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The Effect of Plume Generated on the Microstructural Behavior of the Weld Mixed Zone in High-Speed Laser Dissimilar Welding

Su-Jin Lee ^{1,*} , Seiji Katayama ², Jong-Do Kim ³ and Jeong Suh ¹

¹ Busan Machinery Research Center, Korea Institute of Machinery and Materials, Busan 46744, Korea; jsuh@kimm.re.kr

² JWRI, Osaka University, Osaka 565-0871, Japan; katayama@jwri.osaka-u.ac.jp

³ Division of Marine Engineering, Korea Maritime and Ocean University, Busan 49112, Korea; jdkim@kmou.ac.kr

* Correspondence: leesj@kimm.re.kr; Tel.: +82-51-310-8133

Abstract: Dissimilar laser welding has been researched to combine the excellent anticorrosion and high strength properties of Ti and the low weight and cost of Al. However, when welding dissimilar Al and Ti sheets, many kinds of intermetallic compound are easily generated. Therefore, intermetallic compounds and differences in material properties make joining such dissimilar metals very difficult. Previous studies clarified that ultra-high welding speed could suppress the weld defects. To elucidate the mechanism of Al and Ti dissimilar laser welding, material behavior of the weld fusion zone and components of fume generated during the ultra-high speed welding process were observed and analyzed using energy dispersive X-ray spectroscopy (EDX), transmission electron microscopy (TEM), high speed cameras, and a spectrometer. The results show that the atom movement of Al and Ti in the weld plume affects the behavior of elemental components distributed in the weld fusion zone.

Keywords: dissimilar lap welding; aluminum; titanium; weld plume; solid solution

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1. Introduction

Recently, the application of lightweight, high-performance materials and design technology according to environmental regulations has been receiving a great deal of attention. Dissimilar material welding is a technology that capitalizes on the strengths of both materials and mitigates the weaknesses, and is a useful technology for lightweight and high-performance design. Direct dissimilar joining using a heat source has received significant attention because it exploits the respective desirable properties of materials such as decreased product weight, improved material properties, and reduced manufacturing costs [1–6]. Many researchers have studied various approaches to carry out dissimilar welding, including mechanical joining, brazing, welding using various heat sources, and friction stir welding [7–22]. In this study, to understand the welding mechanism of a dissimilar laser lap welding process, aluminum (Al) and titanium (Ti) sheets, which have large differences of material properties and easily generate intermetallic compounds, were used [23–27]. The large differences in material properties between Al and Ti metals, such as melting and boiling points, thermal conductivity, thermal expansion, density, vapor pressure, hardness, lattice structure, etc. easily cause defects in the weld zone. Furthermore, it is generally known that Al and Ti intermetallic compounds are easily formed and several brittle intermetallic compounds lead to weld defects during the welding process, as shown in Figure 1 [24]. Effectively suppressing the generation and growth of brittle Ti and Al intermetallic compounds is the most important issue in the field of welding dissimilar materials [7–27]. A single-mode fiber laser has a very high energy density in comparison with conventional laser beams [28]. The single mode laser beam with

higher energy density can produce a deeper penetration weld with higher welding speed. Previous studies clarified that ultra-high welding speed could suppress the amount of intermetallic compounds that is generated [24–26]. In this study, laser lap welding of Al and Ti dissimilar sheets was performed with a single mode fiber laser (IPG, Oxford, OH, USA) with ultra-high welding speed. The microstructural and weld plume behavior were observed to understand what happened at the molten pool and keyhole during ultra-high speed dissimilar welding.

Figure 1. Al-Ti binary phase diagram.

2. Materials and Experimental Procedures

The materials used in this experiment were pure Ti and A1050 sheets that were 0.3 mm thick, 30 mm wide, and 60 mm long. Chemical compositions and physical properties of the materials used are shown in Tables 1 and 2, respectively [23,29–32]. Figure 2 schematically illustrates the experimental set-up and method of observing the phenomena by a high speed video camera (NAC, Yokohama, Japan) during laser welding and the arrangement of the spectrometer for the weld plume. Welding was performed by fixing the superimposed sample on the stage, changing the laser output to 1 kW, and the welding speed from 5 to 50 m/min at a focus distance of 0 mm (focal position). The spot size of the installed laser beam was about 30 μ m at the focal point. The incident angle of the laser head was +10° due to avoid damage by the reflection beam. The laser beam was directly irradiated on the surface of metal lapped sheets and Ar shielding gas of 35 ℓ /min was used during lap welding. The shielding gas was used to prevent oxidation of the upper surface and to prevent interference with the laser beam irradiation by the generated plume.

In order to understand the laser welding phenomena related to the state of the molten pool, the plume and the spatter during laser welding were observed with a high speed video camera. The components of the laser induced upper side and lower side plume were analyzed using spectroscopic measurement, respectively. Observation of the molten pool and plume was carried out with a high-speed video camera at a frame rate of 20,000 F/s. As the illumination light source, a semiconductor laser (maximum output $P_{\max}$: 30 W, wavelength λ : 973 nm) was used. For spectroscopic measurements, the spectroscope (Ocean optics, Dunedin, FL, USA) was set horizontally to the generating part of the plume and guided with an optical fiber and measured. Video observation and spectroscopic analysis were performed simultaneously on plumes generated from the front and back surfaces during laser welding.

Table 1. Chemical compositions (wt%) of Al and Ti.

Metal	Al	Ti	Cu	Fe	Si	Mn	Others
A1050	99.57	0.03	0.02	0.26	0.11	0.01	
Ti		99.919		0.002			C:0.01, O:0.04, N:0.01, H:0.001

Table 2. Material properties of Al and Ti.

Properties	Al	Ti
Melting point (K)	933	1941
Boiling point (K)	2743	3560
Density (g/cm ³)	2.70	4.506
Thermal conductivity (W/m·K)	237	21.9
Thermal expansion (μm·m ⁻¹ ·K ⁻¹) (25 °C)	23.1	8.6
Vapor pressure (K) (1kPa)	2054	2692
Vickers hardness (MPa)	167	970
Poisson ratio	0.35	0.32

Figure 2. Schematic illustration of experimental setup to observe plume behavior using spectroscopic measurement during dissimilar lap welding of Al and Ti sheets with a single-mode fiber laser.

3. Results and Discussion

3.1. Result of Ultra-High Speed Dissimilar Welding of Al and Ti

Lap welding of Al and Ti sheets was performed at ultra-high welding speed using a single-mode laser that has extremely high power density. In this study, full penetration welding was carried out by various high welding speeds and specimen location. Under all conditions, a relatively sound weld was produced except under 10 m/min welding speed of Al(upper)-Ti(lower).

Figure 3 shows high speed camera observation and the top and bottom surface appearances of weld beads made at various welding speeds from 10 to 50 m/min in dissimilar Al(upper) and Ti(lower) conditions. When the upper part is Al material, it is observed that the size of the molten pool is wider than Ti upper case. The keyhole was formed relatively small as the welding speed increased. The upper and lower bead widths were narrower with increasing welding speed. Cracks were present in the weld bead of the Ti sheet side under Al(upper)-Ti(lower) combinations made at 5 and 10 m/min. It was

confirmed that the surface of Ti was oxidized by laser welding when the Ti specimen was placed on the lower side.

Figure 3. Images of high speed video and photographs of top and bottom surface appearances of Al-Ti sheets by changing welding speed and specimen locations using a single-mode fiber laser.

To investigate the mechanical properties of welds, a tensile shear test was performed at various welding speeds and metal positions in Al and Ti dissimilar welding. In the results of the tensile shear test, fracture occurred in the Al base metal because the weld was strongly joined with satisfactorily wide welds without fracture in the intermetallic compounds area for the specimen made at welding speed greater than 10 m/min. This tendency is attributed to the reduction and distribution of brittle intermetallic compounds leading to a strong lap joint of Al and Ti dissimilar sheets. And the Al(upper)-Ti(lower) case obtained better results under the Ti(upper)-Al(lower) condition, therefore the oxidation of the lower part of the weld bead was not discussed in this study [24,25].

Cross sections of polished Al(upper)-Ti(lower) and Ti(upper)-Al(lower) combinations were observed and analyzed using EDX (energy-dispersive X-ray spectroscopy) (Hitachi, Tokyo, Japan) mapping, as presented in Figure 4. The mixture area of Al and Ti element decreased by increasing welding speed. A very interesting tendency was discovered in this study. In the case of the Al element, it is widely distributed throughout the molten region (A), and this trend is observed even under the other conditions when the lap position of the specimen is changed or the speed is relatively high. However, in the case of the Ti element, it was confirmed that, regardless of the specimen position and welding conditions, it was generally not distributed in the molten part of the Al material area except at the mixed weld fusion zone. The Ti molten part flowed into the Al plate side partially but was not fully distributed.

Figure 4. Cross-sectional energy-dispersive X-ray spectroscopy (EDX) mapping images of ultra-high speed laser lap welds in dissimilar Al(upper)-Ti(lower) and Ti(upper)-Al(lower) sheets at various welding speeds.

3.2. Microstructural Behavior of Laser Weld Fusion Zones in Dissimilar Al and Ti Sheets

Microstructural behavior of the weld fusion zones was investigated with EDX and, in particular, TEM (transmission electron microscopy) analyses to confirm the exact formation phases of the molten area resulting from the ultra-high speed dissimilar welding process.

Figures 5 and 6 respectively show cross-sectional SEM images, and EDX line analytical results across the centerline of weld beads and spot analytical results of characteristics of the weld location from the upper to lower sheet. In Figure 5a, showing the results for Al(upper)-Ti(lower) dissimilar welds made at 1 kW laser power and 10 m/min welding speed, a more than 15 At % of Al element was distributed all over the weld metal of the lower Ti side, as shown in the EDX analysis results of Figure 5a (C and D). In the EDX analysis results of Figure 5a (A and B), Ti element was not distributed in the upper Al sheet area. This element movement tendency was observed under different welding conditions such as higher welding speed, but the amount of distributed Al element decreased in Figure 5b. Therefore, increasing the welding speed suppressed distribution of the Al element to the Ti molten area.

Figure 5. EDX line analysis mapping images of ultra-high speed laser lap welds in dissimilar welding; (a) Al(upper)-Ti(lower) sheets at 10 m/min welding speed; (b) Al(upper)-Ti(lower) sheets at 50 m/min welding speed.

Figure 6. EDX line analysis mapping images of ultra-high speed laser lap welds in welding; (a) Ti(upper)-Al(lower) sheets at 10 m/min welding speed; (b) Ti(upper)-Al(lower) sheets at 50 m/min welding speed.

In the case of Figure 6a, about 30 At % of Al element was widely distributed in the upper Ti sheet, while the Ti molten pool flowed into the Al welding area located at the lower side but was not fully distributed in the Al molten area at 10 m/min welding speed in the EDX line analysis results. The different material mixture behavior in the weld fusion zone, which was partially compounded, was observed at 50 m/min welding speed (Figure 6b). The Ti molten pool was distributed slightly into the Al sheet molten area, and the Ti and Al enriched areas reduced with increasing welding speed, respectively. Otherwise, a small amount of Al element was distributed relatively equally into the Ti side weld metal area under all conditions but the diffusion and growth of Ti to the Al molten area was inhibited even though the welding speed decreased. This means that the set-up location of sheets, kinds of metal, and material properties were one of the important factors of the dissimilar welding phenomenon. In particular, it is very interesting that a similar amount of Al is distributed throughout the Ti molten area, and it is considered that this is not due to the mixing or diffusion of the melt.

To confirm the exact microstructure of Ti area with Al solid solution in dissimilar laser welding, microstructure phases of Ti were observed and analyzed through TEM with EDX analyses. Figure 7 shows TEM images and results of the electron diffraction pattern analysis for 'B' in Figure 6, which was weld mixed zone of Ti(upper)-Al(lower) case. In Figure 7a, an hcp-AlTi₃ intermetallic compounds and α -Ti solid solution including about 37 At % of Al phase of $[\bar{3} \bar{3} 2]$ and $[\bar{1} \bar{1} 1]$ Miller's indices were identified respectively. Dark field (DF) was obtained from (0 0 0) and (0 2 3), (1 1 2) spots of the diffraction patterns. In the dark field (DF) TEM microphotographs of Figure 7a, lamellar type phases of Ti solid solutions were observed. In Figure 6b Al-rich α -Ti phase including about 40 At % of Al and α -Ti solid solution were viewed from of $[1 \bar{1} \bar{1}]$ and $[\bar{1} 1 2]$, and DF TEM microphotographs of (1 $\bar{1}$ 2), (2 0 1) spots on the diffraction patterns were observed. α -Ti solid solution has lamellar type structures and needle-shaped martensitic phases. It has been well established under the equilibrium conditions that the lattice structure of the hcp (α phase) Ti solid solution depends on the amount of solute Al atoms.

In this study, needle-shaped martensitic Al-rich Ti solid solution phases were created by extremely high melting and solidification rates due to ultra-high speed welding with a high-energy density laser source. The amount of needle-shaped martensitic α -Ti solid solution phases increased by increasing the welding speed. The reason for this microstructural behavior tendency is that, according to the Al-Ti phase diagram, the phase region where the Al element is dissolved in the Ti lattice structure is wide, and thus it is relatively easily dissolved in the high temperature region. In addition, the region in which α -Ti phase is generated is enlarged due to the characteristic that it is melted at a high temperature and solidified rapidly.

Since the solid solution concentration in the weld zone of the Ti side was relatively uniform, this means the molten Al element was dissolved due to other reasons rather than being diffused or the molten pool being mixed to the Ti side. To analyze this, the behavior of plasma generated during welding was observed.

3.3. Effects of Plume on the Material Behavior of the Weld Fusion Zones in Dissimilar Al and Ti Sheets

To confirm the mechanism of Al and Ti dissimilar laser lap welding clearly, the material behavior of the weld fusion zone and components of the fume generated during the ultra-high speed welding process were observed and analyzed using a spectroscopic measurement system. Prior to observation and identification of the plume during lap welding of Al-Ti, spectral data of Al and Ti were collected as basic comparison data by performing the same lap welding of Al-Al and Ti-Ti. The emission spectra results of Al and Ti are shown in Figure 8a,b, respectively. Wavelength and intensity data of each peak were obtained with this signal and data sheets.

Figure 7. Electron diffraction patterns and their identification of Ti solid solution area of 'B' in Figure 6; (a) Ti(upper)-Al(lower) sheets at 10 m/min welding speed; (b) Ti(upper)-Al(lower) sheets at 50 m/min welding speed.

Figure 8. Spectral emission intensity of plasma induced from (a) Al-Al and (b) Ti-Ti similar laser lap welding.

Laser lap welding of Al(upper)-Ti(lower) dissimilar materials was performed at various welding speeds, and the plume generated at that time was observed with a high-speed video camera. The observation results of the brightest top and bottom plumes are summarized in Figure 9. The upper plume generated at the welding speed of 10 m/min was purple and had a narrow shape with a height of approximately 1 mm. On the other hand, a small plume and a small amount of spattering were observed in the lower part. The lower plume and spatter amount increased as the welding speed became higher, but the upper plume did not change as much and spatter generation was small.

The plume behavior was observed during laser welding with a high-speed video camera and at the same time the spectrum of the laser induced plume was measured with a spectroscopic device capable of processing one data point per 2 ms. The visible light region (400 to 800 nm) of the spectral signal from which the highest spectral intensity was obtained is shown in Figure 10. In the case of Al(upper)-Ti(lower), the results of the spectroscopic analysis of the upper plume generated at the welding speed of 10 m/min revealed that the Al component of the Al upper plate is predominant, and two peaks corresponding to Ti were obtained. In addition, evaporated emission of the Ti lower plate was confirmed. High peaks were not observed in the lower spectroscopic analysis obtained at a welding speed of 10 m/min, but as a result of identifying low peaks, both Al and Ti elements were confirmed. In the case of Ti(upper)-Al(lower) case, both peak of Al and Ti elements were observed under the all conditions.

By spectroscopic analysis of the upper plume at a welding speed of 30 m/min or 50 m/min, luminescence of only Al was observed and the Ti peak was not confirmed. On the other hand, it was confirmed that the lower part contained both Al and Ti. Also, as can be seen in Figure 10, the bottom plume and spatter amount increase as the welding speed becomes faster. Along with this, it was confirmed that the lower spectroscopic spectrum intensity becomes higher as the welding speed becomes faster. In the case of abundant sputter generated in the lower part, as can be seen from the spectroscopic spectrum, the entire visible light region became a mountain-like spectrum.

Figure 9. Results of high-speed video observation of plume behavior during laser lap welding of Al(upper)-Ti(lower) dissimilar sheets at various welding speeds; (a) 0 ms, (b) +0.04 ms, (c) +0.08 ms of 10 m/min welding speed; (d) 0 ms, (e) +0.04 ms, (f) +0.08 ms of 30 m/min welding speed; (g) 0 ms, (h) +0.04 ms, (i) +0.08 ms of 10 m/min welding speed.

Based on the above results, the plume generated during lap welding of different materials of Al(upper)-Ti(lower) was observed, when the welding speed was relatively slow (10 m/min), and the peaks of Al and Ti were observed at the upper and lower portions, confirming the presence of Al and Ti. Otherwise, when the welding speed was faster than 30 m/min, in the spectroscopic analysis of the upper plume, the Ti peak was not detected and only the plume of Al was observed (Figure 10c,e). Incidentally, it was confirmed that alloying elements of both Al and Ti were contained in the bottom plume emission.

Figure 10. Observation results of spectral emission intensity of plume induced during Al(upper)-Ti(lower) and Ti(upper)-Al(lower) dissimilar welding at various speeds; (a) Top side plume of Al-Ti at 10 min welding speed; (b) Bottom side plume of Al-Ti at 10 min welding speed; (c) Top side plume of Al-Ti at 30 min welding speed; (d) Bottom side plume of Al-Ti at 30 min welding speed; (e) Top side plume of Al-Ti at 50 min welding speed; (f) Bottom side plume of Al-Ti at 50 min welding speed; (g) Top side plume of Ti-Al at 10 min welding speed; (h) Bottom side plume of Ti-Al at 10 min welding speed; (i) Top side plume of Ti-Al at 30 min welding speed; (j) Bottom side plume of Ti-Al at 30 min welding speed; (k) Top side plume of Ti-Al at 50 min welding speed; (l) Bottom side plume of Ti-Al at 50 min welding speed.

In Al(upper)-Ti(lower) laser overlap welding, the Ti proportion was lower in the upper plume and it was found that the amount of plume of Al and Ti further decreased at high speed. Therefore, it is inferred that the evaporation and the plume ejection accompanying it were stronger in Al. That is, it can be inferred that the evaporation of Al suppressed the lower Ti vapor from being ejected upward toward the Al side, and the upper Al vapor blew upward and downward.

Figure 10g–l show the results of spectroscopic analysis of the plume spectrum while observing the plume during laser lap welding with Ti(upper)-Al(lower). As a result of spectroscopic analysis of the upper plume generated under the condition of welding speed of 10 m/min, many peaks corresponding to Ti were obtained, but some peaks of Al were also detected. Since the strongest peak coincided with Al, it is inferred that the vapors of Al and Ti were well mixed and ejected. According to the spectroscopic analysis data of the upper plume of Ti-Al welding, it can be seen that the higher the welding speed, the lower the spectral intensity and the larger the number of Al peaks detected from the upper plume. This is thought to be because the evaporation pressure of Ti is lower than that of Al, so the lower Al vapor presses out the upper Ti side easily.

As a result of analyzing the components of the laser welding part of the Al-Ti dissimilar material, it was found that the Al element content contained in the Ti solid solution was greater than the amount of the Ti element contained in the Al solid solution generated on the Al thin plate side. This is due to the evaporation of the upper Al, and it was understood that the strong and abundant Al vapor suppressed the movement of the lower Ti vapor, and consequently the Al element entered the lower part through the plume and was dissolved in the Ti molten pool located below.

From the results obtained thus far, the high-speed dissimilar material lap welding mechanism was considered. In particular, for the dissimilar materials of Al and Ti, the high-speed laser welding phenomenon was observed and a spectroscopic analysis was carried out. From this result, the laser overlap welding mechanism is inferred and a schematic diagram is shown in Figure 11.

Figure 11. Schematic representation of phenomena during Al and Ti dissimilar welds at high welding speed from consideration of material properties.

In the case of Al(upper)-Ti(lower), the molten pool on the Al side becomes wider and as the speed increases and the molten pool becomes narrower and longer. Under the ultra-high speed conditions, the keyhole on the back surface intermittently penetrates, and the case of less plume and sputtering and strong plume and sputtering occurs frequently and repeatedly. In the case of welding speed greater than 30 m/min, only the spectrum of Al element was detected in the upper plume, and it was confirmed that Ti vapor in the lower surface was difficult to discharge upwards when the welding speed was relatively fast. It was judged that a large amount of Al evaporated, and it was dissolved in Ti through the keyhole. The amount of Al decreases in the Ti solid solution as the welding speed increases. On the other hand, due to the vapor pressure and behavior of Al vapor and Ti vapor, the amount of Ti dissolved in the Al melt is very small or hardly generated compared to the amount of Al dissolved in the Ti solid solution.

A molten pool of Ti(upper)-Al(lower) is narrower and as the velocity increases, the molten pool becomes narrower and longer. The elements of Al and Ti were detected on both the front and back plumes. In particular, Al evaporates a lot and is solid-solved in Ti through the keyhole. The amount of Al dissolved in Ti is larger than that of the Al(upper)-Ti(lower) case.

The behavior of vapor generated from Al and Ti materials differs depending on the material characteristics and vapor pressure difference, and it has been confirmed that this affects the behavior of elemental components distributed in the weld fusion zone. As a result, the atom movement of Al and Ti in the weld plume affects the behavior of elemental components distributed in the weld fusion zone.

4. Conclusions

This research focuses on understanding the mechanism underlying Al and Ti dissimilar laser welding. The material behavior of the weld fusion zone and components of the fume generated during an ultra-high speed welding process were observed. Some main conclusions are the following;

1. The lamellar and needle-shaped martensitic Al-rich Ti solid solution phases were created by extremely high melting and solidification rates due to ultra-high speed welding. The amount of needle-shaped martensitic α -Ti solid solution phases in-

- creased by increasing the welding speed. The α -Ti solid solution concentration of Al element in the weld zone was relatively uniform.
2. The behavior of vapor generated from Al and Ti materials differs depending on the material characteristics and the vapor pressure difference, and it has been confirmed that this affects the behavior of elemental components distributed in the weld fusion zone.
 3. Atom movement of Al and Ti in the weld plume was influenced by the welding speed and specimen location. It is inferred that the evaporation and the plume ejection accompanying it was stronger in Al because of lower boiling temperature and stronger vapor pressure. That is, it can be inferred that the evaporation of Al suppressed upward ejection of the lower Ti vapor toward the Al side, and the upper Al vapor blew upward and downward.
 4. According to the Al-Ti phase diagram, the phase region where the Al element is dissolved in the Ti lattice structure is wide, and hence is relatively easily dissolved in the weld fusion zone. The solid solution concentration in the weld zone of the Ti side was relatively uniform, indicating that the molten Al element was dissolved by the weld fume in the keyhole rather than being diffused or the molten pool mixing with the Ti.

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Nomenclature

P	Laser power (kW)
P _{max}	Maximum laser output (kW)
λ	Laser wavelength (nm)
BPP	Beam parameter product (mm·mrad)
f _d	Focus length (mm)
Ar	Flow rate of Ar (argon) shielding gas (ℓ/min)
mm ^t	Specimen thickness (mm)

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