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Effect of Laser Power on Microstructure and Micro-Galvanic Corrosion Behavior of a 6061-T6 Aluminum Alloy Welding Joints

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Abstract: The 6061-T6 aluminum alloy welding joints were fabricated using gas metal arc welding (GMAW) of various laser powers, and the effect of laser power on the microstructure evolution of the welding joints was investigated. The corrosion behaviors of 6061-T6 aluminum alloy welding joints were investigated in 3.5 wt% NaCl solution using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). The results showed that the micro-galvanic corrosion initiation from Mg₂Si or around the intermetallic particles (Al-Fe-Si) is observed after the immersion test due to the inhomogeneous nature of the microstructure. The preferential dissolution of the Mg₂Si and Al-Fe-Si is believed to be the possible cause of pitting corrosion. When the laser power reached 5 kW, the microstructure of the welded joint mainly consisted of Al-Fe-Si rather than the Mg₂Si at 2 kW. The relatively higher content of Al-Fe-Si with increasing in laser power would increase the volume of corrosion pits.

Keywords: 6061 aluminum alloy; welding; micro-galvanic corrosion; intermetallic particles

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1. Introduction

The 6061 aluminum alloy is an Al-Mg-Si alloy with good plasticity [1], low density [2], high strength [3,4], great formability [5], and excellent corrosion resistance [6,7]. These advantages enable the aluminum alloy to be widely used in the industry. The traditional welding of aluminum alloy was limited due to the problems that happened in the welding process, including low efficiency, oxide removal, and the burning loss of alloy elements with a low boiling point [8]. Since aluminum alloys are difficult to be welded [9,10], they are usually joined by tungsten inert gas welding (TIG) welding [11], friction stir welding (FSW) [12], and laser welding [13]. Hybrid laser–gas metal arc welding (GMAW) is a new welding technique to join aluminum alloy, it takes the benefits of deep penetration of laser, high speed, and low heat input, and combines the arc source to bridge gaps and change the mechanical properties by using the filler wire [10]. Research studies on aluminum alloys in the welding process are mostly focused on formability and the optimization of process parameters.

The published work on the laser–GMAW is mainly focused on the welding mechanism and numerical simulation. Xu et al. [14] established a three-dimensional transient model to investigate the weld pool behavior of aluminum alloy for a horizontal fillet joint by using hybrid laser–melt inert-gas welding (MIG) fillet welding, and they reported that the deformation in the weld pool surface appeared due to the strong downward flow driven by gravity and arc pressure. Xu et al. [15] study the residual stress and distortion of a 6061-T6 joint welded by using laser–gas metal arc welding and found that when the residual stress in and surrounding the weld zone was higher, a large distortion would appear in the middle and rear part of the welding joint. Cao et al. [16] investigated

the temperature field and fluid flow of a lap joint in the laser-GMAW hybrid welding process and found that the temperature gradient of the sheet decreased from the top to the bottom; the fluid flow governed by droplet impingement force was outward, while it became counterclockwise when it was driven by Marangoni force and gravity. Atabaki et al. [17] use a numerical finite element model to simulate an aluminum alloys joint prepared using laser arc welding and found that the off-distance between the laser beam and arc source and shoulder width would affect the penetration depth and the geometry of the welding joints. Ahmad et al. [18] reported that the post-weld heat treatment could improve the mechanical properties of AA6061 welded joints prepared using gas metal arc welding. Xu et al. [19] found the porousness of the 6061 aluminum alloy welded by laser-GMAW decreased with the increase of arc power. Chu et al. [20] found that the ratio of equiaxed dendrites was proportional with the weld strength, the cube texture in the columnar dendrites would decrease the weld strength, and the weld metal exhibited the characteristic of ductile fracture.

Zhang et al. [21] investigated the corrosion behavior of the weld zone of the AA6061-T6 aluminum alloy in 70% HNO₃, and they found that the corrosion behaviors of the samples were mainly due to the galvanic corrosion couplings between the precipitates and the matrix. Mujibur Rahman et al. [22] examined the galvanic corrosion of an AA6061 welding joint and found that the reason is due to the difference of corrosion potential between the weld fusion zone and the substrate; the dissolution of the surface film and the increase of intermetallic particles aggravated the corrosion of the weld zone. Gharavi et al. [23] found that the increase of intermetallic phases in the weld zone would increase the galvanic corrosion couplings, contributing to the corrosion of AA 6061-T6 aluminum alloy weld zone.

However, the influence of laser power on the corrosion of 6061-T6 aluminum alloy welding joint is still rarely reported. The present work aims to acquire the 6061-T6 welding joints at different laser power by using laser-GMAW and investigate the microstructure of the weld and its corrosion behavior in 3.5 wt% NaCl solution.

2. Experimental

The materials used in the present study are 6061-T6 aluminum alloy plates with a dimension of 60 mm × 100 mm × 6 mm, and the filler material is ER5356. The chemical composition of these materials is listed in Table 1. The experimental welding equipment is the welding system is composed of an IPG YLS-6000W fiber CO₂ laser and a gas metal arc welding (GMAW) heat source. The operating laser power was 2, 3.5, and 5 kW, respectively. A detailed description of the welding experimental procedure is given elsewhere [24]. The welding joints were cut into small pieces with the dimension of 10 mm × 10 mm, as shown in Figure 1. The samples were ground on SiC papers up to 2000 grit and then polished using diamond polishing paste. The polished samples were cleaned with ethanol, degreased by ultrasonic wave, and air dried.

Table 1. The chemical composition (wt%) of 6061-T6 aluminum alloy and ER5356.

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
6061 aluminum alloy	0.50	0.7	0.45	0.15	1.0	0.25	0.25	0.15	Bal.
ER5356	0.25	0.4	0.1	0.11	4.9	0.065	0.1	0.11	Bal.

For metallographic observation, the specimens were etched by Keller's reagent (1 vol.% HF, 1.5 vol.% HCl, 2.5 vol.% HNO₃, and 95 vol.% H₂O) for 1 min. The microstructure and corrosion morphology of the samples were characterized using VHX-900 (KEYENCE, Co. Ltd., Osaka, Japan) an ultra-depth three-dimensional microscope, scanning electron microscope (SEM, JSM-6480, Takeno, Japan), and OXFORD energy dispersive spectrometer (EDS).

The immersion tests of the welding joints were performed in a 3.5 wt% NaCl solution at 25 ± 1 °C (controlled by a thermostat water bath). The details of the immersion and

test was described elsewhere [25]. The samples for corrosion test were sealed with 703 silicone rubber, and only the weld region was exposed. The immersion periods are 20, 100, and 240 h, respectively.

Figure 1. Schematic of 6061-T6 aluminum alloy welded joint.

3. Results and Discussion

3.1. Microstructure of the Welding Joints

The typical microstructure of the 6061 aluminum alloy welding joint prepared by using different laser power is shown in Figures 2–4. It can be seen that the microstructure in the weld center was equiaxed dendrites, while the columnar crystals were found in the fusion zone. At the fusion line, the temperature gradient (G) was the highest and the growth rate (R) was the minimum, resulting in the highest undercooling degree (G/R). Under this circumstance, the columnar crystal was formed in the fusion zone and tended to grow in the direction of heat flux. After an increase in the distance from fusion line, the ratio of G/R decreased, leading to the evolution from columnar crystals to equiaxed dendrites in the weld center [10,26–28].

When the laser power was increased, the morphology of these crystals in the welding joints was similar, but the grain size and dendrites spacing increased. This was mainly because an increase in laser power would increase the heat input and decrease the cooling rate of the weld pool, contributing to the growth of these crystals [29,30].

Figure 2. Microstructure of welded joint at 2 kW: (a) Heat-affected zone; (b) Fusion zone; (c) Weld center.

Figure 3. Microstructure of welded joint at 3.5 kW: (a) Heat-affected zone; (b) Fusion zone; (c) Weld center.

Figure 4. Microstructure of welded joint at 5 kW: (a) Heat-affected zone; (b) Fusion zone; (c) Weld center.

3.2. Corrosion Behavior of the Weld Center

Figure 5 shows the corrosion morphologies of the samples prepared by different laser power after immersion in 3.5 wt% NaCl solution. A large number of corrosion pits with different shapes and diameters can be observed on the surface of samples. Similar results are reported for other aluminum alloys, such as AA 5083 [31], AA 6061 [23], and 7A09 Al–Zn–Mg–Cu alloy [32]. With increasing laser power, the size of the corrosion pits and the number of bright particles (zone B in Figure 4c) both increase.

Figure 6 presents the energy-dispersive X-ray spectroscopy (EDS) analysis of the regions shown in Figure 5. The chemical composition in regions indicated in Figure 5 is listed in Table 2. It showed that zone A was mainly enriched with Mg and Si, while zone B was enriched with Fe and Si. It can be referred that the second phases in the welded joint are Mg_2Si phase and Al–Fe–Si phase. This is consistent with the well-recognized principle that the main type of intermetallic inclusions of 6061-T6 aluminum alloy is the iron-rich phase (Fe–Al–Si) and Mg_2Si [23,24,33,34]. The localized corrosion was associated with the dissolution of the Mg_2Si phase [32] and the Fe-rich intermetallic phase of the multiphase particle [14]. When the laser power is 2 kW, the corrosion pits are small and densely distributed. When the laser power increases, the diameter and volume of the corrosion pits increased significantly, but the number of corrosion pits is dramatically decreased. When prolonging the immersion time, the micro-galvanic corrosion occurring in the Mg_2Si phases and surrounding particular types of Al–Fe–Si intermetallic phases is aggravated, leading to the increase of pit size.

Figure 5. Corrosion morphologies of weld center of 6061 aluminum alloy after immersion in 3.5 wt% NaCl solution. (a) 2 kW and immersion time 20 h, (b) 3.5 kW and immersion time 20 h, (c) 5 kW and immersion time 20 h, (d) 2 kW and immersion time 100 h, (e) 3.5 kW and immersion time 100 h, (f) 5 kW and immersion time 100 h, (g) 2 kW and immersion time 240 h, (h) 3.5 kW and immersion time 240 h, (i) 5 kW and immersion time 240 h.

Figure 6. Energy-dispersive X-ray spectroscopy (EDS) analysis of the regions shown in Figure 4. (a) Zone A, (b) Zone B.

Table 2. The chemical composition (wt%) in regions indicated on Figure 4.

	Mg	Al	Si	Mn	Fe
area A	2.22	95.17	2.61	-	-
area B	2.22	94.41	1.58	-	1.79

The corrosion behavior of aluminum alloy in a solution depends mainly upon the potential difference between the intermetallic particle and the aluminum matrix [24,35–38]. On the basis of the surface characterization of the evolution in the surface morphologies of the samples with the immersion time (Figure 5), it can be stated that the corrosion process

of 6061-T6 aluminum alloy after immersion in 3.5 wt% NaCl solution can be associated with the chemical and anodic electrochemical activity of the intermetallic phases. The micro-galvanic corrosion process in 6061-T6 alloy is summarized in Figure 7. The precipitated phase of 6061-T6 aluminum alloy is Mg_2Si and Al-Fe-Si phase. The corrosion potential of 6061-T6 aluminum matrix, Al-Fe-Si intermetallic, and Mg_2Si intermetallic is about -700 mV_{SCE} [24], -200 mV_{SCE} [38,39], and -1200 mV_{SCE} [36], respectively. The corrosion potential of Mg_2Si phases is much lower than the potential of their adjacent aluminum substrate. The large potential difference makes the micro-couple action more obvious and prone to galvanic corrosion, in which the low potential Mg_2Si phases act as anodes in the corrosion process, take priority in dissolving, and form corrosion pits at Mg_2Si . The Mg_2Si can be hydrolyzed by water according to the following reaction [38]:

Figure 7. Schematics showing the micro-galvanic corrosion process for 6061-T6 aluminum alloy in 3.5 wt% NaCl solution. (a) 6061-T6 alloy, (b) corrosion was initiated on Mg_2Si , (c) Al-Fe-Si was corroded, (d) dissolution and fall off for Al-Fe-Si.

With increasing immersion time, the Mg_2Si became smaller and smaller until it finally disappears. Unlike the Mg_2Si phase, the corrosion potential of the Al-Fe-Si phase is noble compared with that of the aluminum alloy matrix. The galvanic coupling between the Al-Fe-Si phase and the surrounding aluminum alloy matrix leads to the severe localized attack. As a result of the obvious potential difference between the Al-Fe-Si phase and aluminum alloy matrix, the corrosion rate of the matrix is faster.

Increasing laser power will bring an increase in the heat input of the weld pool and decrease the cooling rate, which is contributing to an increase of the solid solubility of the Mg_2Si phase. Under these circumstances, the number of Mg_2Si phases decreases with the increasing laser power. However, the Al-Fe-Si phase is still insoluble in the matrix with the increase of heat input [40,41]. Therefore, when the laser power is 5 kW, the microstructure of weld center is mainly composed of the Al-Fe-Si phase, rather than the Mg_2Si phase at 2 kW. The variation of potential among the matrix, Mg_2Si , and the Al-Fe-Si phase leads to the dissolution of the Mg_2Si phase and the matrix surrounding the Al-Fe-Si phase. When the matrix around the Al-Fe-Si phase continues to dissolve, the Al-Fe-Si particles will fall off from the matrix and form bigger pits. The relative proportion of the Al-Fe-Si phase is higher than the Mg_2Si phase due to the dissolution of the Mg_2Si phase with increasing laser power, which leads to an increase in the volume of the pits.

4. Conclusions

Based on the above results and discussions, the following conclusions can be obtained:

- (1) With the increase of laser power, the segregation structure, equiaxed grain, and HAZ structure and columnar crystal at the fusion line are coarsening, and the dendrite gap increases.

- (2) The micro-galvanic corrosion in the 6061-T6 aluminum alloy welded joint is mainly induced by Mg₂Si and Fe-Al-Si intermetallic particles.
- (3) The decrease in the corrosion pits is related to the lower density of intermetallic particles of intermetallic particles on the surface.
- (4) The volume of corrosion pits increases with the increase of laser power.

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