Materials Characterization 144 (2018) 652–660

Contents lists available at ScienceDirect

Materials Characterization

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

Corrosion behaviors of friction welded dissimilar aluminum alloys

Sori Won[a,1], Bosung Seo[a,1], Jong Min Park[a], Hyo Kyu Kim[a], Kuk Hyun Song[b], Seok-Hong Min[c], Tae Kwon Ha[c], Kwangsuk Park[a,*]

[a] Gangwon Regional Division, Korea Institute of Industrial Technology, Gangneung-Si, Gangwon-Do 25440, Republic of Korea
[b] Department of Welding and Joining Science Engineering, Chosun University, 309 Pilmun-daero, Dong-gu, Gwangju 61452, Republic of Korea
[c] Department of Advanced Metal and Materials Engineering, Gangneung-Wonju National University, 123 Chilbyondong, Gangneung, Gangwon-Do 25457, Republic of Korea

ARTICLE INFO

Keywords:
Friction welding
Dissimilar aluminum alloys
Corrosion
Galvanic effect
Electrochemical impedance spectroscopy

ABSTRACT

Corrosion behaviors of the friction welded dissimilar aluminum alloys were investigated to understand how galvanic effect plays a role in altering corrosion properties of the dissimilar weld. From the fact that the weld had the similar OCP value to that of AA2017, it can be inferred that the corrosion characteristics of the weld is under the control of the AA2017 part in the weld and as a result, only the AA2017 part in the weld had experienced severe corrosion, leaving AA6063 under cathodic protection. Intense corrosion occurring near the interface implies that the area near the interface is placed under the effect of galvanic corrosion and there was the effective distance where the galvanic effect exerts an impact due to the increase in the resistance of the electrolyte with the distance from the interface. The disappearance of Warburg diffusion plot in Nyquist plots for the weld seemed to be the breakdown of the passivation layer related to the formation of the micro-galvanic cell, which in turn presented the shrinkage in the capacitance response, indicating that charge reactions in the form of corrosion occurred.

1. Introduction

Aluminum alloys are a second metal in use as structural ones due to the high strength and excellent corrosion resistance and in particular, low density, approximately one-third as much as steel makes them promising alternatives to steels for lightweight structures such as vehicles and airplanes [1–4]. A broad range of mechanical properties that are designed by controlling alloying elements permits aluminum alloys to be constructed as parts and components in the various fields of applications, which increases the possibility that combination and/or joining between dissimilar aluminum alloys parts would be addressed [5,6]. The difference in physical properties of aluminum alloys, however, gives rise to new concerns when joined together. Basically, fusion welding requires high heat input to melt metals so the difference in thermal conductivity would cause lack of fusion or excessive melting depending on the thermal conductivity of aluminum alloys [7]. Also, due to the melted characteristic of fusion welding, solidification cracking (hot cracking) often occurs and especially is critical for 2xxx and 7xxx series aluminum alloys that contain principal alloying elements such as Cu and Mg [8–10].

Friction welding (FW) is a solid state joining method based on frictional heat generated from the movement between two components under pressure, where the friction heat softens the interfaces of the components and finally forms a sound joint [5,11]. There are three types of friction welding; rotary friction welding (RFW), linear friction welding (LFW) and friction stir welding (FSW) [12–16]. Compared with the latter two that are newly developed to extend the application of RFW to non-axisymmetric and plate-type configurations, RFW is the oldest friction joining technique that is patented in 1891 and has been commercially used since 1940s to join the materials with shapes of wires, rods and tubes and recently, its application reaches to the combinations of dissimilar metals (dissimilar steel alloys, steel-aluminum, steel-copper) where the difference in thermal conductivities of dissimilar metals would commonly cause a variety of defects when fusion welding is used [5,17–19]. As a solid state process, FW is suitable to join dissimilar metals because it does not form a molten pool, thus allowing free of defects related to solidification such as solidification cracking, porosity and segregation which limit usage of the fusion welding [12,17,20].

H. K. Rafi et al. showed availability of RFW process by investigating

---

* Corresponding author.
E-mail addresses: sor22@kitech.re.kr (S. Won), bs3863@kitech.re.kr (B. Seo), pjm2639@kitech.re.kr (J.M. Park), khk4529@kitech.re.kr (H.K. Kim), skhyun7@chosun.ac.kr (K.H. Song), shmin@gwnu.ac.kr (S.-H. Min), tkha@gwnu.ac.kr (T.K. Ha), kpark63@kitech.re.kr (K. Park).

[1] Sori Won and Bosung Seo equally contributed to this work.

https://doi.org/10.1016/j.matchar.2018.08.014
Received 19 June 2018; Received in revised form 3 August 2018; Accepted 9 August 2018

effects of process parameters such as rotating speed, friction pressure and upset length on microstructure and mechanical properties of AA7075-T6, where almost 89% joint efficiency was achieved by controlling process conditions [9]. M. Kimura et al. applied RFW to AA5052-H112 and AA5052-H34 to improve joint efficiency by varying friction time and forge pressure, where 93% and 100% joint efficiency were accomplished, respectively [6]. With the success in achieving sound joint, it is has also been reported that solid state welding methods demonstrate better corrosion resistance than conventional fusion welding which usually forms a dendritic structure with heterogeneous compositions, thus resulting in poor corrosion performances [21,22]. Even if not as serious as fusion welding, solid state welding also suffers from corrosion issues. For example, microstructural changes such as formation of precipitates at grain boundaries and their distribution after friction stir welding (FSW) on AA2024-T3 makes the welded zone sensitive to intergranular corrosion as well as pitting corrosion [23]. While, there are some conflicting results for AA6xxx series. P. Dong et al. showed FSW welded AA6005-T6 had higher intergranular corrosion resistance than the base metal as a result of coarsening of the precipitates at grain boundaries but generated pitting corrosion in the grains located in the heat-affected zone [24]. While, V. Fahimpour et al. reported FSW resulted in the poor corrosion resistance in terms of corrosion potential and corrosion current density with respect to the base AA6061, which was ascribed to the grain refinement of the welded zone [21].

In this study, two dissimilar aluminum alloys such as AA2017 and AA6063 were chosen to be welded by RFW, where galvanic corrosion would give an impact on corrosion behaviors of the weld. As galvanic corrosion is a kind of electrochemical process in which one metal is preferentially oxidized compared to the other, it is vital to understand how the biased corrosion characteristic affects performances of the joint to prevent failures of the welds on service. RFW is known to be a well-established solid state welding technique that has already had numerous industrial applications and now popular in joining dissimilar metals, however, there are very few works on corrosion properties of the friction welded dissimilar aluminum alloys. Therefore, to achieve reliable and sound welds composed of dissimilar aluminum alloys joined by RFW, it is necessary to investigate changes in corrosion behaviors resulting from the galvanic effect.

2. Experimental Procedure

2.1. Welding Procedure

The aluminum alloys used in this study are ϕ 12 mm AA6063 (extruded and recrystallized state) and ϕ 20 mm AA2017 (extruded state) rods and the chemical compositions of two alloys are shown in Table 1. To adjust the dimension of the welded area for RFW process, the one end of AA2017 was machined to reduce the diameter to 12 mm from 20 mm (see Fig. S1 in Supplementary material). The friction welding was carried out with the mode of continuous-drive friction welding (CDFW), where AA6063 was held stationary and moved to AA2017 that kept rotating at a speed of 2000 rpm. The friction force, upset force and upset length applied were 1.2 MPa, 2.5 MPa and 2.3 mm, respectively.

Table 1
Chemical compositions of the materials used in this study.

AA6063	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Composition (wt %)	0.50	0.17	0.012	0.036	0.45	0.01	0.003	0.01	Bal.

AA2017	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr + Ti	Al
Composition (wt %)	0.75	0.27	3.86	0.63	0.50	0.01	0.05	0.03	Bal.

2.2. Characterizations

Microstructures of two base metals and the dissimilar joint were examined by optical microscopy (OM) and scanning electron microscopy (SEM) equipped with electron backscatter diffraction (EBSD). To reveal precipitates in the aluminum alloys, the etchant composed of 2.5 mL HNO_3, 1.5 mL HCl, 0.2 mL HF and 95.8 mL DI water was used. Vickers microhardness test was conducted by applying 100 g for 10 s to find out the variation of mechanical property in the welded zone. Various electrochemical analyses such as potentiodynamic polarization, open circuit potential (OCP) measurements and electrochemical impedance spectroscopy (EIS) measurements were applied to characterize corrosion behaviors, where the deaerated 3.5 wt% NaCl solution was used as an electrolyte. Polarization tests were conducted to obtain Tafel plots, with a scan rate of 0.05 mVs^{-1} and potential range between +1.5 V and −1.5 V from the OCP. OCP variations with time were detected by immersing the samples in the deaerated 3.5 wt% NaCl solution. EIS was performed at the open circuit potential to characterize corrosion properties, where the sinusoidal voltage with an amplitude of 10 mV and frequency from 10,000 to 0.05 Hz were applied. All electrochemical tests (Autolab PGSTAT302N) used in this study were conducted with three electrodes configuration, where Pt plate and Ag/AgCl electrodes were used as counter and reference electrodes, respectively.

3. Results and Discussion

3.1. Microstructural Investigation

It is well known that during RFW process, increase in temperature as well as intense plastic deformation around the welded zone occurs, leading to dynamic recrystallization and finally, grain refinement [9,25]. As shown in Fig. 1 showing microstructures of AA6063, AA2017 and the weld, the grains in the welded zone were refined and aligned to the rotational direction of RFW, supporting that during RFW the metals became plasticized with the rotation and finally, dynamically recrystallized with the increase in temperature. The joint showed defect-free, very clear and distinct interface between two metals, which is a typical characteristic of solid state welding processes, as shown in Fig. 2(a). Friction welds are known to have three distinct microstructures; dynamically recrystallized zone (DRZ), thermo-mechanical affected zone (TMAZ) and heat-affected zone (HAZ) [9,17,26]. However, in this study, both metals exhibited only two microstructural regions such as DRZ and TMAZ and in particular, AA6063 showed much wider equiaxed DRZ than AA2017, as shown in Fig. 2(b) and (c). It could be two reasons for the well-developed DRZ in AA6063. One is relatively softener characteristic of AA6063 than AA2017, which would cause severer deformation of AA6063 than AA2017 during the FW process and result in more amount of the dynamic recrystallization (see Fig. S2 in Supplementary material). The other is AA6063 was placed at the stationary side where more heat would generate because the rotating side (AA2017) had convection effect, enabling effective heat dissipation. Therefore, it can be imaged that AA6063 experienced higher temperature than AA2017 during the welding, which could be the favorable condition for the plastic deformation and resultant dynamic recrystallization. For a similar reason, the welded zone including TMAZ of AA6063 looked bigger than that of AA2017. The grains in TMAZs of both metals were revealed to be aligned parallel with the radical direction as a result of the plastic deformation during the welding and their size became bigger with the distance away from the weld interface. These microstructural changes in the weld zone give an impact on mechanical properties of the joint. Fig. 2(d) displays variations of microhardness values as a function of the distance from the interface. After the welding, AA6063 became soften, while the hardness of AA2017 seemed to be slightly increased. It can be known that