Journal of Alloys and Compounds 509 (2011) 891–898

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Joining mechanism of Ti/Al dissimilar alloys during laser welding-brazing process

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ARTICLE INFO

Article history:
Received 8 July 2010
Received in revised form
22 September 2010
Accepted 22 September 2010
Available online 29 September 2010

Keywords:
Laser welding–brazing
Joining mechanism
Ti/Al dissimilar alloys
Stacking fault

ABSTRACT

Joining mechanism of Ti/Al dissimilar alloys was investigated during laser welding–brazing process with automated wire feed. The microstructures of fusion welding and brazing zones were analysed in details by transmission electron microscope (TEM). It was found that microstructures of fusion welding zone consist of α-Al grains and ternary near-eutectic structure with α-Al, Si and Mg_2Si. Interfacial reaction layers of brazing joint were composed of α-Ti, nanosize granular $Ti_7Al_5Si_{12}$ and serration-shaped $TiAl_3$. For the first time, apparent stacking fault structure in intermetallic phase $TiAl_3$ was found when the thickness of the reaction layer was very thin (approximately less than 1 μm). Furthermore, crystallization behavior of fusion zone and mechanism of interfacial reaction were discussed in details.

1. Introduction

In aeronautic and automotive industries, weight reduction is strongly demanded for energy and natural resource savings. The joining of dissimilar alloys is one of the effective measures to reduce weight of the structures or save rare metal, such as joining of Ti/Al [1–3], Cu/Al [4–6], Fe/Al [7,8]. Among above partners, hybrid structure of Ti/Al dissimilar alloys is an attractive design for the weight reduction and some local requirements. However, thermal joining of aluminum and titanium has a metallurgical challenge due to unavoidable formation of brittle intermetallic compounds [9–13]. Therefore, it is necessary to control effectively formation and growth of Ti–Al intermetallic compounds.

In order to suppress the growth of the brittle intermetallic phase, explosive welding [14], diffusion–bonding [3,9] and brazing [15] have been widely used to join aluminum to titanium. However, these methods are not suitable for joining tailored blanks and flexible manufacture due to the limitation of especial joint configuration or whole heating. In recent years, friction stir welding was attempted to weld aluminum and titanium [16]. However, the maximum failure load of the joint is only about 62% that of Al alloy base metal and needs further improvement.

As a heat source of materials processing, laser has been widely applied in the fields of welding [17] and cladding [18,19]. In the joining of dissimilar alloys, laser welding method provides some advantages such as high energy density, rapid heating/cooling velocity and accessibility to the heating zone [20,21]. Specially, the laser welding–brazing method to attach metallurgical non-fitting partners to each other can suppress effectively the growth of brittle intermetallic compounds [22–25]. Hence, tensile strength of the joint by laser welding–brazing was enhanced significantly. In addition, this method provides good adaptability and a good relation between weight reduction and costs in serial production.

In our study [26–28], circular and rectangular spot laser welding–brazing processes of Ti/Al dissimilar alloys was developed, while V-shaped groove with 45° angle was fabricated on parent materials. The thickness of brittle reaction layer could be limited to the level of just a few microns under the condition of appropriate process parameter (laser power 2400 W, offset of laser beam to Al 0.4 mm, welding speed 0.8 m/min, wire feed rate 3.2 m/min), and the tensile strength of the joints is up to 290 MPa, which exceeds 80% that of Al alloy base metal. In general, thermal cycle of laser welding–brazing have characteristics of high peak temperature, high heating/cooling velocity and short interaction time between liquid filler and solid base metals. So in such environment of far from equilibrium, interfacial reaction mechanism has novel interesting characteristic. Expounding the process has significant to control mechanical property of joint, as well as to guide composition design of welding materials. In addition, it is important to describe crystallization behavior of the fusion zone, which will influence on appearance and mechanical properties of the joint.

This study focused on joining mechanism of Ti/Al dissimilar alloys during laser welding–brazing process. Crystallization behavior of the fusion zone, element diffusion behavior and growth

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doi:10.1016/j.jallcom.2010.09.125

Table 1
Compositions of 5A06 Al, Ti–6Al–4V alloy and filler metal used in this study.

Alloys	Elements (wt.%)											
	Al	Ti	Mg	Si	Cu	Mn	Fe	Zn	V	C	N	H	O
5A06	Bal.	0.02	5.8–6.8	0.4	0.1	0.5–0.8	0.4	0.2	–	–	–	–	–
Ti–6Al–4V	5.5–6.8	Bal.	–	–	–	–	0.3	–	3.5–4.5	0.1	0.05	0.01	0.2
Filler wire	Bal.	0.15	0.1	12.0	0.3	0.15	0.8	0.2	–	–	–	–	–

mechanism of interfacial intermetallic compounds were discussed based on detailed microstructure analysis.

2. Experimental details

Ti–6Al–4V alloy and 5A06 Al alloy plates with thickness of 1.5 mm were selected as the laser joining materials. In this study, flux-cored wire with the diameter of 2 mm was used as filler materials. The compositions of parent metal and filler wire are listed in Table 1.

Non-uniform heating and small heating area are disadvantages to melt stably filler wire and wet base metals. Therefore, the laser beam was modulated to a rectangular spot (focal spot size 2 mm × 4 mm) by the integral mirror to get relatively uniform energy distribution. To further improve the spreadability, the V-shape groove with 45° angle was fabricated on base metals. Double shielding argon gas was used at double sides of workpieces to avoid oxidation of liquid metals. The laser beam irradiated vertically on the surface of workpiece, and there was a focal spot position at the top surface of the workpiece during laser welding–brazing process. The angle of the filler wire and the workpiece was adjusted to 30°. Filler wire was fed at the front of the laser beam, as illustrated in Fig. 1. To decrease differences of heat conductivity and reflectance of Ti and Al, the offset of laser beam toward Al base metal was 0.4 mm.

In this research, the microstructure of joints was observed by optical microscope (OM) and scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS) after standard grinding and polishing procedures and etching with mixed solution (1 vol.% HF + 1.5 vol.% HCl + 2.5 vol.% HNO_3 + 95 vol.% H_2O). Transmission electron microscopy (TEM) with a Philips CM12, operating at 120 kV, was used to characterize the microstructure in details.

Specimens for transmission electron microscopy (TEM) were prepared with cutting, grinding and ion milling to electron transparency. Thin sheets (5 mm × 8 mm × 0.2 mm) were cut from brazing zone where the interface reaction zone was approximately located in midline and fusion welding zone by a linear cutting machine. The thin sheets were thinned down into parallel sided and semi-thin sheets with thicknesses of around 40 μm through several steps of coarse grinding, fine grinding and mechanical polishing. The semi-thin sheets were then cut into 3 mm discs. Ion milling was performed on both sides of the specimens with two beams of 4 kV Ar ions by using a Gatan 691 Ion-Miller. It should be pointed out that the preparation of specimens for brazing zone was very difficult to obtain electron transparency at reaction layer due to positional uncertainty of Ar ions bombardment. After repeated attempts the specimens with electron transparency at reaction layer have been achieved.

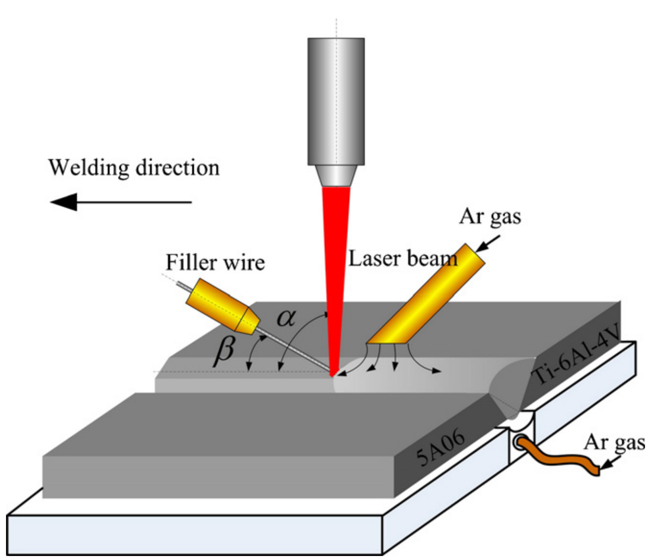

Fig. 1. Schematic drawing of the laser welding–brazing processing.

3. Results

Macroscopic cross section of the Ti/Al dissimilar joint by laser welding–brazing is shown in Fig. 2. In the laser welding–brazing process, Al alloy composed about of 6% (wt.) Mg and filler wire composed of eutectic composition of Al and Si were melted and mixed under irradiation of laser beam. Consequently, a fusion welding zone with hypoeutectic microstructure was formed in the one side. At the same time, Ti alloy in solid state interacted with liquid mixed metal, and a brazing zone was formed in the other side. Therefore, laser welding–brazing joint has dual characteristics of fusion welding and brazing. The formation of intermetallic compounds could be suppressed effectively by this method, and so mechanical property of joint was enhanced markedly. These results had been described in detail elsewhere [26,28]. In the following parts, we will analyse the microstructures of fusion welding and brazing zone.

3.1. Microstructure of fusion zone

Fig. 3 shows the microstructure of fusion zone magnified in Fig. 2 marked with rectangles A and B, as shown in Fig. 3(a). There were four different zones: parent metal (PM), fusion line (FL), columnar crystal zone (CCZ), equiaxed crystal zone (ECZ). Fig. 3(c) presents fine hypoeutectic microstructure of fusion zone magnified in Fig. 3(a) marked with rectangle C. The microstructures in CCZ and ECZ are similar to that in FL as partial melting Al alloy mixed with the completely melting filler wire. The CCZ contains coarse columnar α-Al solid grains and near-eutectic structures between neighbouring α-Al grains. The coarse columnar structure was nearly vertical to the fusion line, which was induced by the higher cooling rate and the preferential direction of the thermal conduction. In addition, microstructure morphology of fusion zone near Ti alloy is the vertical to the interface. However, there is no significance compared with microstructure morphology of adjacent Al alloy, as shown in Fig. 3(b).

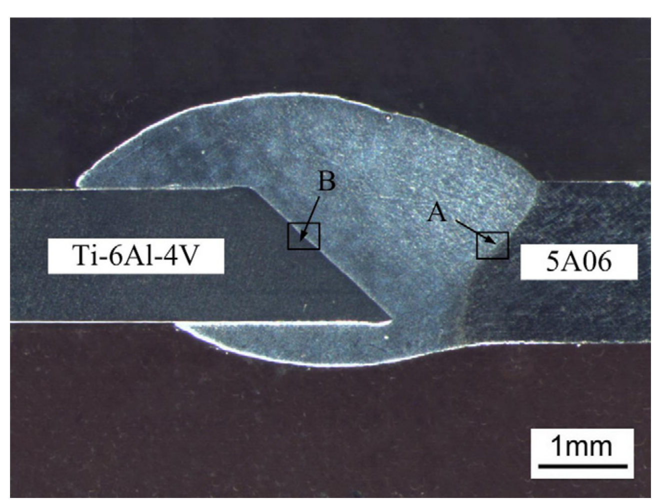

Fig. 2. Macroscopic cross section of the joint by laser welding–brazing.