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Research paper

Effect of groove shape on laser welding-brazing Al to steel

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ABSTRACT

Defocused laser welding-brazing of 2-mm-thick 6061-T6 aluminum alloy and DP590 steel in butted configuration was performed with AlSi12 flux-cored filler metal. Three different groove shapes at steel side were made: square-shape, half Y-shape and half V-shape. The experimental results indicated that inhomogeneous intermetallics compounds (IMC) morphology along the steel appeared from top to bottom region. In top region, IMCs consisted of needle θ-$Fe(Al,Si)_3$ + serrated τ_5-$Fe_{1.8}Al_{7.2}$ for three joints and their average thickness was different (10.2-µm for square-shape, 10.1-µm for half Y-shape while 8.6-µm for half V-shape). In middle region, only 2.0-µm τ_5-$Fe_{1.8}Al_{7.2}$ was detected in joint with square-shape groove while θ-$Fe(Al,Si)_3$ + τ_5-$Fe_{1.8}Al_{7.2}$ with the average thickness of 7.2-µm and 4.9-µm were observed in joints with half Y-shape and half V-shape grooves. In bottom region, insufficient metallurgical reaction occurred in joint with square-shape groove while τ_5-$Fe_{1.8}Al_{7.2}$ with the average thickness of 1.2-µm and 1.1-µm were formed in joints with half Y-shape and half V-shape grooves, respectively. The smallest temperature gradient along the steel interface in thickness direction was noticed in joint with half V-shape groove, resulting in the least difference of IMC thickness values from top to bottom. The results of tensile test indicated that the highest tensile strength was achieved in joint with half V-shape groove because of its excellent spreading behavior of molten filler metal, largest bonding interface area and suitable interfacial IMC distribution along the steel interface.

1. Introduction

Connection of Al to steel by welding method becomes significant in the fabrication of automobile since it matches the tendency of energy-saving and emission reduction. Various solid welding techniques such as diffusion bonding, friction stir welding and brazing have been explored. For the diffusion bonding, the welding was achieved by the inter-diffusion between Fe and Al atoms under high temperature and pressure. Kobayashi and Yakou (2002) found that tensile strength of joint was very sensitive to welding parameters and thus acceptable welding parameters window was relative narrow. For the friction stir welding, the joint was produced by the plastic deformation of base metal and Taban et al. (2010) obtained a joint with tensile strength of 250 MPa while the average thickness of interfacial IMC was only about 250-nm due to the low temperature at the interface. But the joint configuration was limited as welded section should be contacted directly with pin. As for the brazing, the interfacial IMC could be controlled since composition of flux could be adjusted flexibly. The size of workpiece was relative small as brazing process was performed in furnace. Liu et al. (2005) produced various Al/steel brazing joints by different fluxes while the joints dimension were only 20 × 40 × 3 mm. To break these limitations, welding-brazing technique was developed. It was suitable for the joining of Al to steel with great difference in melting point since the brazing joint was formed by spreadability of molten filler along the steel while the welding joint was fabricated by mixing molten filler and Al base metal. Laser welding-brazing is now attracting more attention for its relative high welding-brazing speed, smaller welded deformation and adaptation of joint configuration. For example, Filliard et al. (2017) achieved a 500-mm-length Al/steel flange coached joint at a welding-brazing speed of 6m/min.

In laser welding-brazing of Al to steel, two key factors should be considered: spreadability of molten filler metal and formation of intermetallic compounds (IMC). Many welding parameters, such as laser power, initial temperature of base metal and laser configuration had influence on the spreadability of molten filler metal. Tadashi et al. (2009) investigated the effect of laser power and traveling speed on the spreading behavior of Zn filler metal during the laser welding-brazing A6061 to steel. They found that the best wetting condition of molten filler metal was achieved at relatively medium laser power and traveling speed. Mei et al. (2013) proposed that a preheat process before

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welding-brazing would make contribution to the improvement of molten filler metal in brazing interface. Laukant et al. (2005) and Haboudoua et al. (2003) discovered that a wider wetting length of the molten filler metal in steel would appear when using dual spot compared to single spot. The spreadability of molten filler metal was found to be closely associated with the thermal history in filler metal and interface. Factors which could affect the thermal history at the interface had great influence on the spreadability of the molten filler metal.

Another issue was the interfacial IMC distribution in brazing interface, which was also determined by the thermal history. Besides welding parameters mentioned in above descriptions, the groove shape also had great impact on the interfacial IMC distribution. Zhang et al. (2013) investigated the interfacial reaction in a laser keyhole welded-brazed 6061/steel butted joint without groove at steel side. They found that an inhomogeneous IMC distribution appeared along the steel interface in thickness direction. The IMC thickness was about 13-μm in upper part of the steel interface while was about 5-μm in lower part of the steel interface although the component was similar:θ-$Fe(Al,Si)_3$ (θ phase for short in later content) and η-$Fe_2(Al,Si)_5$. Sun et al. (2016) investigated the influence of half-V shape groove angles on the interfacial IMC distribution during defocused laser welding-brazing 2.5-mm-thick 6061 aluminum and Q235 steel. They observed that average thickness of IMC was about 5.5-μm for the joint produced at a 45°half V-shape groove while 8.29-μm at a 30°half V-shape groove under the same welding parameters.

It could be concluded that the groove shape had great effect on the interfacial thermal history which would also determine the spreadability of molten filler metal. Therefore, the aim of this research is to investigate the influence of three typical groove shapes (square-shape, half Y-shape and half V-shape) on weld appearance and cross section. Temperature distribution at the interface was calculated and interfacial IMC morphology was observed and compared under different groove shapes. Then interfacial IMC compositions were analyzed and tensile strength of joints with different groove shapes was tested. Furthermore, relationships between interfacial temperature, IMC morphology and tensile strength were clarified.

2. Experimental procedure

2.1. Materials

DP590 dual phase steel and 6060-T6 aluminum alloy with the same dimension of 120 × 30 × 2 mm^3 were used as base metals in this study. Table 1 presented the chemical compositions and tensile strength of these two base metals. A 1.6-mm-diameter flux-cored Al-Si12 filler was chosen as filler metal. Its melting point was about 575–590 °C. The chemical composition of filler metal was also listed in Table 1. Flux Nocolok in powder form contained in filler was used in this research and its composition was 65 wt% $KAlF_4$ and 35 wt% K_3AlF_6.

Three kinds of grooves at the steel side were fabricated as shown in Fig. 1: square-shape groove, half Y-shape groove and half V-shape groove. In the case of joining to the steel with square-shape groove, the groove with half V-shape was cut at aluminum base metal as smallest filling space was provided while the filler-feeding speed was constant. Half Y-shape grooves were cut at aluminum base metals connecting to the steel with half Y-shape and half V-shape grooves.

Both base metals were cleaned before welding process. The DP590 sheets were soaked in acetone for 180 s and clean water for 600 s to remove the residual oil contamination. After that, the washed base metals were dried at 393 K for 1800s. 6061-T6 aluminum alloy sheets were soaked in acetone for 180s, 20%(in mass) NaOH solution for 240s, 30%(in mass) HNO_3 solution for 300 s and finally clean water for 600s, respectively. Before the final welding, the groove should be polished by 1200# abrasive paper to make a further cleaning.

A 10 kW IPG YLR-6000 CW fiber laser with a wavelength of 1070-nm and a KUKA six-axis robot were employed in this work. The laser beam was transmitted by a 200-um-core-diameter fiber and then focused by a 200-mm lens to obtain a spot with a diameter of 0.2-mm. Fig. 2 shows the schematic diagram of laser welding-brazing of Al to steel. The laser beam was irradiated on the workpiece surface vertically. To make the filler metal feed smoothly and maintain a stable welding process, the filler metal was fed in front of the laser beam and a +40 mm defocused laser beam was also employed. The angle between workpiece and filler metal was 30°. The laser offset was set a 0.4-mm distance from the butted interface to Al base metal side as the difference in heat conductivity and reflectivity between steel and Al. Double shielding argon gas was used to protect the molten filler metal from oxidation during welding-brazing process. Before the experiment, preliminary trials were conducted to obtain visually acceptable joints. The process parameters were listed in Table 2.

2.2. Analysis method

After laser welding-brazing process, specimens were cut perpendicular to the traveling direction. Standard grinding and polishing procedures were applied during the preparation for observed and tested samples. The microstructure of the joint was observed by optical microscope (OM) and scanning electron microscope (SEM) with energy-dispersive X-ray spectronmeter (EDS). In this research, the tensile strength rather than interface strength of the joint was tested. Bacha et al. (2005) and Mathieu et al. (2007) proposed that the joint strength was the tensile strength of the joint with reinforcement. So the reinforcement of the joint should not be machined off during the tensile test. The tensile strength of the joint under room temperature was tested by a testing machine (INSTRON MODEL 1186) at a cross head speed of 1 mm/min.

2.3. Numerical analysis

To obtain interfacial thermal history, numerical simulation software MSC.Marc was employed. The dimensions of the simulation model are the same as the experimental workpieces. Fig. 3 showed the FE(finite element) models and meshes for different samples. To ensure the accuracy of the simulation, finer mesh with about 0.35 × 0.35 × 0.5 mm^3 in the welded zone and heat affected zone while coarse mesh in the outer region were divided for the plate as seen in Fig. 3(b-d). All meshes consisted of eight nodes and hexahedron elements. For the joint with square-shape groove, the total nodes and meshes number were 80400 and 65200, respectively. For the joint with half Y-shape groove, the total nodes and meshes number were 73968 and 60000, respectively. For the joint with half V-shape groove, the total nodes and meshes number were 107535 and 88400, respectively. The ‘birth and death element’ method was adopted during the simulation to simulate the filler-feeding during actual welding-brazing process.

Table 1
Chemical compositions and tensile strength of base metals and filler metal.

	C	Mn	Si	S	P	Fe	Mg	Zn	Cu	Al	Ti	σ(MPa)
DP590	0.06	1.61	0.447	0.002	3.5 – 4.5	Bal	–	–	–	–	–	590
6061-T6	1.0	0.15	0.8	–	–	0.7	–	0.251	0.4	Bal	–	310
AlSi12filler	–	0.15	12	–	–	0.8	0.1	0.2	0.3	Bal	0.15	210