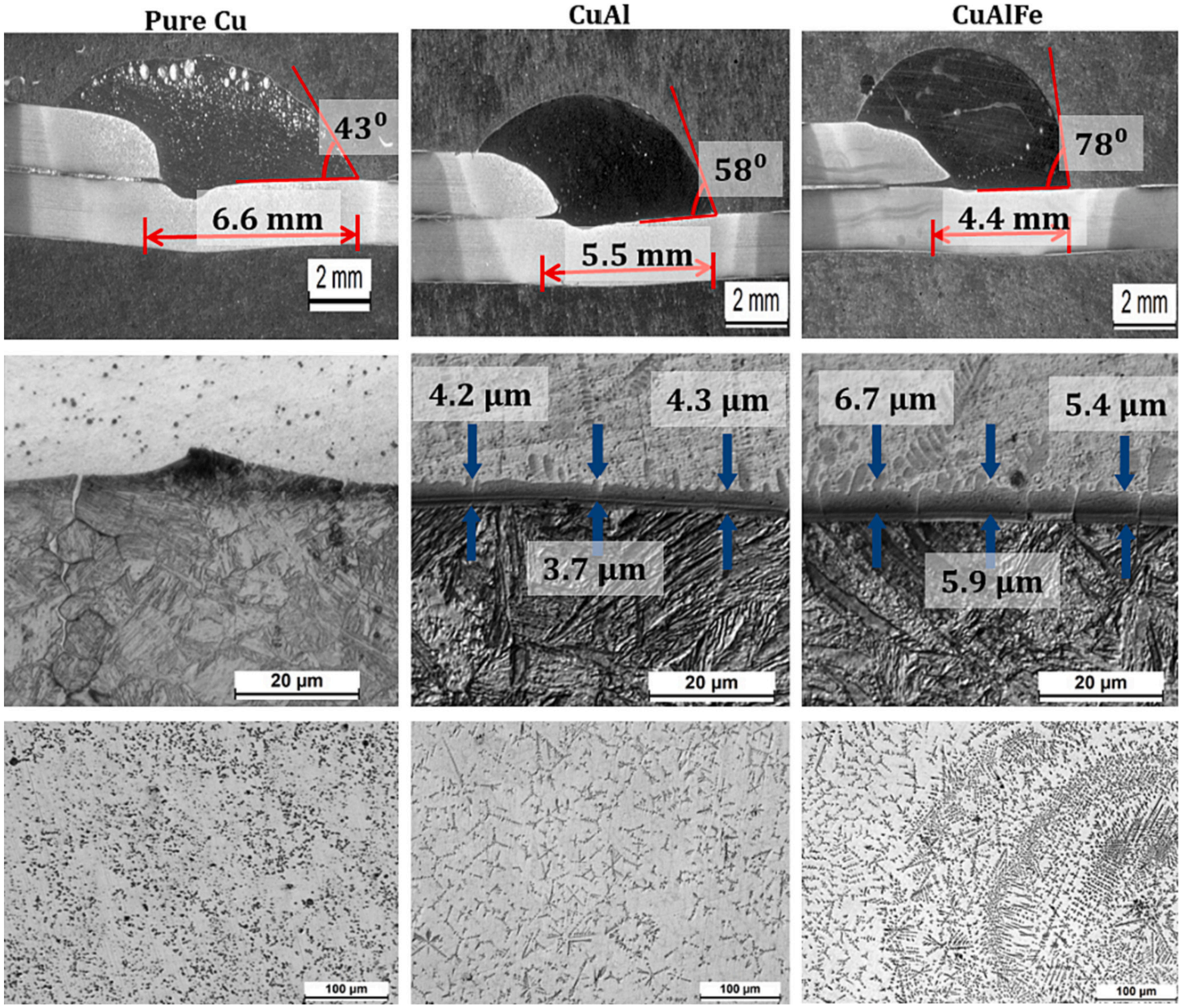


Fig. 15. Effect of filler composition on wettability and microstructure of brazed joints. The addition of alloying elements Al and Fe to Cu-based filler resulted in reduced wettability but formation of intermetallics in the deposited bead and interface. [32].

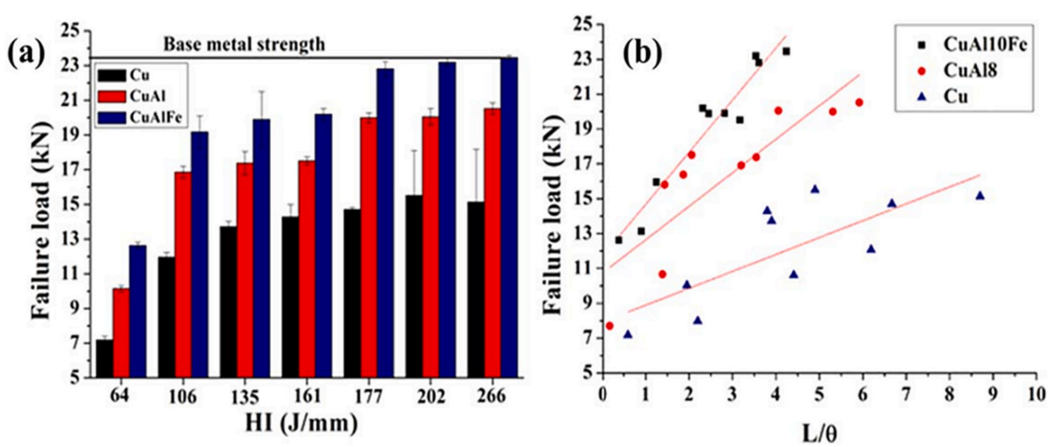


Fig. 16. Effect of heat input and bead geometry on strength of brazed joints of three different filler wires namely pure Cu, CuAl8, and CuAl10Fe [32].

in increased load to failure of the joints. At heat input of 133 J/mm, increased fraction of dispersed intermetallic phases (13.9 to 15.6 %) at 0° work angle and the improved wettability at 40° successfully improved the mechanical integrity of brazed joints. Severe melting at the corner of the upper base metal sheet due to higher energy input at 0° was found to be not beneficial for the application of brazed joints in corrosive environments while excessive wettability at 40° degraded the performance of brazed joints under dynamic/cyclic loading. Furthermore, to explore the effect of work angle and travel angle on metallurgical and mechanical properties of brazed joints, Cho et al. [28] reported that both torch position and angle significantly influence the heat transfer of the system, which directly impacts the properties of brazed joints. The size and shape of intermetallic particles in the brazed bead varied with both work and travel angle as shown in Fig. 17.

5.4. Hybrid joining process

Every welding/joining process has certain limitations. For example, CMT is not suitable for joining thick sheets (thickness > 3 mm). Therefore, it is essential to develop new joining technologies or to

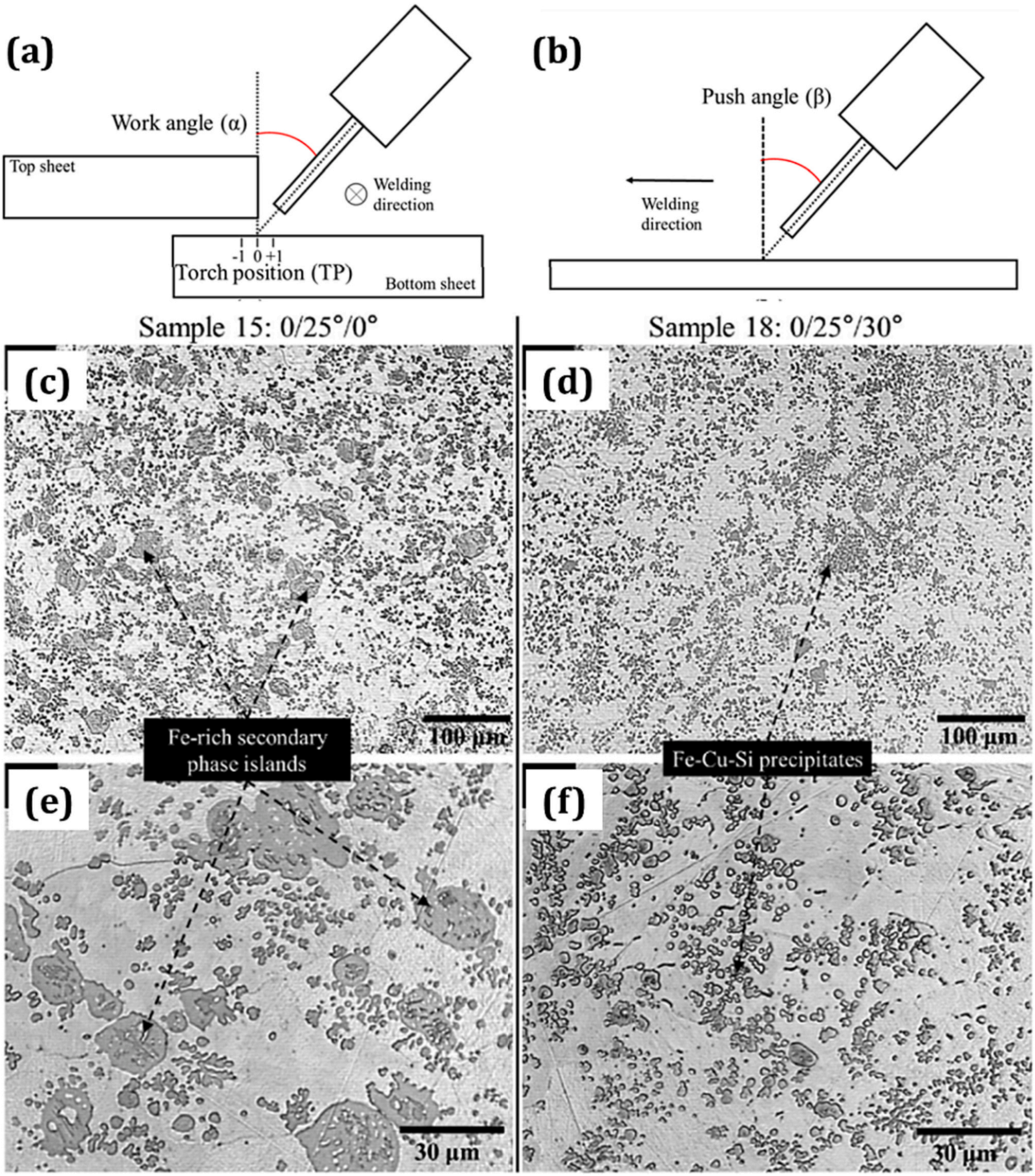


Fig. 17. Influence of torch angle and position on microstructure of brazed joints [28].

rejuvenate the existing ones. Process hybridization i.e., combination of two welding methods such as laser-GTAW, laser-GMAW, and laser-CMT is a trending research domain as it utilizes the characteristics of both processes. Wen et al. [93] used hybrid CMT arc-laser welding process for dissimilar joining of aluminium to steel and achieved significant improvement in the joint properties. Pang et al. [94] adopted advanced CMT plus pulse (CMT + P) welding process for bead on plate experiments and reported that high level of current during pulsing phase provides precise control over the heat input in comparison to conventional CMT welding. CMT + P is a combination of the conventional CMT and pulsed MIG processes, allowing for the adjustment of the number of CMT weld cycles and pulses to meet specific joining requirements. Pickin and Young [95] observed a considerable improvement in the wetting ability with the addition of high current pulses. Singh et al. [96] reported a noticeable improvement in the joint efficiency using CMT + P weld-brazing method during dissimilar joining of aluminium to steel. They observed a significant improvement in the wettability of joints on adding the high current pulses in the weld cycle. A schematic of the CMT + P process, illustrating the various phases of the welding cycle, is presented in Fig. 18. This process has been shown to efficiently join different material combinations and sheet thicknesses, as reported by Singh et al. [96]. Therefore, efforts are required on process hybridization to overcome the major issue of under-matching by improving the wettability and microstructure of steel-steel brazed joints.

5.5. Gap between the sheets to be brazed

The occurrence of an offset loading condition (i.e., load eccentricity) during tensile testing encountered by a solitary lap joint, results in the generation of bending moments along the length of the overlapped region of the joint (i.e., the root of the joint) [97]. This leads to the development of a stress concentration at the joint root, which can be seen in Fig. 19c, encompassing both peel and shear stresses [19,98,99]. In the course of extensive tensile testing of gas metal arc brazed samples that experienced failure within the FZ, consistent observations indicated that cracks consistently originated at the joint root and traversed along the length of the FZ, as depicted in Fig. 19, which aligns with prior findings as well [21,28,69,100].

Interestingly, the results showed that gap clearance at the joint root had a significant correlation to strength and the location of failure in the weld-brazed samples, as depicted in Fig. 19. GMA-brazed joints consistently exhibited superior strength levels when the gap size at the joint root ranged from 0.3 to 0.7 mm (Fig. 19c), and failure predominantly occurred in the BM. Conversely, results showed that minimal or no gap at the joint root led to joint fracture at drastically reduced loads with minimal elongation. Notably, peak load drops distinctly when the root gap exceeds 0.7 mm (Fig. 19d–e). This behaviour was attributed to the pronounced build-up of stress at the joint root, which increases significantly as the size of the root gap diminishes. The Digital Image Correlation (DIC) results in Fig. 20a–c underscored this finding, indicating a notably greater strain accumulation before reaching failure in the specimen with an effective gap of zero (i.e., 0.05 mm gap as shown in Fig. 19b), when compared to the specimen with a 0.5 mm gap, at the same point in time during a given tensile test. Numerical modelling of strain build-up during loading of a lap jointed sample with a no-gap and 0.5 mm gap validated the experimental findings, as shown in Fig. 20d.

The tensile testing curves (Fig. 20b) further demonstrated that zero-gap specimens experienced brittle failure that propagated through the FZ, whereas samples with a larger gap clearance displayed significantly improved mechanical properties with failure observed in the substrate. For a more complete understanding of the influence of gap clearance on the properties of GMA-brazed lap joints, readers are referred to [91]. These observations clearly highlight the critical role of gap clearance in controlling the strength and associated failure behaviour of GMA brazed lap-joints, emphasizing the significance of carefully optimizing the gap to ensure desirable joint performance.

5.6. Geometry of the root of brazed lap joints

The root geometry (i.e., the physical profile of the joint root) has not been significantly important in traditional arc welding lap-jointed steels because the weld material is typically the same material as the workpiece. In such cases, the mechanical properties between the substrate and the FZ are similar, and the focus is often on the HAZ. However, in the process of GMAB, the FZ, which is mostly a Cu alloy has a crystal structure which is face-centred cubic (fcc), while the steel substrate retains a crystal structure that is body-centred cubic (bcc) [30,70]. This results in an uneven and complex distribution of local material properties and morphology for the brazed joint. In the process of GMAB, the molten filler material CuSi3Mn1 is applied to the joint and it is

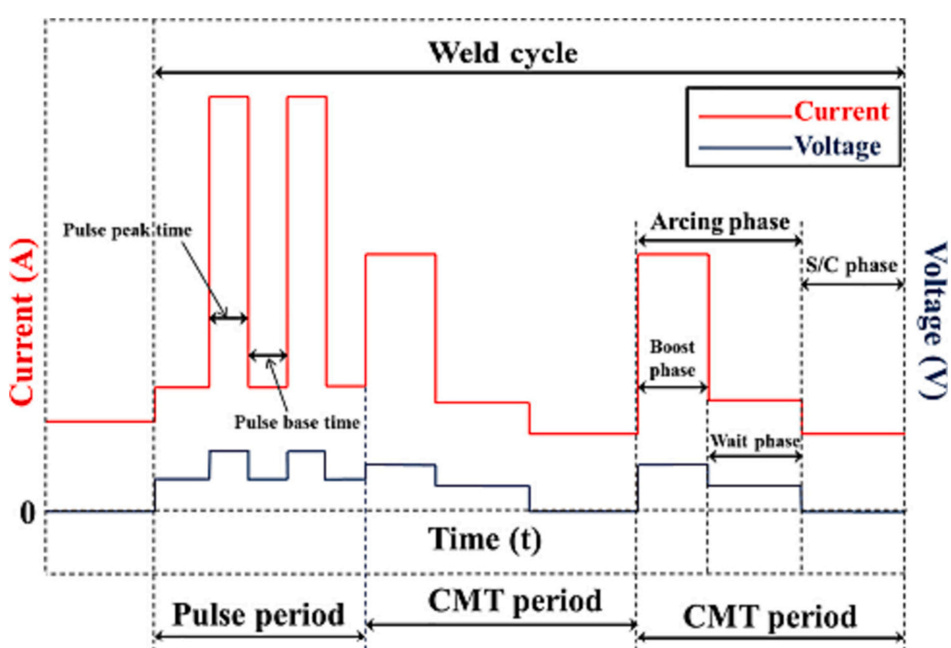


Fig. 18. Schematic of the welding cycle for 1 CMT cycle and 2 pulse cycles in the CMT + P process [96].

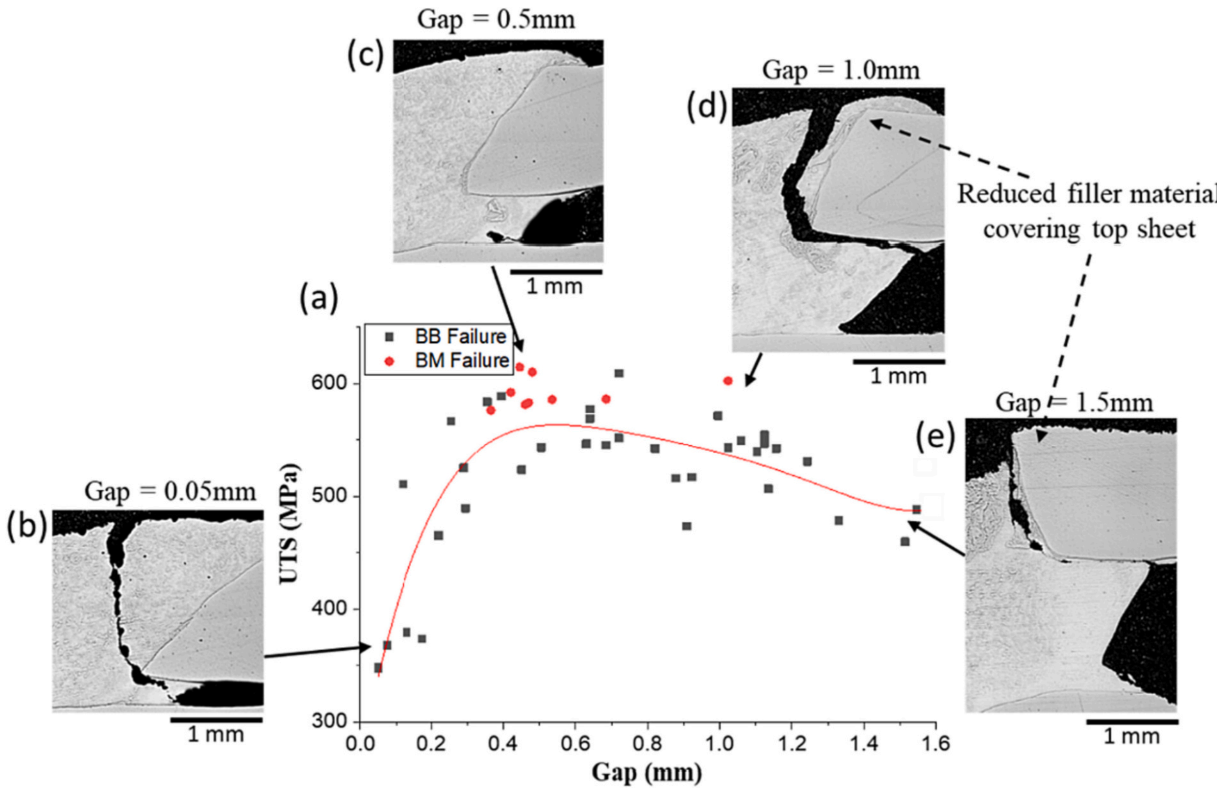


Fig. 19. (a) Plot illustrating the relationship between strength and gap size with (b–e) showing cross-sections of fractured samples with a gap size of 0.05 mm, 0.5 mm, 1.0 mm, and 1.5 mm, respectively [91].

introduced into the space between the upper and lower sheets of that will make up the lap joint. This results in the formation of a distinctive "root geometry," which varies based on the extent to which either the upper or lower surface at the root becomes wetted by the filler material that flows into the gap, as shown in Fig. 21. The root geometry becomes of paramount importance in GMA-brazed joints, as this critical location experiences the load transfer during loading applications.

Khan et al. [30,73] comprehensively demonstrated that the wettability of the upper and lower surfaces of the joint root could be controlled using a plasma cleaning surface treatment. This resulted in 3 types of root geometries, classified as Type 1, Type 2, and Type 3. The type of root geometry was distinguished using the "wetting ratio," which was defined as the "ratio between the top wetting length (TWL) and the bottom wetting length (BWL)" i.e., TWL/BWL, as depicted in Fig. 21. In this context, TWL denotes the overall length of the wetted area on the upper sheet, while BWL denotes the total length of the wetted region on the lower sheet. As defined by Khan et al. [101], a root geometry of $TWL/BWL \geq 2$ is classified as Type 1; $1 \leq TWL/BWL < 2$ is classified as Type 2; and $TWL/BWL < 1$ is classified as Type 3. The results of multiple studies clearly showed that the root geometry played a crucial role in influencing the mechanical properties of weld-brazed joints [101]. DIC results of tensile tests showed that Type 3 samples experienced significantly larger build-up of stress at the root in comparison to type 1 samples, as evidenced in Fig. 21. Moreover, characteristic flow curves for GMA weld-brazed lap joints produced using galvannealed steels (shown in Fig. 21) confirmed that the Type 1 and Type 2 specimens exhibited superior mechanical performance, while Type 3 samples had the lowest measured strength, and elongation and demonstrated consistent failure in the joint. For further in-depth information regarding the effect of root geometry on the behaviour of GMA-brazed lap joints, readers are referred to [73].

5.7. Type of zinc coating

Khan et al. [30] conducted an extensive study on the influence of zinc coating type (specifically galvanized (GI)- and galvannealed (GA)-coatings) on the wettability of a molten Cu-based filler material using arc-brazing. The results showed that the wettability of the molten Si-Bronze brazing filler material on Zn-coated steels was found to be influenced by surface roughness and cleanliness, such that the molten braze material displayed superior wettability on the GI coating, attributed to the ease with which it wet the pure-Zn GI coating. This phenomenon, known as the "tailing-out" effect, resulted in the formation of a Zn-rich Cu—Zn alloy at the toe, which was not observed in GA-coated samples. Akbarian et al. [102] observed similar phenomena during laser brazing, although the tailing-out effect was somewhat diminished. This was due to smaller differences in wettability between the GI and GA coated steels which was attributed to the much lower and focused heat input of the laser brazing process compared to the arc brazing process.

The differences in the measured surface roughness of galvanized and galvannealed steels (as shown by the 3D profilometry results in Fig. 22a–d) led to variations in the calculated surface free energy (SFE), with GI-coatings exhibiting an approximately twofold higher SFE than GA-coatings [30]. SEM images of the coating surfaces showed a significantly smoother GI coating (Fig. 22e) with a nearly pure Zn chemistry, while the GA-coating showed a much rougher surface morphology made up of different Fe—Zn compounds (Fig. 22e). High-speed camera images confirmed that the GI-coated substrate provided improved wettability, resulting in a smooth molten periphery along the braze pool (green arrows in Fig. 23a–c), while the GA-coated substrate showed restricted flow of the melt pool (red arrows in Fig. 23d–f).

Although better wettability during weld-brazing has been shown to improve mechanical performance of lap-jointed samples, Cho [20] and Khan et al. [73] investigated the mechanical behaviour of GMA-brazed samples with GI and GA coatings and observing that GI-coated samples consistently exhibited lower ultimate tensile strength (UTS) (~400

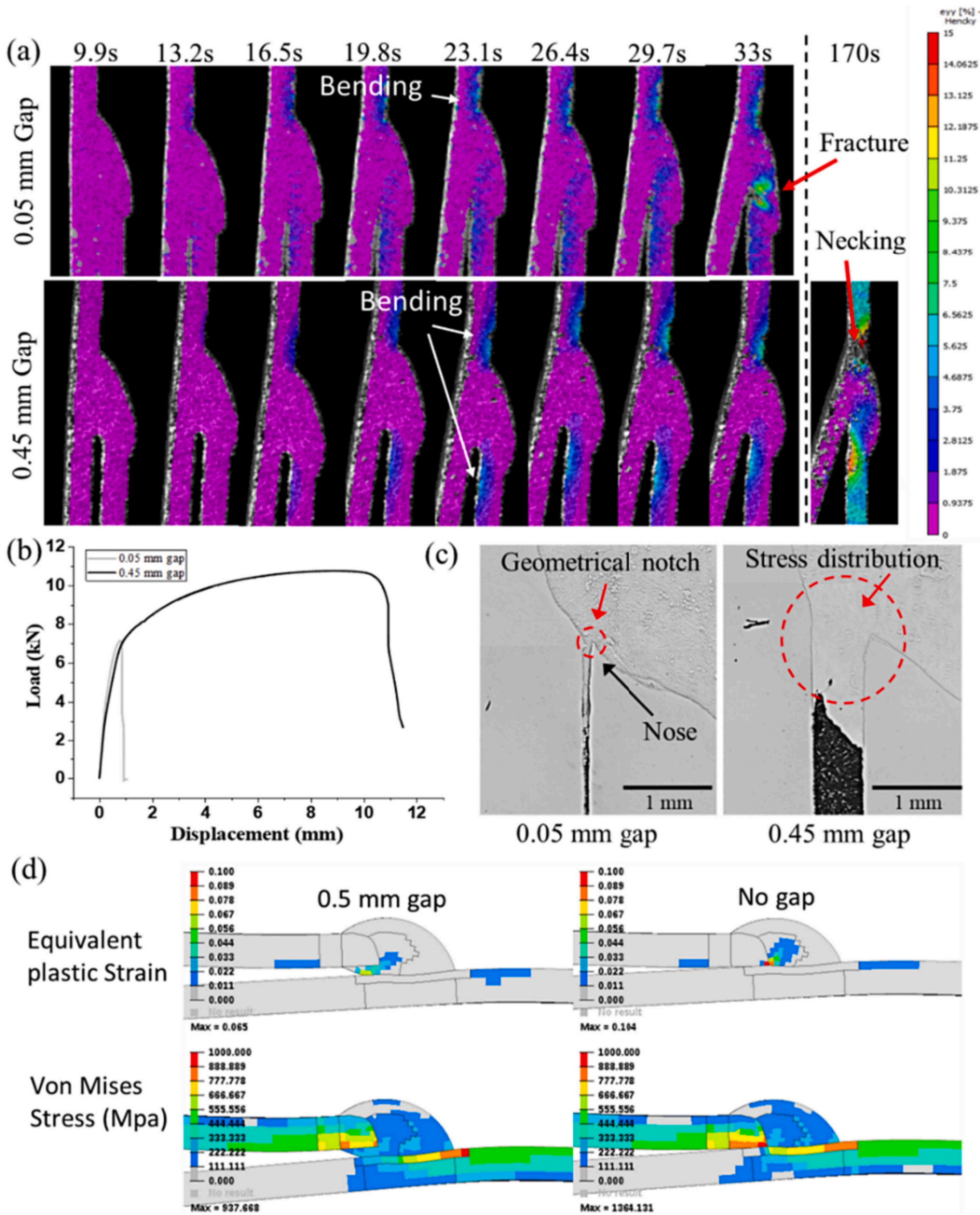


Fig. 20. (a) Digital image correlation of lap-jointed tensile coupons with controlled gap sizes of 0.05 mm and 0.45 mm, respectively. In the zero-gap specimen, fracture occurs much more quickly compared to the specimen with 0.45 mm gap [91].

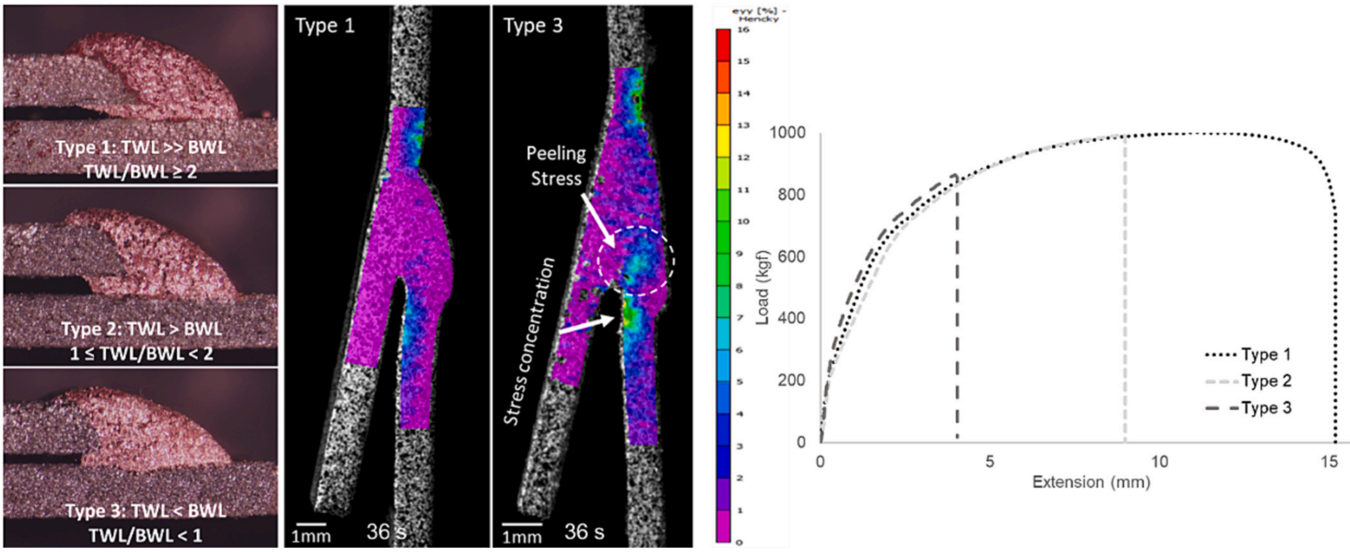
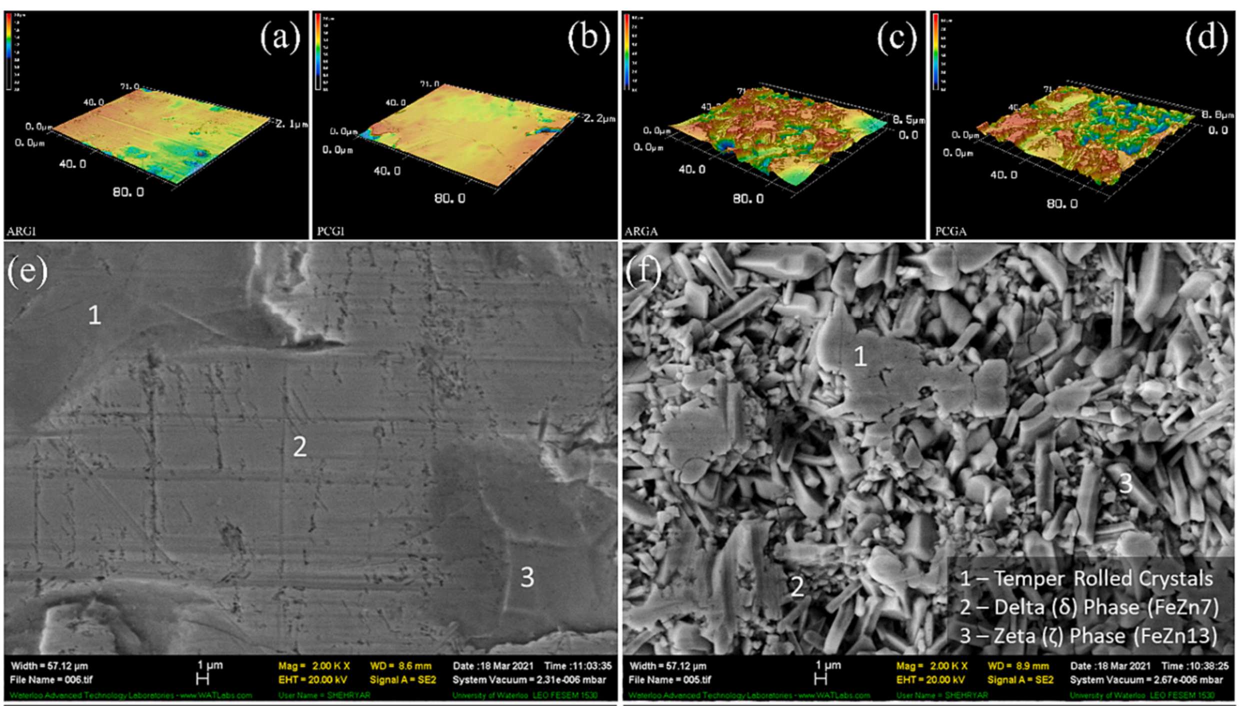


Fig. 21. Cross-sectional views of GMA weld-brazed specimens displaying 3 distinct characteristic root geometries known to form during GMAB. The DIC results illustrate a significantly higher strain build-up at the joint root for Type 1 root geometry compared to Type 3 during a given tensile test [10,101].



Region	Al wt% (at %)	Fe wt% (at %)	Zn wt% (at %)	Total
1	0.59 (1.41)	1.50 (1.74)	97.91 (96.85)	100
2	0.52 (1.24)	1.59 (1.85)	97.89 (96.91)	100
3	0.31 (0.76)	1.15 (1.33)	98.54 (97.91)	100

Region	Al wt% (at %)	Fe wt% (at %)	Zn wt% (at %)	Total
1	0.27 (0.64)	6.11 (7.05)	93.62 (92.31)	100
2	0.40 (0.96)	10.02 (11.47)	89.58 (87.57)	100
3	0.92 (2.17)	6.06 (6.93)	93.03 (90.90)	100

Fig. 22. 3D laser microscopy images illustrating the surface morphology of the galvanized and galvannealed coatings in the (a, b) as-received and (c, d) plasma cleaned condition, respectively. The corresponding electron microscopy images with accompanying EDS data is shown in (e, f) [30].

MPa) and experienced catastrophic failure in the fusion zone (FZ). In contrast, GA-coated samples consistently resulted in ductile failure that occurred away from the joint in the base metal when the joint geometry and root clearance was properly optimized [73]. Furthermore, fracture paths differed among similar samples that experienced failure in the FZ. GI-coated samples exhibited crack propagation along the top sheet, while the GA-coated samples displayed failure through crack propagation along the length of the bottom sheet [73]. This dissimilarity in the mechanical behaviour of weld-brazed joints, specifically in the case of the GI-coated samples, that have improved wettability but exhibit poorer mechanical attributes can be credited to the distinctive microstructures and morphologies of the Cu—Zn alloys that form at the extreme tip of the joint root along the top and bottom sheets (commonly referred to as the “tail”) [101].

Microscopy images of the tail cross-sections revealed that galvanized-coated weld-brazed specimens exhibited a tail-region that was rich in zinc and larger in comparison to the GA-coated samples [73]. The Cu—Zn rich regions of the galvanized samples also displayed

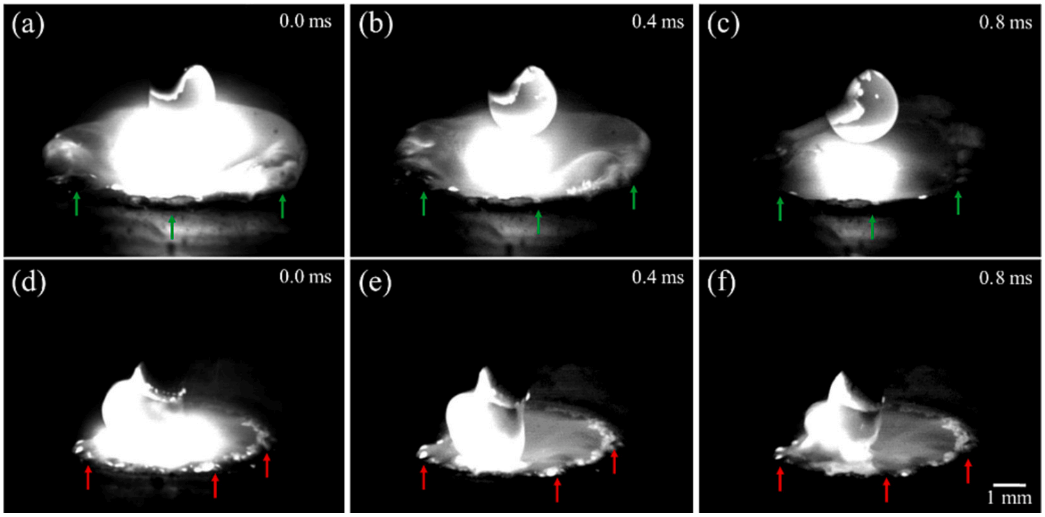


Fig. 23. High-speed camera images of one similar sequence taken from the molten Si-Bronze filler material deposition onto the substrate with (a–c) galvanized and (d–f) galvannealed coatings [30].

microcracks which were not observed in the galvannealed samples. Chemical analysis performed by Khan et al. [30,73] confirmed that the Cu—Zn alloy in the galvanized-coated weld-brazed specimens consisted of Cu-47 wt% Zn. In contrast, the galvannealed specimens had lower Zn content and relatively lower traces of Fe, Mn, and Si, with a Cu—Zn alloy composition of Cu-25 wt% Zn. This alloy composition is the most ideal for higher strain-to-failure values [103]. The presence of the brittle Cu—Zn compound in the galvanized-coated weld-brazed specimens was the most likely contributor to thermally induced cracks. Microhardness results indicated that the Cu—Zn compound in the galvanized-coated weld-brazed specimens was significantly harder compared to the galvannealed specimens [73]. The thickness of the IMC layer at the joining interface was reduced in the galvanized-coated weld-brazed specimens compared to the galvannealed specimens [30]. However, it's worth noting that the IMC layer thickness did not have a direct impact on the strength of GMA brazed lap joints since failures rarely exhibited interfacial characteristics. For an in-depth understanding of the influence of different types of zinc coatings on the structure and mechanical characteristics of GMA weld-brazed lap joints, readers are directed to Ref. [30,73].

6. Concluding remarks and recommendations

Producing strong and in-service reliable steel-steel brazed joints plays a key role in manufacturing crash-resistant automobile structures. The bottleneck is to acquire defect-free brazed joints with negligible undesired microstructural evolutions in the HAZ. Producing mechanically sound, defect-free, and reliable brazed joints primarily depends on adjusting the heat input, which necessitates precise control and systematic parameter adjustments in the processing. In addition, it is necessary to have clear understanding of the physics and chemistry of the selected joining process and fundamental knowledge of atomic processes to understand and control the microstructural evolutions in brazed joints especially at the interface. The main aim of researchers should be to overcome the issue of under-matching during steel-steel brazing without affecting metallurgical properties such as corrosion resistance, and hardness of the HAZ, for example. The following remarks should be considered in future research:

(i) *Solution of process-related issues:* The main issue with the use of conventional arc welding processes is the associated higher heat input which influences the microstructure and hardness in the HAZ of steels in an adverse manner. At higher heat inputs, excessive formation of martensite in the HAZ of dual phase (DP) steel is disadvantageous for some applications due to a parallel rise in the brittleness of the joints. The tempering of martensitic structures can lead to HAZ softening phenomena which can also be problematic. In addition, high heat input may degrade the stability of brazed joints in corrosive environments due to melting and evaporation of zinc coating from the steel surface. Due to the requirement of reducing distortion and zinc vaporization of the joints, low heat input processes/techniques are feasible. Short-arc ensures a lower energy transfer to base metal sheet (less melting of steel, less zinc evaporation) but poor wetting characteristics. In this regard, several low heat input welding techniques have been developed recently such as surface tension transfer (STT), cold metal transfer (CMT), and coldArc. The common feature of these techniques is the smooth deposition of molten brazing filler at comparatively low heat input with negligible distortion which is beneficial for joining heat sensitive and coated materials. Arc brazing can further reduce the energy transfer to the base metal due to lower melting temperature of brazing filler wire (~1040 °C) than that of steel filler used for welding which is advantageous from the metallurgical point of view.

(ii) *Penetration of Cu into grain boundaries of steel:* There is a lack of systematic research on the susceptibility of steel-steel brazed joints to liquid metal embrittlement caused by the penetration of molten Cu into steel grain boundaries. It emerged from the literature that modifying the chemistry of the filler can effectively suppress this phenomenon in brazed joints as it influences the atomic reactions which ultimately contribute to the microstructural evolutions at the interface of both steel and deposited braze filler metal. Addition of alloying elements such as Si, and Al to Cu-based fillers has shown remarkable results in preventing liquid penetration of Cu into the steel substrate. The formation of ferrite bands and a reaction layer at the interface prevents penetration of Cu into the intergranular regions. Modifications in composition of the base metal, coating and filler wire constitute a possibility for production of brazed joints with improved resistance to LME.

(iii) *Deficiency of fundamental research on the role of filler wire composition:* The composition of filler wire influences the geometrical, metallurgical, and mechanical characteristics of the brazed joints. Alloying elements such as Al and Si improve the wettability of the joints and strengthen the deposited bead as well as the interfacial region by forming intermetallic phases during steel-steel brazing.

For different filler wire compositions, further efforts are required to improve the fundamental understanding on the influence of alloying elements on the formation and growth of intermetallic compound layer. Furthermore, comprehensive and systematic investigations into the atomic processes/reactions at the interface of steel and deposited filler during solidification is necessary using advanced characterization techniques such as EBSD and TEM.

(iv) *Improvement of joint properties:* A fundamental bottleneck is to acquire a mechanically and metallurgically sound brazed joint. Under-matching is one of the critical issues which limits widespread application of brazing in thin sheet joining applications, particularly in the automotive industry. Recent developments showed remarkable achievements in overcoming the issue of under-matching. The load bearing capacity of steel-steel lap brazed joints can be improved significantly by inserting a filler strip in between the sheets without increasing the heat input. The literature shows that process parameters such as filler composition, torch position, wire feed rate, speed, and type of coating influence the joint strength. The type and thickness of the selected coating on the steel surface influences the wetting behaviour of the filler metal and the properties of brazed joints. However, there is limited systematic investigations on improving the dynamic/fatigue strength of the steel-steel brazed joints. The minimization of stress concentrations at the toe of lap brazed joints (e.g., decreasing the wetting/contact angle) has been identified as an effective approach for improving fatigue strength. However, the influence of metallurgical strategies for improvement of fatigue strength of steel-steel brazed joints is not extensively explored yet.

(v) *Scope for future research:* The performance of arc-brazed steel-steel joints is highly sensitive to heat input, as it directly affects corrosion resistance, the wettability of the molten filler on the steel surface, and the interatomic reactions both at the interfacial zone and within the deposited bead. Therefore, various strategies can be explored to manipulate the heat input, including the use of techniques that slow down the cooling rate, such as employing a backing plate made of less conductive material (the inverse case would be an interesting study as well to limit the formation of intermetallics). Additionally, incorporating interlayers of different materials or introducing nanoparticles into the molten pool aims to facilitate dispersion hardening of the deposited bead. However, the implementation of these techniques may have adverse effects on the corrosion resistance of the brazed joints. Furthermore, it is crucial to consider the impact of different joint geometries, with the goal of enhancing both wettability and dynamic strength. In summary, it is clear that detailed investigations into various approaches that have been highlighted are essential to optimize the performance of arc-brazed steel-steel joints for more widespread acceptance of this novel joining process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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