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Microstructure and welding penetration of wire and arc additive manufactured Pure Titanium and A5356 dissimilar alloys using cold metal transfer welding

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Abstract
Due to the substantial differences in the chemical and physical characteristics between aluminum (Al) and titanium (Ti) alloy wires, few researchers have investigated dissimilar metal deposition using Al and Ti alloy wires in the wire and arc additive manufacturing (WAAM) process. Therefore, we objected to clarify the effect of the processing conditions on the welding penetration and the intermetallic compounds (IMC) of the Ti/Al bead by WAAM. This study focused on the A5356 and ERTi-2 as filler materials. An A5052 substrate fabricated on the Al alloy bead or wall at first, and then a pure Ti bead was deposited on the Al layer. From the microscopic observations, in the conditions with the high heat input and the Ti deposition on the Al wall structure, the Ti penetrated in the large area. And the upper part of the Al wall structure was molten and broken. Besides, the observation revealed an acicular and an equiaxed structure with the Ti and Al elements around the Ti/Al interface layer due to dilution of the Ti layer by Al alloy.

Keywords: Wire and arc additive manufacturing, Dissimilar metal deposition, Aluminum, Titanium

1. Introduction

Recently, the dissimilar metal deposition by wire and arc additive manufacturing (WAAM) has been increasingly gaining prominence year by year. The components of titanium (Ti) / aluminum (Al) dissimilar alloys have attracted various industry fields due to their valuable characteristics. However, the Ti/Al welded joint made the process extremely challenging since the formation of a large number of brittle intermetallic compounds (IMC) in the Ti/Al interface layer. Some researchers reported the joining of Al and Ti in the tungsten inert gas (TIG) welding[1] or metal inert gas (MIG) welding process[2]. In the WAAM process, Yinbao Tian et al. deposited AlSi5 beads on a Ti-6Al-4V layer using cold metal transfer (CMT) welding[3]. However, as far as the authors' knowledge, there are no reports about fabricating the Ti beads on the Al layer by WAAM.

In this paper, first, we investigated the effects on the penetration and the metal compositions by the processing parameters and dimensions of the welding members on a pure Ti bead that was welded on A5356 layers by WAAM. Then, we observed the IMC and element mass ratios of the Ti and Al on the fabricated Ti/Al beads by an optical microscope and energy-dispersive X-ray spectroscopy (EDX).

2. Fabricating process and conditions

In this study, we used A5356 and ERTi-2 as the filler materials for the representative example of the industrial Al and Ti. Table 1 shows the chemical compositions of filler materials. The followings show the fabricating process. First, an Al bead or about 10-layer walls with 80 mm length and 10 mm width fabricated on an A5052 plate (150 mm x 150 mm x 5 mm) using a MIG welding power source (P500L, DAIHEN Corp.). After the fabricated part cooled to room temperature, a pure Ti deposited on an Al layer(s) using CMT welding (TPS5000CMT, Fronius Corp.). In this process, a local shield was located on the edge of the welding torch for sake of improving the shieldability and inhibiting the oxidation of Ti or Ti/Al bead parts. Besides, for comparisons of the penetration widths (PW) between Ti/Ti and Ti/Al bead, we fabricated a pure Ti bead on a Ti-6Al-4V plate (150 mm x 100 mm x 5 mm). Table 2 shows the processing parameters.

Table 1 Chemical compositions of the filler materials.

	O	H	N	C	Fe	Ti
ERTi-2	≦0.15	≦0.008	≦0.02	≦0.03	≦0.20	Bal.

	Si	Fe	Cu	Mn	Cr	Mg	Al
A5356	≦0.25	≦0.40	≦0.10	0.05-0.20	0.05-0.20	4.5-5.5	Bal.

Table 2 Processing parameters.

Welding machine				TPS5000 CMT
Welding mode				CMT-P(c1011+P)
Welding current ***I***			A	69
Welding voltage ***V***			V	17.3
Torch feed speed ***TFS***			mm/min	50, 70, 100, 200
Wire feed speed ***WFS***			m/min	3.6
Wire	Material			WT2G (ERTi-2)
	Diameter		mm	1.2
Shielding gas	Ar		%	≧99.99
	Flow rate	from torch	L/min	15
		from local shield	L/min	20

3. Microscopic Comparison of Fabricated Ti/Ti vs. Al/Ti bead

Fig. 1(a), (b), and (c) show the cross-sections of Ti/Ti and Ti/Al bead that were located about 50 mm from the welding start point, respectively. The pure Ti bead was deposited under the same conditions, and the torch feed speed (*TFS*) is 70 mm/min. Fig. 1(d) shows the measurement results of PW of all Ti bead. According to Fig. 1(a), (b), and (d), the PW of the Ti/Al deposited on an Al bead is 40% smaller than Ti/Ti bead. Besides, Ti/Al bead has little penetration, and a component value was equivalent to the Ti filler material. It assumed that the thermal conductivity of

A5356 is about ten times higher than that of pure Ti. Thus, the thermal energy input on the Al bead was rapidly conducted to the A5052 substrate. Hence, the heat concentration decreased and impeded the formation of a sufficient molten pool. Also, Fig. 1(b) indicates cracks and gaps around the interface layer of the Ti/Al because the polishing process of the test piece separated the fragile Ti-Al IMC layer.

According to Fig. 1(b), (c), and (d), the PW of the Ti/Al deposited on the Al wall is 2.5 times or more than that of the Ti/Al bead deposited on an Al bead. When Ti bead was deposited on the fabricated Al wall, the heat concentration was higher because the welding pool was far from the substrate, and the temperature of the part around the molten pool tended to rise. Moreover, near the end of the welding point, the PW significantly increased because the temperature of the fabricated object at the end point was much higher than that at the start point.

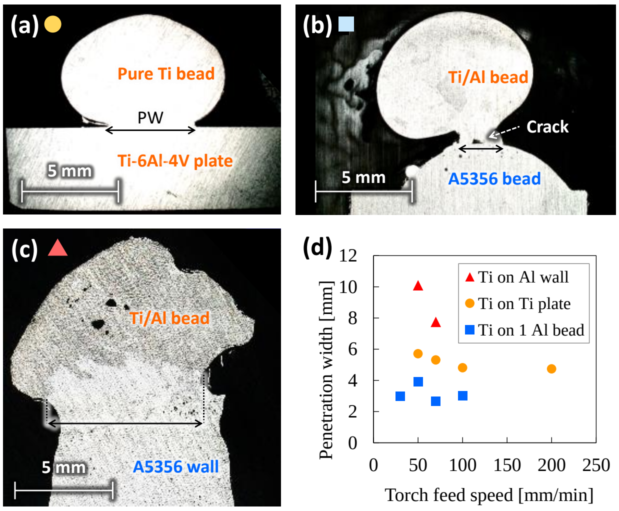

Figure 1. PW of the fabricated Ti beads (*TFS*:70 mm/min).
(a) On Ti plate, (b) On Al bead, (c) On Al wall, (d) Measurement results.

4. Results of EDX analysis on Ti/Al boundary

Fig.2(a) shows the observed cross-section of Ti/Al bead deposited on the fabricated Al wall using *TFS* 70 mm/min. This cross-section was polished with 1 μm diamond slurry. Ti/Al bead part diluted with the upper layer of the fabricated Al wall, and the part contains several types of IMC phases with different Ti-Al composition ratios. It seemed that the multiple types of Al-Ti IMC formed in the molten pool at the same time, and the convection generated in the molten metal agitated the IMC. Fig.2(b) and (c) respectively show Area.1 around the Ti/Al boundary and Area.2 around the deepest part of the penetration dashed with the pink line in Fig.2(a). In Area.2, Ti-Al precipitates shown in Fig.2(c) scattered into the penetration area with about 5 mm depth. In the Area.1, acicular structures precipitated as in Fig.2(b). Fig. 3(a) and (b) show the results of the area analysis of the Ti element around Area.1 and 2 by EDX. And, Fig.3(c) summarizes the results of the quantitative investigation at Point.1 to 4 marked in Fig.2 and 3. Regarding the elemental mass ratio of the precipitation of Fig.3(a), about 20-43% accounted for Ti, and 55-77% accounted for Al. On the other hand, at the acicular structures scattered in Fig.3(b) around the Ti/Al boundary, Ti accounted for 20%, and Al accounted for 80%. Also, the Ti/Al bead part was constracted by the IMC with different element mass ratios of Ti and Al. At the upper part of the Ti/Al bead (Point.1), Ti and Al accounted for 55% and 45%, and at the middle part (Point.2), those accounted for 75% and 25%, respectively.

5. Conclusions

This paper objected to revealing the characteristics of the dissimilar metal deposition using pure Ti and A5356 as filler materials by the WAAM, the microscopic analyses clarified the following results by analyzing the PW of the Al/Ti bead parts.

1. The thermal conductivity and the temperature of the welded object affected largely the penetration of the Ti /Al bead.
2. The PW of the Ti/Al deposited on an Al wall was 2.5 times or more than that of the Ti/Al bead deposited on an Al bead.
3. When the Ti/Al bead with a large penetration, Ti-Al precipitates with multitype shapes were observed in the entire area of the penetration part. Besides, the Ti/Al bead part was constracted by the IMC layers with different element mass ratios of Ti and Al.

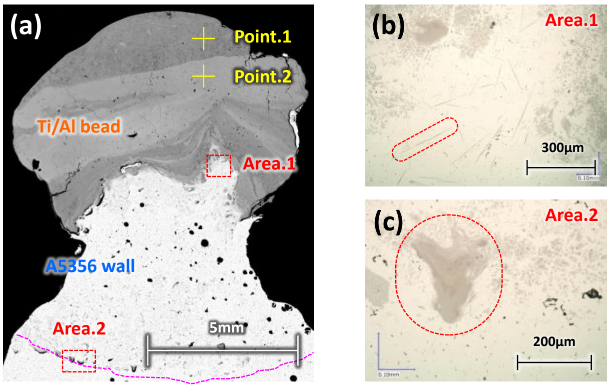

Figure 2. Pure Ti bead deposited on A5356 wall (*TFS*:70 mm/min).
(a) overview, (b) Area.1 around Ti/Al boundary, (c) Area.2 around the deepest penetration part.

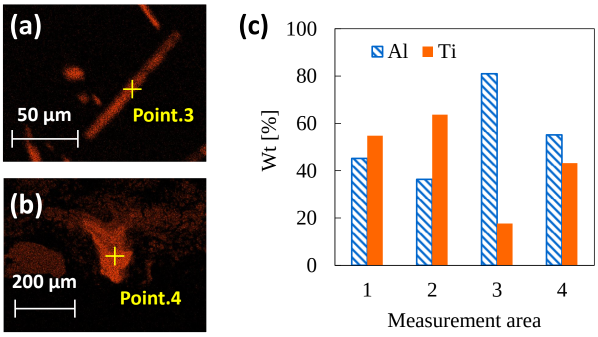

Figure 3. Results of EDX analysis. (a) surface analysis for Ti element on an acicular structure, (b) surface analysis for Ti element on Area.2, (c) quantitative analysis on Point.1-4.

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