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Effect of Si content on the interfacial reactions in laser welded-brazed Al/steel dissimilar butted joint

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ABSTRACT

6061-T6 aluminum alloy and DP590 steel were joined successfully by a laser welding–brazing process with pure Al, AlSi5, and AlSi12 filler metals. Interfacial microstructure of the joints with highest tensile strength (under laser powers of 2000 W, 2000 W and 2500 W for joints obtained with pure Al, AlSi5 and AlSi12 filler metals, respectively) were selected for comparison. The interface produced with the pure Al filler metal consisted of a thick layer of η-Fe_2Al_5 with scattered rod-shaped θ-$FeAl_3$, with average thicknesses of 10.1 μm in the bottom region and 16.7 μm in the top region. When 5 wt.% Si was added to the filler metal, the interfacial intermetallic compound (IMC) components remained similar, whereas the interface thickness decreased to 3.8 μm in the bottom region and 7.5 μm in the top region. On further increasing the Si addition to 12 wt%, the interfacial IMC acquired 1.2 μm-thick τ_5-Fe_2Al_8Si in the bottom region with 5.6-μm-thick θ-$Fe(Al,Si)_3$ and τ_5-Fe_2Al_8Si in the top region. The chemical potential of Si in the Fe-Al-Si ternary system was lower at the Fe-Al side comparing with weld seam and steel substrate, which led to a preferentially diffusion of Si to the Fe/Al interface and finally caused the aggregation of Si in the Fe/Al interface. Si addition improved the joint strength and reduced the required laser power for a suitable joint. The joint produced with the AlSi5 filler metal had the highest tensile strength and largest fracture displacement.

1. Introduction

It is necessary to replace heavy steel components with light aluminum to meet the goal of lightweight design in vehicle manufacturing. Solid-phase joining methods, such as friction stir welding, diffusion bonding, and brazing, were explored to obtain a sound joint between Al and steel. For instance, Watanabe et al. (2006) obtained a visually acceptable friction stir-welded Al/steel dissimilar joint with a tensile strength as high as close to 90% of the Al base metal. However, the joint configurations welded with this technology were mainly limited to simple geometries, such as butt or overlapping. For diffusion bonding, the connection of Al to steel was achieved by mutual atomic diffusion under the effect of pressure at high temperatures. Howlader et al. (2010) joined an Al bar to a steel sheet by diffusion bonding, achieving a joint strength of 60 MPa. Nevertheless, the required pressure and high temperature would impose an extra cost on the practical industrial application. As for brazing, the interfacial IMC could be flexibly controlled by adjusting the flux compositions or heating duration, which finally enabled the convenient improvement of joint strength. Zhang et al. (2017) obtained a brazed Al/steel dissimilar joint with the highest shear strength of 260 MPa under a heating temperature of 850 °C and heating duration of 720 s. Because brazing was performed in a furnace, the joining efficiency was relatively low and the brazed workpiece had small dimensions.

To overcome these limitations and broaden the industrial application of Al/steel dissimilar joints in vehicle fabrication (Zhou et al. (2017) and Sun et al. (2016)), laser welding–brazing of Al/steel dissimilar metals was employed. It provides benefits such as higher joining efficiency, accurate melting location, and low welding deformation. In the welding–brazing of Al/steel dissimilar metals, the joint strength is highly associated with the interfacial IMC, which was determined by the adopted filler metals. To date, Zn-Al, Al-Cu, and Al-Si have always been chosen as filler metals and scholars investigated the influence of these alloying elements (Zn, Cu, and Si) on the interfacial IMC. For example, Yang et al. (2015) observed the presence of $Fe_2Al_{5-x}Zn_x$ and $FeZn_{10}$ when Zn-22Al was employed as filler metal during laser welding-brazing Al/steel. They found that the newly formed $FeZn_{10}$ could inhibit the propagation of cracks and hence improve the shear strength of the joint. Song et al. (2010) reported that the Cu atoms would replace the Fe atoms in the Fe-Al IMC during TIG welding-

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brazing Al/steel with Al-Cu filler metal. The existence of Cu in the Fe-Al IMC could reduce the IMC hardness and enhance the crack resistance of the interface, which finally made contribution to improvement of joint strength.

Apart from Zn-Al and Al-Cu filler metals, Al-Si was also widely used in the welding–brazing Al/steel dissimilar joints, owing to its lower cost and effective control of the interfacial IMC (Ma et al., 2018 and Qin et al., 2017). However, the impact mechanism of Al-Si on the interfacial IMC was different from that of Zn-Al and Al-Cu filler metals. The existence of Si at the Fe/Al interface would inhibit the mutual diffusion between Fe and Al. For instance, Dong et al. (2012) observed that the interfacial IMC thickness decreased from 5 μm to 2 μm when the filler metals changed from AlSi5 to AlSi12. They also reported that the Si content at the interface was higher than that in the weld seam indicating an aggregation of Si atoms at the Fe/Al interface. Shi et al. (2015) also found that Si atoms at the interface would inhibit the growth of η-$Fe_2(Al,Si)_5$. For this mechanism, Springer et al. (2011) proposed that it was caused by the reduced reaction rate between Fe and Al atoms due to the addition of Si at the Fe/Al interface. The Si at the Fe/Al interface would even alter the interfacial reaction mechanism. For example, Song et al. (2009) observed that the interfacial IMC components changed from η-Fe_2Al_5 + θ-$FeAl_3$ to θ-$Fe(Al,Si)_3$ + τ_5-Fe_2Al_8Si when the filler metals changed from pure Al to AlSi5. Lemmens et al. (2016) found an aggregation of Si atoms along the IMC boundary and they reported this aggregation of Si atoms would provide convenience for changing interfacial reaction mechanism.

From the above discussion, it could be concluded that Si atoms showed preferentially diffusion and aggregation at the Fe/Al interface and hence affected the interfacial IMC reactions. Chen et al. (2010) reported that the preferential diffusion and aggregation of elements at the interface was greatly associated with the chemical potential gradient. To the best of authors' knowledge, most of the research to date has focused on the observation of this preferentially diffusion and aggregation, whereas few reports explained this phenomenon from the standpoint of chemical potential in the Fe-Al-Si ternary system.

The aim of this research was to investigate the influence of Si addition to filler metals on the microstructure, chemical potential, and tensile strength of laser welded–brazed Al/steel dissimilar butted joints. Thermal cycle in the brazing interface was calculated by FEM software MSC. MARC (Produced by MSC. Software Corporation in United States, feature for welding simulation was adopted in this research). The chemical potential of Si in the Fe-Al-Si ternary system was evaluated to clarify the preferentially diffusion and aggregation of Si atoms at the Fe/Al interface. The fracture behaviors of the joints obtained with different filler metals were observed and compared.

2. Experimental procedure

2.1. Selected materials

In this work, non-galvanized DP590 dual phase steel produced by deep drawing (owned to its high strength (Ma et al., 2016) and strain rate deformation (Bleck and Schael, 2000) and 6061 aluminum alloy (owing to its relative high tensile strength and good ductility (Yang et al., 2018) with T6 state (Solid Solution Treatment + Artificial Aging) were chosen as base metals. The dimension for DP590 and 6061-T6 were 50 mm (length) × 25 mm (width) × 1.2 mm (thickness) and 50 mm × 20 mm × 1.5 mm, respectively. Their chemical compositions and tensile strength were listed in Table 1. Three different filler metals (pure Al-1100, AlSi5-4043, and AlSi12-4047), with different Si contents and diameters of 1.6 mm, were used. They all contained noncorrosive Nocolok flux with a melting point of 575–590 °C, which consisted of 65 wt.% $KAlF_4$ and 35 wt.% K_3AlF_6. Their corresponding chemical compositions are listed in Table 2.

Table 1
Nominal compositions and tensile strength of base metal.

element	Cr (%)	C (%)	Mn (%)	Si (%)	S (%)	P (%)	Fe (%)	Zn (%)	Cu (%)	Al (%)	σ(MPa)
DP590	0.2	0.06	1.61	0.4	0.002	0.0014	Bal	–	–	0.01	590
6061	0.08	1.0	0.15	0.71	–	–	0.35	0..04	0.19	Bal	310

Table 2
Nominal compositions of filler metals.

	Si	Fe	Cu	Zn	Mn	Mg	Ti	Al
Pure Al	0.05	0.10	0.10	0.05	–	–	–	Bal.
AlSi5	5.0	0.80	0.30	0.10	0.05	0.05	0.20	Bal.
AlSi12	12.0	0.80	0.30	0.20	0.05	0.10	–	Bal.

2.2. Laser welding–brazing process

Al/steel dissimilar lapped joint was more widely studied since the molten filler metals was spread directly along the steel substrate. The formation of back appearance was out of consideration. More accurate irradiated location of laser spot should be controlled in laser welding-brazing Al/steel dissimilar butted joint to guarantee its back formation. This brought extra difficulty for the fabrication of Al/steel dissimilar butted joint. Nevertheless, during the fabrication of tailored blanks in vehicle, the butted joint was in a higher demand. Therefore, laser welding-brazing Al/steel dissimilar butted joint was studied in this research.

A fiber laser (IPG YLR-6000) with a maximum power of a 6000 W was employed in this research. A vertical irradiation setup was adopted for the laser beam. The defocused laser beam with radius of 0.28 mm was completely focused on the filler metal. The angle between the filler metal and assembled workpiece was 30°. To obtain a smooth weld appearance and sound cross-section, the filler metal was fed in front of the laser beam and the defocused distance of the laser beam was +20 mm. Double argon shielding gas was employed to prevent the molten filler metal from oxidizing and hence improve the molding ability of the weld seam. The gap between the assembled steel and Al substrates was set to 1.0 mm to ensure good coverage of the molten filler at the brazing interface. A schematic diagram of the Al/steel laser welding–brazing process is presented in Fig. 1. Before the actual welding, several trial experiments were conducted to obtain visually acceptable weld appearances. The optimized welding–brazing parameters were thus determined, as listed in Table 3.

To enhance the wettability and spreadability of the molten filler metal along the brazing interface, a 45° half-V shaped groove was fabricated on the steel side. The DP590 steel and 6061 Al-T6 sheets were both cleaned with different cleaning procedures before laser welding-brazing process. For the DP590 sheets, they were firstly soaked in the acetone for 180 s. Then the soaked DP590 steel sheets were washed by deionized water to remove surface contamination. After that, the washed DP590 steel sheets were dried in furnace at drying temperature of 393 K for 1800 s. As for the 6061-T6 sheets, they were also immersed in the acetone for 180 s to remove the surface contamination. Then, these 6061-T6 sheets were soaked in 20% (in mass) NaOH solution for 240 s, 30% (in mass) HNO_3 solution for 300 s respectively to make a further cleaning. After completing this process, the Al sheets were washed with deionized water and then dried in a furnace at the same temperature and for the same duration as the steel sheets.