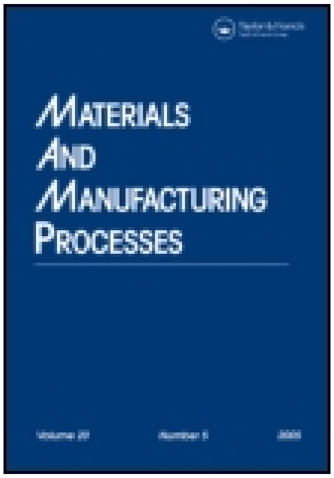

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Review of Research Progress on Aluminum–Steel Dissimilar Welding

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This paper presents a review of research progress on aluminum–steel dissimilar welding. Current issues and recent developments in improving the intermetallic compound layer of weld joint are critically assessed. Several welding factors that improve joint quality, such as welding method, weld and material preparations, as well as welding parameters, are also discussed. This study also examines recent developments in hybrid welding techniques and proposes a preheating method to enhance the weld joints of aluminum–steel dissimilar welding.

Keywords Aluminum; Dissimilar; Joining; Joint; Preheating; Steel; Welding.

Introduction

Dissimilar welding has received considerable attention in various industries, particularly in the automotive sector. One of the technologies that use dissimilar welding is known as tailor-welded blank (TWB). TWBs are manufactured by welding two or more sheets with different properties or thicknesses to form a single blank. The use of TWBs in automotive applications is increasing because of their sustainable advantages, such as reducing manufacturing costs and production operations, decreasing vehicle weight, and improving the mechanical properties of materials, as well as enhancing the quality of sheet metal stampings [1–4].

Current and potential dissimilar welding applications in the automotive industry include wind shield frame, center pillar, bumper reinforcement, and floor pan, among others [5]. In particular, the process of combining lightweight materials such as aluminum and high-strength materials such as ferrous alloys has undergone extensive research because of its potential for the automotive and other industrial sectors [4, 6, 7]. Such weldments benefit from the rigidity of steels and the light weight of aluminum, integrating the best of both worlds.

This paper examines the current issues and progress in improving the aluminum–steel weld joint. Various reports on weld methods to enhance solubility and inhibit intermetallic compound (IMC) formation are also discussed. Finally, this study argues for the significance of heat input in the welding process and proposes a hybrid method of preheating prior to arc welding to improve the joint strength of aluminum–steel dissimilar welding. The following sections are divided into three subsections which includes issues in aluminum–steel dissimilar welding, current progress in the improvement of joint strength, and preheating method as a novel approach to weld joint improvement.

Issues in aluminum–steel dissimilar welding

Aside from the dissimilar welding of similar metals with different thicknesses, the welding of two different materials can also be conducted. Arguably the most widely investigated dissimilar metal-welding process is between ferrous and aluminum alloys because of the unique combination of high strength and toughness of steel as well as light weight and formability of aluminum alloys, which has significant potential in the automotive and marine industries [6, 8].

Combining these two metal groups is difficult. Mathers [9] presented several dissimilar aspects of thermophysical and mechanical properties that complicate the process; namely, the melting and boiling points of the two metals and their oxides are different; aluminum has approximately twice the coefficient of thermal expansion and six times the coefficient of thermal conductivity compared to steel; the specific heat of aluminum is twice that of steel; and the modulus of elasticity of aluminum is three times that of steel. These differences pose a significant problem because a certain degree of distortion, metallurgical precipitation, and defect is anticipated, particularly in the weld region [10, 11].

One of the primary reasons for the limited research papers on aluminum–steel dissimilar welding is the near-zero solubility between aluminum and steel [12–14]. This condition results in the formation of brittle IMC layer between the two sheets. This layer has been studied rigorously and numerous papers commonly consider this layer as the weakest zone, crack propagation point, and the cause for the deterioration of the mechanical properties of the joint [15–17]. However, Borrisutthekul et al. [18] and Zhang et al. [7, 19] refuted this claim and revealed that because of grain growth, the heat-affected zone (HAZ) in the aluminum region would be the weakest zone, where tensile tests showed that fractures occurred in this zone.

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Aluminum–steel joining involves a welding–brazing interaction, since the welding temperature is higher than the melting point of aluminum (welding joint), but lower than the melting point of steel (brazing joint). Due to the near-zero solubility as mentioned above, inevitably an IMC layer is formed throughout the contact surface of the materials. This layer possibly consists of Fe_xAl_y brittle phases such as Fe_4Al_{13}, Fe_2Al_5, $FeAl_3$, and FeAl [20, 21]. Kobayashi and Yakou [22] suggested that the growth of these IMC layers was diffusion-controlled growth of Fe atoms. The IMC thickness under the diffusion control process is expressed as follows:

$$X = K\sqrt{t} \tag{1}$$

and

$$K = K_o \exp\left(-\frac{Q}{RT}\right) \tag{2}$$

where X is the IMC thickness (mm), t is the time (s) for diffusion, K_o is a constant, Q is the activation energy (J) for the growth of the layer, R is gas constant, and T is the absolute temperature (K) [23].

The IMC growth mechanism can be understood from a particular investigation of 5A06 aluminum alloy and AISI 321 stainless steel welding using Si-rich filler metals, as reported by Song [17]. It consists of several stages during the welding process. First, the Fe atoms undergo dissolution and diffusion and Si atoms begin to aggregate in the interface. The nucleation and growth of a θ-$Fe(Al,Si)_3$ phase and a τ_5-$Al_{7.2}Fe_{1.8}Si$ phase follow, eventually culminating with the solidification of the welded seam.

The formation of these brittle layers between the alloys through diffusion adversely affects weld strength. Thus, Kreimeyer and Sepold [24] proposed that for an IMC layer thickness of less than 10 µm, the joint could be considered mechanically sound. Therefore, a thinner IMC layer contributes to improved dissimilar weld joint strength [12, 23, 25–28].

Current welding method and techniques to weld aluminum–steel

The IMC layer is a major concern in aluminum–steel dissimilar welding. Thus, most published papers in this field mainly focused on parameter optimizations and techniques to inhibit the formation of this layer. Reports have suggested several welding techniques and welding parameters that have been shown to cause a decrease in IMC growth and a consequent improvement in the strength of the joint. The subsections that follow discuss several common attributes and improvements.

Welding Method

Previous studies show that the most common arc welding method and weld joint type used to produce aluminum–steel welds are the tungsten inert gas (TIG) and lap joint weld, respectively [18, 20, 21, 29]. TIG welding is more favorable than metal inert gas (MIG) welding, since [9, 30]; the TIG arc is stable even at low currents, making welding of thin parts possible; it produces very good weld quality, and is an ideal candidate for aluminum welding.

Although the most common weld configuration is the butt joint, forming aluminum–steel butt joints is relatively difficult, and numerous researchers opt for the lap joint configuration instead. In this configuration, opinions differ as to which configuration yields the best joint. Several researchers used aluminum stacked on top of steel to induce aluminum brazing on the steel surface [7, 12, 19–21, 31]. Other researchers used steel stacked on top of aluminum to elevate steel temperature and promote better aluminum–steel mixture [19, 20, 23]. Preliminary experiments conducted by the author supports the latter formation because it promotes temperature increase close to the steel melting point. Details are discussed in the final subsection of this paper.

Several studies successfully conducted overlap arc/laser welding of aluminum and steel without the use of filler metals [18, 20, 32–34]. This method is called the self-brazing technique, where the molten zone of steel caused by the TIG torch/laser heat input is controlled to become a partial penetration on the opposite surface directly in contact with the aluminum sheet. For TIG aluminum–steel self-brazing, Borrisutthekul et al. [23] suggested that a higher heat input and weld speed, coupled with low electric current, would result in a thinner IMC layer. Notably, heat propagation through the steel counterpart can initiate aluminum melting, without having to melt the whole steel thickness. This is to avoid liquid steel and liquid aluminum interaction in order to prevent cracking in the aluminum side due to rapid formation and growth of IMCs [20].

The use of nonconventional welding methods such as laser welding in dissimilar welding research has also grown steadily. Laser welding has been shown to have numerous advantages over conventional arc welding. These advantages include localization of fusion with reduced HAZ, low heat input level that limits the IMC thickness to a few microns, and deep weld penetrations [35–37]. Numerous studies have shown that penetration depth, which is controlled by laser power and travel speed, can serve a major function in defect formation, IMC layer thickness, and mechanical strength of the weld joint [12, 37–39].

Another current development is the hybrid welding processes, where two distinct welding methods are used simultaneously to take advantage of both methods [40]. Several hybrid welding methods reported include laser–TIG welding [41–44], laser–MIG/MAG welding [45–49], TIG–MIG welding [50], laser–friction stir welding [51], and TIG–friction stir welding [15, 52]. These hybrid approaches have been shown to enhance plastic flow, improve elongation, shorten welding time, and yield better weld joints. However, research on the use of hybrid welding in aluminum–steel welding is limited and remains a potentially intriguing field to venture into.

Depending on the intended output, that is, aluminum brazing or temperature elevation of steel, when using lap joint configuration, either the aluminum or the steel counterpart can be stacked on top. Current hybrid welding techniques have been proven to improve the joint quality significantly. Other than the welding method, other factors to consider in inhibiting IMC thickness are welding and material preparations.

Welding and Material Preparations

A thorough welding preparation is necessary before experimentation. Aside from common requirements such as oxide layer and grease removal, an improvement in material preparation prior to the arc welding process is the use of a noncorrosive flux such as Nocolok ($KAlF_4$ and K_3AlF_6 eutectic) [14, 16, 17, 20, 36]. These fluxes have been proven to improve the wetting and spreading of filler metals by removing aluminum and steel oxides because such fluxes have a melting temperature range just below the melting point of aluminum (565–572°C). When melted during the welding process, fluxes dissolve the aluminum oxide layer, thereby enabling direct contact between aluminum (liquid state) and steel (solid state) as well as preventing the oxidation of molten aluminum [20]. In the case of laser welding, Sierra et al. [20] proved that, without flux, the wetting angle of an aluminum–steel lap joint becomes smaller, i.e., better grip can be achieved. Meanwhile, by using flux, the IMC thickness can be reduced because better spreading results in low heat input requirement and faster travel speed. Despite its good reputation, Nocolok flux is expensive and is difficult to obtain. Therefore, affordability and availability are primary concerns. Alternatively, the use of flux-cored fillers in arc aluminum–steel welding has also been shown to improve the dissimilar joining process [53–55].

In terms of improvements on the parent metals, the 5XXX series (Al–Mg) and 6XXX series (Al–Si–Mg) are considered as good aluminum base metal candidates, where Mg increases strength and corrosion resistance, whereas Si increases strength and fluidity of the alloy [9]. The selection of galvanized iron (GI) as the ferrous counterpart has also been shown to have a positive effect on aluminum–steel welding. This observation can be attributed to the existence of a thin Zn layer on the surface of the GI. This layer initially acts as corrosion preventer and assists in the welding process because Zn has good metallurgical compatibility with both aluminum and steel [7, 16, 20, 21, 31, 56]. However, additional precautions have to be considered when using such materials. More heat input yields better wettability, but the Zn layer has a lower boiling point (907°C) than steel and can evaporate during the welding process, thereby leaving pores in the weld joint that can decrease joint strength [21, 37].

Several common key points can be obtained in this subsection. For the aluminum counterpart, the Al–Mg and Al–Si–Mg alloy sheets can be chosen. Meanwhile, Zn-coated steel is a good nominee for the steel side. Alternatively, a noncorrosive flux can be used when other steel types are considered.

Welding Variable Improvements

To prevent the formation of brittle IMC layers, an alternative approach has been introduced to improve the filler metals used during welding by increasing the Si composition percentage. Several studies proved that Si-rich fillers could suppress IMC growth by replacing brittle Al–Fe phases with Al–Fe–Si ternary phases which has a lower formation enthalpy [17, 21, 31, 37, 55]. In addition, by increasing the Si percentage, the solubility and dissolution rate of Fe in the Al molten pool increased significantly. Additions of Si-rich aluminum fillers also mitigated hot cracking in weldments [9, 57]. However, this notion was contradicted by Lin et al. [16] and Song et al. [17], who argued that larger percentage of Si additions in the filler metal had low impact on improving the IMC's crack resistance, since the formed Al–Fe–Si phase also presented high brittleness. The Si percentage should be limited to 5 wt.% to produce optimum mechanical property.

The last but apparently the most significant factor to consider in improving the aluminum–steel joint is the heat input from the welding process. For arc welding, heat input is expressed by the following equation [58]:

$$J = \frac{\mu \times UI}{1000 \times V} \tag{3}$$

where J is the heat input (kJ/mm), η is the coefficient of welding efficiency, U is the current (A), I is the voltage (V), and V is the travel speed (mm/s). Varying the heat input variables can adversely affect the weld penetration, width, defects, and distortions, as well as the IMC thickness. Therefore, thorough parameter optimization is crucial in the investigation of the optimum heat input variables, where the welding type, welding power source (alternative or direct current), as well as base metal property and thickness must be considered [7, 14, 18, 19, 30].

Welding variables, such as filler metals and heat input, serve a major function in weld output. Si-rich fillers improve weld quality, whereas the heat input has to be controlled to achieve the desired weld penetration and width, as well as to minimize defects.

Preheating as a Novel Approach to Improvement of Weld Joint

The heat obtained in situ during the welding process is not the only source of heat input for base metals. Preheating, i.e., the act of heating the samples at a certain desired temperature prior to welding, is also a means of obtaining external heat to be induced on the material. This process is mainly reported in the case of steel alloys. In traditional steel welding, four reasons necessitate the preheating of a welding material [59, 60]; it slows the cooling rate of the joint, thereby producing a more ductile and greater crack resisting structure; hydrogen elements present inside could diffuse out harmlessly; it

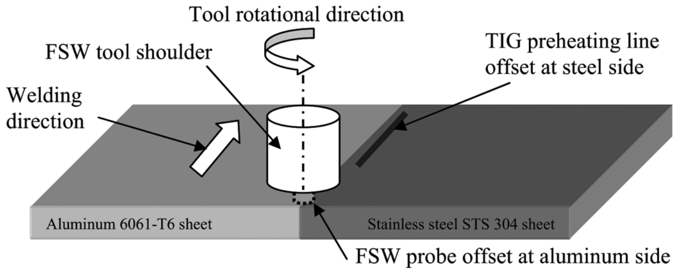

FIGURE 1.—Schematic of hybrid FSW/TIG process.

can reduce the shrinkage stresses of the weld joint and base metal, as well as prevent brittle fracture of steels during fabrication.

Kreimeyer and Vollertsen [61] suggested that the limitations faced in aluminum–steel welding can be overcome by the use of a hybrid welding process. To support this notion, several studies have also proposed that heating using a secondary heat source can also be employed to improve dissimilar welding joints [52, 62–64]. Bang et al. [15] suggested the use of a hybrid TIG and friction stir welding (FSW) method, where the TIG functions as an additional heat source. Figure 1 shows a schematic of the hybrid FSW process. Without any additions of filler metals, the TIG torch becomes a secondary heat source to preheat the stainless steel side of the butt joint to elevate the initial temperature of the stainless steel sheet and to soften the microstructure to a more plastic state. Once the initial temperature is increased, the FSW tool welds the sheets together with an offset position toward the aluminum alloy. Along with tool rotation (rpm) and travel speed (mm/min) optimization, this hybrid method has successfully shown that a preheating process can create a better aluminum–steel mixture, which consequently yields better joint strength. A similar approach was proposed by Sinclair et al. [63], where the TIG torch was replaced by an induction heating device.

Basing from the utilization of the hybrid FSW–TIG/FSW-induction heating welding mechanism, we propose a hybrid TIG/MIG welding method for dissimilar welding. The TIG torch also functions as a steel preheating heat source, where the desired preheating temperature can be controlled and adjusted to the desired value, before MIG welding is conducted. Kanemaru et al. [50] reported that a TIG/MIG hybrid technique can improve similar weld joint quality and welding efficiency as well as reduce welding time by as much as 44% compared with the conventional TIG process.

Alternatively, a conventional blow torch can be a substitute for the preheating process, and the TIG torch can function as the primary heat source. Several preliminary results of preheating using blow torch prior to TIG welding conducted by Shah et al. [65] and Razak et al. [66] have shown better steel and aluminum mixture as well as an increase of as much as 80% in the tensile strength of the weld joint. Figure 2 presents a comparison of the cross-sectional view of the non-preheated and preheated aluminum–stainless steel samples.

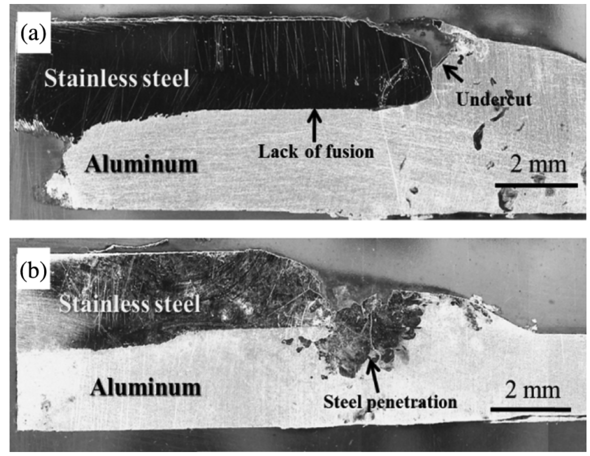

FIGURE 2.—Cross-sectional view of the (a) nonpreheated and (b) preheated aluminum–stainless steel TIG welding [65].

SUMMARY AND CONCLUSION

The welding industry has been rejuvenated with the introduction of dissimilar welding and nonconventional as well as hybrid welding methods. Recent developments in dissimilar welding are considered as a way forward for the industry and are leading toward a bright future for what was previously thought to be a saturated field. Dissimilar welding has exhibited significant potential to cut down manufacturing cost and time, particularly in the automotive and shipbuilding industries. The optimization of welding method, base metals, filler metals, heat input, and other key variables of dissimilar welding remain as major topics for research.

A critical review has been discussed in the paper concerning dissimilar welding of aluminum and steel. Based on the review of several previous studies on aluminum–steel welding, a number of common aspects are observed. For arc welding, TIG welding is generally preferred. As regards to parent metals, aluminum 5XXX and 6XXX series are excellent aluminum candidates. For the steel counterpart, galvanized steel can be utilized for its Zn-coating to aid in the aluminum–steel mixture. When other steel groups or codes are considered, a noncorrosive flux or a flux-cored filler can be utilized to improve mixture and limit IMC formation. A preheating technique in the form of hybrid welding is also proposed to develop a sound mixture between aluminum and steel. However, a precise preheating heat input is crucial to yield the best quality joint. Thus, this research area should be further explored.

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