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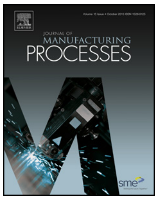

Influence of laser power on interfacial microstructure and mechanical properties of laser welded-brazed Al/steel dissimilar butted joint

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ABSTRACT

Laser welding-brazing 2-mm-thick 6061-T6 aluminum alloy to DP590 dual phase steel in butted configuration was performed with AlSi12 filler metal. The influence of laser power on weld appearance, interfacial microstructure and tensile strength was studied. Thermal cycle at brazing interface was calculated by numerical simulation in order to clarify the interfacial reaction mechanism. A sound weld appearance and cross section could be obtained under laser powers of 2200 W and 2500 W. When the laser power was 1800 W, the interfacial intermetallic compound (IMC) was continuous thin 2-μm-thick τ_5 phase while no reaction layer was detected at the bottom of groove at the brazing interface. When the laser power was 2200 W, the interfacial IMC consisted of needle-shaped θ phase+serration-shaped τ_5 phase with average thickness of 5.2 μm. With the further increase of laser power to 2500 W, the interfacial IMC was composed of planar η phase, needle-shaped θ phase and serration-shaped τ_5 phase with average thickness of 12 μm. When the laser power increased to 3000 W, the interfacial IMC components were composed of thick planar η phase, θ phase and τ_5 phase with average thickness of 30 μm. Highest tensile strength with 140 MPa was obtained when the laser power was 2200 W. The interfacial reaction mechanism under different laser powers and relationship between IMC components and tensile strength was clarified.

1. Introduction

With the severe consumption of global limited resource, improvement of the fuel efficiency becomes a great significance. For example, U. S. Congress passed the Corporate Average Fuel Economy (CAFE) in July 2011. They proposed that average fuel efficiency should be improved to 54.5 mpg (23.2 km/l) by 2025 comparing with 35.5 mpg (15.1 km/l) at present. To match this goal, lightweight design for automobile provided a solution. It was reported that an 8–10% less fuel would be consumed if 10% total weight of the automobile was reduced [1,2]. Therefore, an increasing light aluminum alloys were introduced into the fabrication of car body to replace conventional heavy steel component. It was a great necessity to obtain a sound connection between Al and steel and welding process provided a potential method.

Conventional fusion welding was not suitable for the joining of Al and steel due to their great differences in melting points (650 °C for Al while 1450 °C for steel) and thermal expansion coefficients ($23.5 \times 10^{-6}/^{\circ}C$ for Al while $12.5 \times 10^{-6}/^{\circ}C$ for steel) [3]. Besides, excessive thick IMCs would be generated at the Fe/Al interface under fusion process due to their low mutual solid solubility and metallurgical immiscibility. These excessive thick IMCs were hard and brittle and disadvantage to the mechanical properties of the Al/steel dissimilar joint. Solid phase method, such as friction stir welding [3] ultrasonic spot welding [2] and explosive welding [4,5], were adopted to minimize the thickness of interfacial IMC. Although joints with satisfied tensile strength were obtained due to presence of thin IMC, the joint configurations were limited. And this limitation in joint configurations became a restriction for their industrial application.

To break this limitation, welding-brazing process was proposed. In this method, the fusion zone was formed at the lower melting-point base metal by mixing molten filler metal and base metal while the brazing interface was produced by spreading molten filler metal along the base metal with higher melting point. Arc [6], laser [7], laser-arc hybrid [8] and electron beam [9] were adopted as heat sources. In these welding-brazing methods, laser welding-brazing process was paid an increasingly attentions for its higher automation and smaller welding deformation. Besides, faster heating and

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Table 1
Compositions and tensile strength of base metals and filler metal.

	C	Mn	Si	S	P	Fe	Mg	Zn	Cu	Al	Ti	σ (MPa)
DP590	0.068	1.61	0.447	0.002	4.0	Bal.	–	–	–	–	–	590
6061-T6	1.0	0.15	0.8	–	–	0.7	–	0.251	0.4	Bal.	–	310
Filler	–	0.15	12	–	–	0.8	0.1	0.2	0.3	Bal.	0.15	210

cooling rate during laser welding-brazing process was beneficial to the growth inhibition of IMC [9].

During the laser welding-brazing Al/steel dissimilar joint, two factors were important to the tensile strength of the joint: wetting-spreading ability of molten filler metal and interfacial IMC. Laukant et al. [10] discovered that a better wettability and spreadability of molten filler metal was produced by dual-spot laser beam due to its larger heating area compared with that of single-spot laser beam under the same condition. This better wettability and spreadability of molten filler metal finally resulted in a higher strength of the joint. Alexandre et al. [11] investigated the relationship between laser power and wetting length (L), wetting angle (θ) during their laser welding-brazing Al/steel dissimilar lapped joint. They reported that larger L and smaller θ would be produced with the increase of laser power in certain range, which was beneficial to improve the tensile strength of the joint. In addition to this factor, the interfacial IMC also had a great influence on the mechanical properties. Sun et al. [12] found that the interfacial IMC was composed of Fe_2Al_5 (η phase for later content) and $FeAl_3$ (θ phase for later content) during laser welding-brazing Al/steel dissimilar butted joint with AlSi5 filler metal. Their experimental results showed that the total thickness of IMC would become larger with the increase of laser power. The highest tensile strength of joint was achieved when the interface was joined with about 2-μm-thick IMC under the laser power of 3.05 kW. Yang et al. [13] found the η phase would be newly formed under relatively larger laser power during welding-brazing Al/steel dissimilar lapped joint. The presence of η phase would decrease the strength of the joint. According to these researches, it could be concluded that the interfacial heat input had a great influence on the wettability and spreadability of molten filler metal and interfacial IMC, which finally determined the tensile strength of the joint.

Laser power, as one of the most important parameters during welding-brazing process, had a significant effect on the interfacial heat input which would exert great influence on the interfacial microstructure and tensile strength of the Al/steel dissimilar joint. So the aim of this research is to investigate the characteristics of laser welding-brazing dissimilar metals 6061-T6 aluminum alloy to DP590 dual phase steel with AlSi12 filler metal under different laser powers. First, weld appearances and cross sections of the joints under different laser powers were observed. Then the interfacial microstructure evolution under different laser powers was analyzed. Numerical simulation was conducted to calculate the thermal cycle at the brazing interface to explain this microstructure evolution. After that, tensile strength of the joints obtained by different laser powers was tested. Finally, interfacial reaction mechanism under different laser powers was clarified and the influence of interfacial IMC on tensile strength was discussed.

2. Materials and experimental procedure

2.1. Selected materials

Commercial dual-phase steel DP590 and 6061-T6 aluminum alloy were chosen as base metals. Their dimension were the same: $100 \times 50 \times 2 mm^3$. Chemical compositions and tensile strength of the two base metals were listed in Table 1. Flux-cored AlSi12 eutectic with a 1.6-mm diameter was selected as filler metal. Its melting point was about 575–590 °C and its corresponding chemical compositions were also listed in Table 1. Non-corrosive flux Nocolok (65 wt% KAlF4 and 35 wt% K3AlF6) was contained in filler metal with powder form. 45° half V-shape grooves were cut in the DP590 and 6061-T6 base metals to improve the wettability and spreadability of molten filler metal during welding-brazing process.

Table 2
Detailed laser welding-brazing parameters.

Welding parameters	Value
Laser powers, W	1800, 2200, 2500, 3000
Defocused distance, mm	+20
Distance of laser spot offset to Al, mm	0.4
Welding speed, m/min	0.5
Feeding speed of filler wire, m/min	3.5
Flowing rate of shielding gas, L/min	20
The angle of between filler wire and workpiece, θ	30°

2.2. Laser welding-brazing process

The DP590 and 6061-T6 sheets were cleaned by different cleaning processes before welding. The DP590 sheets were firstly soaked in acetone for 180 s and then in clean water for 600 s to remove the residual oil and oxidation contamination on surface. Then the washed DP590 steel sheets were dried at 120 °C for 1800 s. 6061-T6 sheets were soaked in acetone for 180 s, 20% (in mass) NaOH solution for 240 s, 30% (in mass) HNO_3 solution for 300 s and then in clean water for 600 s, respectively. Before the final welding-brazing process, the grooves should be polished by 1200# abrasive paper to make a last cleaning.

A 6kW IPG YLR-6000 CW fiber laser and KUKA six-axis robot were employed in this research. The focusing and collimating lens were all produced by Precitec and owned 125 mm and 300 mm focal length, respectively. Fig. 1 showed the schematic diagram of laser welding-brazing Al to steel. The laser beam irradiated the workpiece vertically and a 30° angle was set between workpiece and filler metal. Laser beam with a +20 mm defocused distance was employed to obtain a larger heating area under a spot diameter of about 0.28 mm. Double shielding argon gas system was used to protect the liquid filler metal from oxidation during its cooling so as to improve the molding ability of the weld seam. Filler metal was fed in front of the laser beam to make the molten filler metal flow into the molten pool smoothly and keep a stable welding-brazing process. A 0.4-mm laser offset distance from the butted interface to Al base metal side was set due to the difference in heat conductivity and reflectivity for laser beam between steel and Al. To make the filler metal spread better along bottom surface, a 1.0 mm gap distance was set between welded workpiece. Before actual welding, several trial experiments were conducted to obtain visually acceptable weld appearance. The final detailed welding parameters in Table 2 were adopted during the welding-brazing process.

2.3. Analysis method

After laser welding-brazing process, specimens were cut perpendicular to the welding-brazing direction. Standard grinding and polishing procedures were applied during the preparation of