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Influence of Al additions in Zn–based filler metals on laser welding–brazing of Al/steel

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ABSTRACT

Laser welding–brazing Al/steel with different Zn–Al filler metals was performed. Experiments and thermodynamics calculations were conducted to analyze microstructure evolution and elemental diffusion behavior, respectively. The interfacial intermetallic compounds (IMC) was composed of dominating layered η–$Fe_2Al_5Zn_{0.4}$ phase and two different types of δ–$FeZn_{10}$ phase. Scattered δ–$FeZn_{10}$ phase among layered η–$Fe_2Al_5Zn_{0.4}$ matrix was found in all joints while continuous δ–phase adjacent to steel substrate appeared in joint obtained with Zn–Al2 and Zn–Al15 fillers and disappeared in the case of Zn–Al22 filler. Thermodynamics calculation showed that Zn element preferentially diffused to the Fe–Al interface and steel substrate, and reacted with generated Fe–Al IMC and residual Fe elements, leading to the presence of Zn element in η–$Fe_2Al_5Zn_{0.4}$ phase and the formation of δ–$FeZn_{10}$ phase. The increasing Al addition in filler metals induced a more sufficient Fe–Al reaction, causing a thicker Fe–Al IMC layer and insufficient residual Fe elements at the interface. It would be harder for the Zn elements to diffuse through the η–$Fe_2Al_5Zn_{0.4}$ layer with larger thickness. A higher Gibbs free energy of δ–$FeZn_{10}$ phase compared with η–$Fe_2Al_5Zn_{0.4}$ phase, insufficient Fe and Zn elements at the interface were all responsible for the disappearance of continuous δ–$FeZn_{10}$phase. Joint with the highest tensile strength was produced with Zn–Al22 filler owing to the disappearance of continuous δ–$FeZn_{10}$ phase and crack–inhibitation effect of scattered δ–$FeZn_{10}$ phase among layered $Fe_2Al_5Zn_{0.4}$ matrix.

1. Introduction

Each 1% reduction in total weight of vehicle reduces fuel consumption by about 0.75% [1]. Replacing heavy steel component with light metal aluminum alloy provides a promising solution for this light–weight design. With this kind of Al/steel hybrid structure, the total weight of vehicle reduces and the emission of polluting gas will be limited [2–4]. Welding technology is an effective method to join the steel and Al. The formation of interfacial intermetallic compounds (IMCs) must be controlled precisely since it exerts great influence on the mechanical properties of Al/steel hybrid component [5].

Laser welding–brazing Al/steel dissimilar joint has attracted much more attention due to its high joining efficiency, accurate melting location, low welding deformation and thin interfacial IMC thickness [6–9]. In the laser welding–brazing Al/steel dissimilar joint, alloying elements contained in filler metals had a great influence on the formation of interfacial IMC. To date, Zn–based eutectic (Zn–Al2, Zn–Al4, Zn–Al15 and Zn–Al22) and Al–based eutectic (Al–Cu6, pure Al, Al–Si5, Al–Si10–Mg and Al–Si12) have always been selected as filler metals and many researches about influence of these alloying elements (Si, Cu and Zn) on the interfacial reaction mechanism were investigated [2,6,10–16].

For the alloying element Si, Spring et al. [16] held the view that presence of Si element at the Fe/Al interface would reduce the reaction rate between Fe and Al elements and finally reduce the thickness of interfacial IMC. In addition, the interfacial IMC components would change from η–Fe_2Al_5phase + θ–$FeAl_3$ phase to θ–$Fe(Al,Si)_3$ phase + τ_5–Fe_2Al_8Si phase when the Si content in filler metals increased from 0 wt.% to 5 wt.% [14]. As for the Cu element, it was found that the Cu elements would replace some existed Fe elements in θ–Fe_4Al_{13} phase [12]. With this kind of Fe–Cu–Al IMC (θ–$(Fe,Cu)_4Al_{13}$ phase), the hardness of IMC was reduced and hence an interface with higher cracks resistance was produced.

Nevertheless, for the alloying Zn element at the Fe/Al interface, the influential mechanism on interfacial reaction was reported to be different. Dharmendra et al. [10] discovered that the Al element owned a

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higher affinity with Zn element than that with Fe element. They considered this higher affinity between Al and Zn elements was responsible for the presence of Zn elements in η–$Fe_2Al_5Zn_{0.4}$ phase. Yang et al. [11] found scattered δ–$FeZn_{10}$ phase would be newly formed among the dominating layered η–$Fe_2Al_5Zn_{0.4}$ phase. This dispersive distributed δ–$FeZn_{10}$ phase owned a low hardness and better ductility. During the tensile load process, this dispersive distributed and softer δ–$FeZn_{10}$ phase would provide a higher resistance to cracks and hence improve the joint strength. In addition, Spring et al. [2] discovered that a pronounced growth–acceleration of interfacial IMC (η–Fe_2Al_5 phase) would be appeared when the Zn element diffused into the Fe–Al interface.

According to research results above, it could be found that the Zn elements would diffuse to the Fe/Al interface during welding–brazing process and finally influence the interfacial reaction between Al and Fe elements. The different Al additions in Zn–based filler would result in formation of η–Fe_2Al_5 phase with different thicknesses, which affected the difficulty level of Zn element diffusion through η–Fe_2Al_5 phase. As a result, different morphology and compositions of IMCs formed. It was reported that the elemental diffusion was determined by the reduced tendency of chemical potential [17]. The appearance of Zn element at the Fe–Al interface showed that lower chemical potential value of Zn element was obtained at the Fe–Al interface. Nevertheless, most present researches mainly focused on the observation of Zn element existence at the Fe/Al interface while rare investigations were conducted to analyze this phenomenon by chemical potential of Zn element in Fe–Al–Zn ternary system [2,10,11,18,19].

Therefore, the aim of this study was to investigate the influence of different Al contents in Zn–Al filler metals on microstructure, diffusion behavior of Zn element at the Fe–Al interface and mechanical properties of the laser welded–brazed Al/steel dissimilar butted joint. The interfacial microstructure of the joints obtained by Zn–Al2, Zn–Al15 and Zn–Al22 filler metals was observed and compared. Corresponding interfacial thermal cycles along the brazing interface at selected regions were calculated by FEM software MSC.MARC. The chemical potential value of element Zn in Fe–Al–Zn ternary system was investigated to clarify the diffusion behavior of element Zn at the Fe/Al interface. Finally, fracture behaviors of the joints obtained with different Zn–based filler metals were evaluated.

2. Experimental procedures

2.1. Selected materials

In this research, non–galvanized DP590 dual phase steel and 6061Al–T6 aluminum alloy sheets were selected as base metals. The dimension for DP590 steel was 100 mm × 50 mm × 1.2 mm while 6061Al–T6 alloy was 100 mm × 50 mm × 1.5 mm. Their chemical compositions and tensile strength were listed in Table 1. Three different Zn–based filler metals (Zn–Al2, Zn–Al15 and Zn–Al22 with different contents of Al elements) with the diameter of 2.0 mm were selected for comparison. The corresponding chemical compositions and tensile strength for these Zn–base filler metals were listed in Table 2. These three filler metals all contained non–corrosion Nocolok flux. The Nocolok flux consisted of 65 wt.% $KAlF_4$ and 35 wt.% K_3AlF_6, with its melting point of about 575–590 °C.

Table 2
Nominal compositions of three different Zn–based filler metals [11,18,19].

	Cu	Mn	Mg	Ni	Zn	Al	σ(MPa)
Zn–Al2	0.28	0.15	0.10	–	Bal.	2.00	210
Zn–Al15	–	–	–	0.13	Bal.	15.00	236
Zn–Al22	0.41	–	0.08	0.21	Bal.	22.00	225

2.2. Laser welding–brazing process

A fiber laser (IPG YLR–6000) with a maximum power of a 6000 W was employed for welding–brazing Al/steel dissimilar metals. The workpieces were joined by a vertical–irradiation laser beam. A 30° angle was set between the filler metal and welded–brazed workpieces. The defocused laser beam with radius of 0.28 mm completely irradiated on the filler metal. A front filler–feeding method was adopted in this research to guarantee the stability of molten pool. A +20 mm defocused laser beam was employed during welding–brazing process to obtain a larger heating area and hence stabilize the welding–brazing process. The argon shielding gas was flowed to the front and back surfaces of the welded–brazed workpieces to protect the molten filler metal from oxidation. The gap distance between Al and steel sheet was set as 1.0 mm so as to improve the wettability and spreadability of molten filler metal along the back surfaces. Detailed schematic diagram of laser welding–brazing Al/steel butted joint was presented in Fig. 1. Before the final welding–brazing process, several trial experiments were conducted to obtain visually acceptable weld appearances. The finally selected welding–brazing parameters adopted in this research were listed in Table 3.

A 45° half–V shape groove was cut in the steel base metal to improve the wettability and spreadability of molten filler metal along the brazing interface. Before laser welding–brazing, the DP590 steel and 6061Al–T6 sheets should be cleaned. The DP590 steel sheets were firstly soaked in the acetone for about 3 min. Then these DP590 steel sheets should be washed by clean water to remove the residual surface contamination. Finally, the washed DP590 steel sheets were dried in the furnace for about 30 min at temperature of 400 K. The 6061Al–T6 sheets were also soaked in the acetone for the same duration with that of DP590 steel sheets. Then the soaked 6061Al–T6 sheets were immersed orderly in the NaOH (20% in mass) and HNO_3 solutions (30% in mass) to make a further cleaning. After that, these 6061Al–T6 sheets were washed by clean water. Finally, the washed 6061Al–T6 sheets were dried in the furnace at the same temperature and duration with that of DP590 steel sheets. Before the actual welding–brazing process, the surfaces of DP590 steel and 6061Al–T6 were ground by 1200# abrasive paper to further improve quality of the welded–brazed joint.

2.3. Analysis methods

When the laser welding–brazing process was finished, the observed or tested specimens were cut perpendicular to the welding–brazing direction. The observed specimens were ground to mirror–like surface according to the standard grinding and polishing procedures. The cross sections of joints produced with different Zn–based filler metals were observed by optical microscope (OM, OLMPUS). The interfacial microstructure was observed by the scanning electron microscope (SEM, Quanta 200FEG) equipped with energy–dispersive spectrometer (EDS).

Table 1
Nominal compositions and tensile strength of base metals [20,21].

Element	Cr (%)	C (%)	Mn (%)	Si (%)	S (%)	P (%)	Fe (%)	Zn (%)	Cu (%)	Al (%)	σ(MPa)
DP590 steel	0.2	0.06	1.61	0.4	0.002	0.0014	Bal.	–	–	0.01	590
6061Al	0.08	1.0	0.15	0.71	–	–	0.35	0.04	0.19	Bal.	310