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Research paper

Interfacial microstructure and shear properties of aluminum alloy to steel fusion-brazed welded joint

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A B S T R A C T

A nearly symmetrical wavy interface of steel and intermetallic compounds (IMCs) layer formed in the central zone of fusion-brazing welding joint of aluminum alloy to steel. The process temperature of brazed interface, nearly reaching up to steel melting point, greatly facilitated the formation of wavy interface. With the increase of the welding current, the wavy interface was much more evident. The preferable growth of Fe_2Al_5 perpendicular to slope of wavy interface could lead to the formation of void at the tip of wavy interface, which might deteriorate joint strength. During shear test, cracks initiated at the interface of IMCs layer and steel or the inner parts of IMCs layer with the consideration of great lattice misfit degree and brittleness of IMCs. If welding current was lower than 45 A, cracks then propagated into weld toe, indicating weld toe had a higher bonding strength with steel which was proved by the shear strength results, while when the welding current was higher than 55 A, fracture just occurred at brazed interface. Not only the thickness of IMCs layer but the wavy interface affected the fracture behavior and strength of joint.

1. Introduction

With the demand of high strength-to-weight ratio structures, the joining of aluminum (Al) alloy to steel becomes one of the hottest topics in recent years. However, the great differences in thermo-physical properties and the formation of brittle intermetallic compounds (IMCs) between the two metals are two crucial factors influencing the properties of Al alloy to steel joint. Different joining methods have been employed to realize a sound joint of Al alloy to steel. Tanaka et al. (2015) and Leitao et al. (2016) studied friction stir welding of Al alloy and steel by numerical simulation and experiment respectively, while Springer et al. (2011a,b) investigated the diffusion welding of Al alloy to steel and resistance spot welding of Al alloy to steel was researched by Wan et al. (2017). A novel joining method, fusion-brazing welding, taking advantage of the difference in melting point of two metals, is attracting increasing attention due to the high working efficiency as well as excellent joint performance, as presented by Zhang et al. (2017). During welding process, base metal and filler metal with relatively low melting points melt to form the fusion welded joint, while the base metal with high melting point keeps the solid state and forms the brazed joint with the molten low melting point base metal and filler metal. Through this approach, the formation of IMCs layer can be greatly compressed which is favorable for the improvement of mechanical properties.

In the fusion-brazed welded joint, the complex metallurgical reaction still happens at the brazed interface, the brazed interface is one of the most important factors influencing the joint properties, especially the formation of IMCs layer. The phase composition of IMCs formed at brazed interface or the evolution of IMCs under different conditions was usually investigated. Zhang et al. (2017) discovered Mn and Si restricted the growth of IMCs layer without changing composition and crystal structure of IMCs in laser fusion-brazing welding of Al alloy to steel. Ma et al. (2016a,b) investigated the growth behavior of IMCs layer by altering the initial temperature of base metals. It was widely shared that the formation of IMCs layer was a proof of these two alloys realizing the metallurgical bonding, while when the IMCs layer was too thick, there might get a spontaneous fracture that deteriorated joint strength. The thickness of IMCs should be suppressed at a relatively low value. A critical thickness value of IMCs layer for satisfied joint strength was not greater than 10 μm which was obtained by Schubert et al. (2001). For fusion-brazing welding of Al alloy to steel, Cao et al. (2013) found out when the thickness of IMCs layer was about 5 μm, the joint had the highest tensile strength. When the thickness of the IMC exceeded 5 μm, the joints failed at the brazed interface with relatively low strength. By adopting optimized fusion-brazing welding process parameters, Murakami et al. (2003) constrained the thickness of IMCs layer less than 2.5 μm with joint fractured at heat affected zone on Al alloy side. The strength of joint dropped quickly after the thickness exceeded

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2.5 μm. The thickness of IMCs layer could reveal the mechanical properties of the joint to some extent, but the morphology of brazed interface is also another key factor in influencing joint strength, which is still needed exploring.

Although different kinds of methods were applied to join Al alloy to steel and the IMCs phases were identified by different material analysis methods, such as diffusion welding, friction stir welding and gas metal arc fusion-brazing welding, an Al-rich phase – Fe_2Al_5 can be formed with the consideration of the lowest Gibbs free energy at the certain temperature range in a relatively high growth rate. Rest et al. (2014) and Su et al. (2014) both discovered that Fe_2Al_5 was formed adjacent to steel. For Al-rich phases, like Fe_2Al_5, presenting a rather high hardness, cracks could easily initiate and propagate from these phases. Song et al. (2009) found that the fracture happened at Fe_2Al_5 layer in tensile test of brazed-fusion welded joint of Al alloy to steel, which was further confirmed by Qin et al. (2017). Su et al. (2014) observed that the fracture could occur at interface between Fe_2Al_5 sub-layer and steel. Wang et al. (2016) found that numbers of porosity and cracks existed in the Fe_2Al_5 layer of laser welding joint of Al alloy to steel. However, how the cracks initiating and propagating in brazed-fusion welded joint of Al alloy to steel at different welding parameters are key points for analyzing the facture mechanism which is seldom reported.

As another mechanical property testing approach, shear test provides a more distinct way to observe the cracks propagation than the tensile test does for the lap joint. The characterization of fracture morphology after shear test can also offer a unique way to analyze the fracture mechanism and the role of IMCs layer during fracture process. Thus a special shear test fixture was designed to conduct the shear test in present study. The microstructure of brazed interface as well as cracks propagation during shear test was investigated. An inerratic wavy interface between steel and intermetallic compounds layer in brazed-fusion welded joint of Al alloy to steel was identified and its formation mechanism was discussed. The fracture mechanism of the joint after shear test based on the combination of the wavy interface and phase composition was analyzed in detail.

2. Materials and methods

The 5052 Al alloy plate with the thickness of 1 mm and the hot-dip galvanized steel plate with the thickness of 2 mm were used as the base metals. ER4043 (Al – 5% Si) with the diameter of 1.2 mm was adopted as the filler metal. The chemical compositions of 5052 Al alloy, galvanized steel (not including the zinc layer) and filler metal provided by the suppliers are presented in Table 1. The Al alloy plate was cleaned with abrasive paper and acetone, and the galvanized steel plate was cleaned with acetone before welding.

A pulsed metal insert gas arc welding (GMAW) with pulse mode of 1 droplet/pulse was employed. After choosing specific filler metal, average arc voltage and average welding current could be adjusted automatically with the wire feeding rate. Al alloy plate was lap joined on galvanized steel plate, as shown in Fig. 1(a). Welding speed was kept at 0.6 m min^{-1}. The detailed welding parameters are listed in Table 2. In order to clearly exhibit the variation of welding parameters in this study, the welding current (*I*) was picked. During welding process, the temperature was measured by using a type-B thermocouple with acquisition frequency of 1000 Hz embedded at brazed interface in the central zone of Al alloy to steel brazed-fusion welded joint.

Table 1
Chemical compositions of 5052 aluminum alloy, galvanized steel and filler metal (wt.%).

Materials	C	Si	Mn	Mg	Cu	Zn	Fe	Al
5052 Al alloy	–	0.25	0.10	2.2–2.8	0.10	–	0.16	Bal.
Galvanized steel	0.04	0.05	0.29	–	–	–	Bal.	–
ER4043	–	4.5–6.0	0.05	0.05	0.30	0.10	0.80	Bal.

After fusion-brazing welding, the cross-section of joint was cut by wire cutting electrical discharge machining, then was ground, polished by the standard metallographic procedures. The microstructure of brazed interface in the central zone was analyzed by scanning electron microscopy (SEM). The cross-sectional joint with width of 10 mm was firstly obtained and then the excess Al alloy and steel base metals were cut for shear test, as shown in Fig. 1(b). Then specimens were fixed in the fixture to perform the shear test, as indicated by Fig. 1(c). During the shear test, the cross-head speed was fixed at 1 mm/min. The shear strength of joint was calculated as (Qin et al., 2014):

$$\sigma_b = \frac{F}{A} = \frac{F}{l \times \delta} \tag{1}$$

where *F* was the maximum load, *A* was cross-section area of fracture position, *l* was the width of test sample (10 mm), δ was the length of brazed interface. At least five samples were used to conduct the tensile test and the average of results was regarded as the shear strength. The side of joint (grey region in Fig. 1(c)) after shear test was observed by SEM in order to analyze the fracture behavior.

3. Results

There exist three zones in cross-sectional joint identified by their distinct microstructures, which are weld toe, central zone as well as weld root, in all the joints regardless of welding parameters. Weld toe and weld root are characterized by the residual existence of Zn due to the relatively low temperature during welding process, while the central zone forms a typical IMCs layer with consideration of the highest process temperature compared with the other two zones, becomes a critical part influencing the joint strength. The detailed studies of the microstructures evolution mechanism in weld toe and weld root had been already reported by Liu et al. (2015).

3.1. Microstructure of the central zone

Fig. 2(a)–(c) shows the morphology of brazed interface in the central zone at different welding currents. The microstructures of brazed interface are not presented when the welding current is lower than 45 A due to the quite thin IMCs layer and relatively smooth brazed interface. As illustrated by Fig. 2, with the increase of welding current, not only the thickness of IMCs layer increases but also the stratification phenomenon of IMCs layer becomes more and more obvious (dashed line in Fig. 2(b) and (d)). As aforementioned, though different kinds of Fe-Al IMCs can form in different joining methods, the layer adjacent to steel, marked as layer II in Fig. 2, presenting in a compact plate-like shape, is composed of Fe_2Al_5, whose composition will not be further studied in present study. With respect to layer I, according to our previous study, this needle-like layer forms due to the interdiffusion of layer II and Al atoms, consisting different phases, such as Al_8Fe_2Si and Fe_4Al_{13}, from our pervious study (Ma et al., 2016a,b).

Moreover, it can be observed that the interface on steel side is wavy – a unique kind of wave has formed, marked in the dashed ellipse in Fig. 2(a)–(c). These waves present a nearly symmetrical shape, and waves with different sizes can form at the same welding current. When I = 75 A, voids are formed between the wavy interface and IMCs layer, which may be the result of the unique growth behavior of IMCs layer by wavy interface, as revealed by IMCs grain boundary marked by red dashed line in Fig. 2(d). However, the formation mechanism of this wavy interface and its effect on the IMCs layer are not clear, which will be discussed in Section 4.1.

3.2. Fracture path of joint

During shear test, two different fracture paths are identified at different welding currents: mode I fracture and mode II fracture. Mode I fracture is that the cracks firstly initiate at brazed interface and then

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