

Galvanic Corrosion Between Component Parts of Aluminum Alloys for Heat Exchanger of Automobile

Y. R. Yoo¹, D. H. Kim², G. B. Kim³, S. Y. Won³, S. H. Choi³, and Y. S. Kim^{1,3,†}

¹Materials Research Center for Energy and Clean Technology, Andong National University,
1375 Gyeongdong-ro, Andong, Gyeongbuk, 36729, Korea

²Research & Development Team, SEJONG EV, 137 Cheomdansaneop1-ro, Daesowon, Chungju, Chungbuk, 27466, Korea

³Department of Materials Science and Engineering, Andong National University, 1375 Gyeongdong-ro, Andong, Gyeongbuk, 36729, Korea
(Received October 06, 2023; Revised October 23, 2023; Accepted October 24, 2023)

There are a variety of heat exchangers used in automobiles, such as shell and tube heat exchangers, double tube heat exchangers, and plate heat exchangers. Most of them are water-cooled to prevent engine overheating. There have been reports of corrosion damage to these heat exchangers due to continuous wetting caused by external temperature differences, road pollutants, and snow removal. In addition, galvanic corrosion, which occurs when two dissimilar materials come into contact, has been identified as a major cause. In this study, corrosion characteristics and galvanic corrosion behavior of Al alloy (AA3003, AA4045 and AA7072) used in automobile heat exchangers were analyzed. Effective clad materials for heat exchanger tubes and fins were also evaluated. It was found that AA7072 should be applied as the cladding material for fin AA3003 and that AA4045 was suitable as a cladding material for tube AA3003 because this clad materials application was the most effective clad design to delay the occurrence of pinhole in the tube. Main factors influencing galvanic corrosion dissolution were found to be galvanic corrosion potential difference and galvanic corrosion current density.

Keywords: Heat exchanger, Aluminum alloys, Galvanic corrosion, Clad materials, Sacrificial anode

1. Introduction

A heat exchanger is a device designed to exchange heat between fluids. Heat exchangers are commonly found in various applications, including air conditioners, radiators, refrigerators, and more. These heat exchangers are applied in various ways and are also used in automotive and industrial applications, especially in recent years to improve the performance and miniaturize the size of heat exchangers to reduce energy consumption and air pollution [1,2]. The use of lightweight materials can reduce weight and improve fuel efficiency [2,3]. The replacement of copper heat exchangers with heat exchangers made of aluminum for weight reduction has been made due to its high strength-to-weight ratio, good formability, excellent corrosion resistance, and recyclability [2-5].

Generally, the temperature of combustion gases inside an automobile engine can reach approximately 2,000 to 2,500 °C, and a significant amount of this heat is transferred, affecting engine performance, and must be removed through a heat exchanger [6-8]. There are various types of heat exchangers such as shell and tube, double tube heat exchangers, and plate heat exchangers [9]. To prevent engine overheating, most of these heat exchangers are water-cooled, using a mixture of tap water or antifreeze (ethylene glycol) and water to prevent freezing in winter [4,6,10]. Ethylene glycol contains oxides of glycol, which can accelerate corrosion of metallic materials used in the cooling system, especially aluminum parts, so corrosion inhibitors are added separately [10,11]. While the coolant circulating internally serves the purpose of lowering the temperature of the heat exchanger, but it is also accompanied by various problems, so various studies are being conducted to improve performance and stability [12-14].

It can be divided into internal and external factors: include the introduction of corrosive substances such as

[†]Corresponding author: yikim@anu.ac.kr

Y.R. Yoo: Senior Researcher, D.H. Kim: Researcher, G.B. Kim: M.S. Student, S.Y. Won: M.S. Student, S.H. Choi: Ph.D. Candidate, Y.S. Kim: Professor

sulfur and chlorine, which are detrimental to aluminum, as well as mechanical corrosion due to cavitation caused by fluid flow and velocity, leading to tube damage. It is known that the presence of chlorine (Cl) has a significant impact on the corrosion of aluminum alloys [10,15-18]. The use of distilled water is recommended because even common tap water contains corrosive chloride and precipitable calcium and magnesium, which are potential sources of corrosion [10].

As external factors, there have been reports of corrosion cases of continued wet conditions due to the difference in temperature between the heat exchanger and the outside, severe road pollution, or snow removal agents. In addition, galvanic corrosion, which occurs when two dissimilar metals come into contact, has been cited as a significant cause of damage [4,5,10]. To minimize the damage caused by galvanic corrosion, aluminum alloy brazing is used [19-23]. In general, 3000 series of Al-Mn alloy is widely used as a heat exchanger material because it has enhanced the formability and corrosion resistance of aluminum and improved the strength by adding a small amount of Mn [19,20]. The radiator core acts as a sacrificial anode, causing localized galvanic reactions, which can lead to pitting corrosion and pin-hole formation [8,10]. Since heat exchangers are frequently exposed to harsh conditions and are expensive to maintain, corrosion

prevention is very important. Corrosion can occur in all possible forms (electrochemical, physical, localized, etc.) [23]. However, it is also necessary to consider these possible corrosions and predict the lifetime of the product under different conditions.

Therefore, in this study, we evaluated the corrosion properties of three alloys, AA3003 (3000 series), AA4045 (A4000 series), and AA7072 (A7000 series), which are commonly used as heat exchanger materials for automobiles and analyzed the electrochemical galvanic corrosion behavior for each galvanic pair. In addition, the applied fins are designed to increase heat exchange efficiency and to corrode before the tubes, thereby delaying corrosion of the connection between the tubes and fins. The connection was usually brazed using a clad material with a relatively low melting point. To design the most effective cladding, the galvanic corrosion behavior of the applied alloys was discussed.

2. Experimental Methods

2.1 Specimen

The specimens used for the polarization and galvanic corrosion tests were three type of aluminum alloy (AA3003, AA4045, AA7072). Fig. 1 shows a schematic cross-section of these alloys and Table 1 shows the

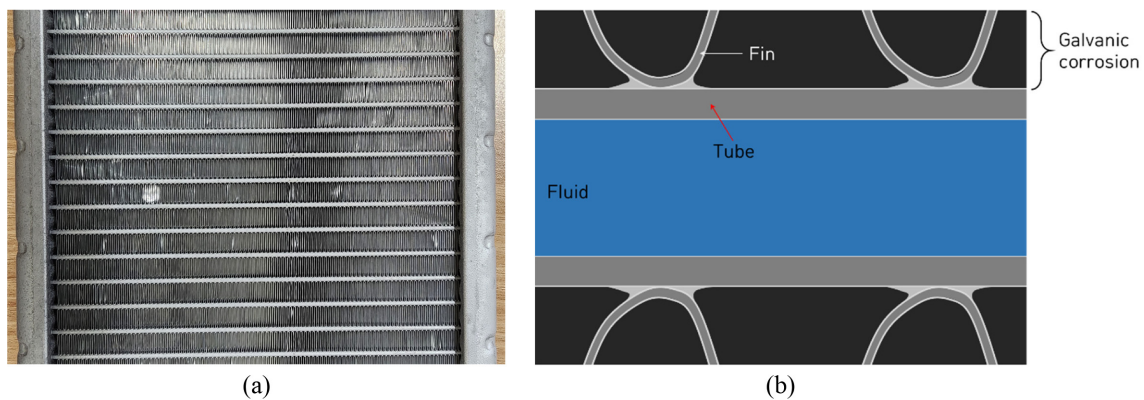


Fig. 1. (a) Micro channel heat exchanger and (b) schematic diagram of cross-section and galvanic corrosion area

Table 1. Chemical composition of aluminum alloys (wt%) and their melting points

Alloys	Si	Fe	Cu	Mn	Zn	Ti	Al	M.P. (°C)
AA3003	0.76	0.50	0.83	1.32	0.03	0.09	Bal.	654
AA4045	9.68	0.14	-	-	0.01	-	Bal.	590
AA7072	0.55	0.55	-	0.06	1.10	0.01	Bal.	640 to 657

composition and melting points for the aluminum alloys. As shown in Fig. 1, galvanic corrosion due to external factors occurs where the fins are connected to the tubes for efficient heat exchange.

2.2 Polarization test

The specimens used in this test were AA3003, AA4045 and AA7072 alloy. Each specimen was appropriately cut and connected to a Plate Cell in a way that exposed an area of 1 cm². In the polarization test, a Potentiostat (Gamry DC 105, Gamry Instruments, Warminster, PA, USA) was used, with a saturated calomel electrode (SCE) as the reference electrode and a platinum electrode (Pt) as the counter electrode. The test solution was degassed using N₂ gas at a flow rate of 200 ml/min for 30 minutes. After installing the specimens, conditioning and initial delay were performed for 10 minutes to equalize the surface condition. The polarization was then performed at a scan rate of 0.33 mV/sec. The experimental solution used was a 1% NaCl solution at 20 °C.

2.3 Electrochemical galvanic corrosion test

The specimens used AA3003, AA4045 and AA7072 alloy and these specimens were combined to form three galvanic couples. Each specimen was cut to appropriate size and then connected to the Plate Cell so that only a 1 cm² area was exposed. The combination of specimens is as follows: in AA3003 and AA4045, AA3003 acts as the cathode, so AA4045 is used as the anode; in AA3003 and AA7072, AA3003 acts as the cathode, so AA7072 is used as the anode; in AA4045 and AA7072, AA4045 acts as the cathode, so AA7072 is used as the anode. The electrochemical galvanic corrosion test was performed using a Potentiostat and the reference electrode was a SCE. The test solution was evaluated using a 1% NaCl solution at 20 °C and degassed using N₂ gas at a rate of 200 mL/min for 30 minutes.

3. Results and Discussion

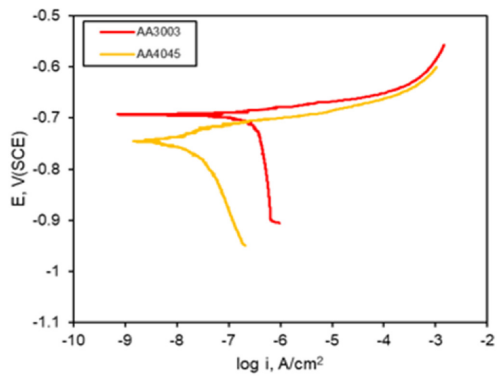
The alloys used in this study were AA3003, AA4045, and AA7072. A3000 series alloys are Al-Mn alloys that can maintain corrosion resistance by solid solution hardening of manganese and are used in automotive micro channel heat exchangers due to their excellent machinability.

A4000 series alloys are Al-Si alloys, which have a lower melting point than A3000 series alloys due to the addition of Si and are used for casting and are used where excellent wear and heat resistance is required. The A7000 series alloy, an Al-Zn-Mg alloy, inherently possesses good corrosion resistance. Among these alloys used in this study, the A7000 series alloy had the lowest potential, serving as a sacrificial anode to prevent corrosion of the base material when used as cladding in heat exchangers.

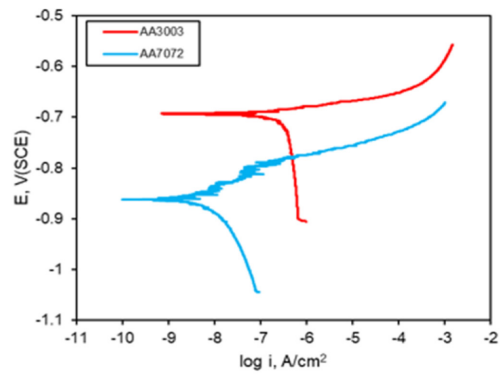
Fig. 1 shows a cross-section of a finned heat exchanger designed to facilitate effective heat exchange in the fluid flowing inside the tubes. Both the tube and the fins are made of the same material. If the surface of the heat exchanger continues to be wet due to external factors and a corrosive environment is created, a pin-hole phenomenon may occur due to pitting corrosion. In order to delay the occurrence of such pin-holes, the anode material is cladded on the surface of the tube to artificially form a galvanic couple, so that corrosion would preferentially proceed on the surface rather than inside the tube. In addition, the applied fins were designed to increase heat exchange efficiency and to corrode before the tubes, thereby delaying corrosion of the connection between the tubes and fins were brazed using a cladded material with a relatively low melting point. To design the most effective cladding, the galvanic corrosion behavior of the applied alloys was evaluated.

The tube and fin materials of the heat exchanger are AA3003, and the alloys used as cladding to delay pinhole formation are AA4045 and AA7072. To evaluate the galvanic corrosion properties of these three aluminum alloys, polarization tests were performed initially. And then the working (anode) electrode and counter electrode were distinguished. The electrochemical polarization test was performed deaerated 1% NaCl solution at 20 °C.

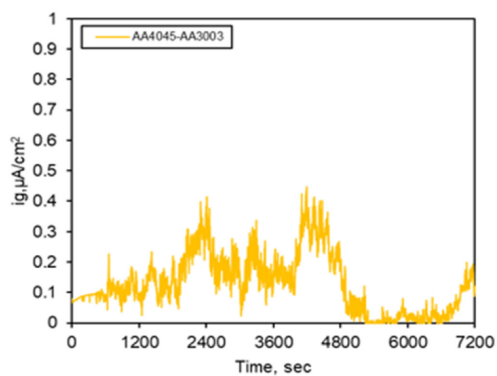
Fig. 2a shows the polarization behavior of AA4045 and AA3003. As shown in the figure, the corrosion potential of the base material AA3003 was higher than that of AA4045. When the two alloys are exposed to the mentioned environment, galvanic corrosion is expected to occur, AA3003 is expected to act as the cathode, and AA4045 as the anode. Therefore, a galvanic cell with AA4045 as the working electrode and AA3003 as the counter electrode was performed to evaluate the galvanic corrosion current density and galvanic corrosion potential,



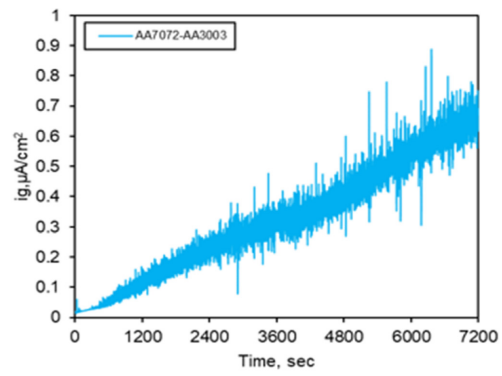
(a)



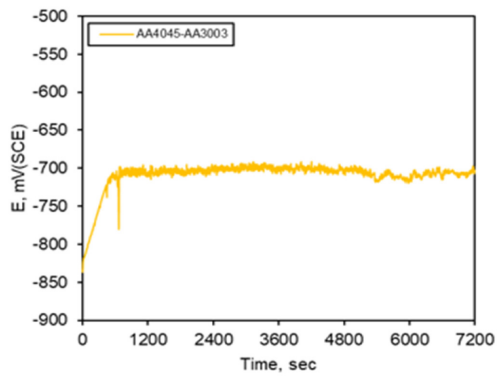
(a)



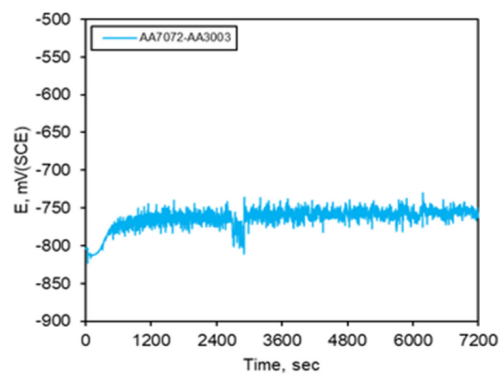
(b)



(b)



(c)



(c)

Fig. 2. (a) Polarization curves of AA4045 and AA3003, (b) galvanic current density of AA4045 (working electrode) and AA3003 (counter electrode), (c) its galvanic potential (test solution: deaerated 1% NaCl at 20 °C)

Fig. 3. (a) Polarization curves of AA7072 and AA3003, (b) galvanic current density of AA7072 (working electrode) and AA3003 (counter electrode), (c) its galvanic potential (test solution: deaerated 1% NaCl at 20 °C)

which are shown in Figs. 2b and 2c. As expected, the galvanic current density is positive, indicating that AA4045 is more active than AA3003. It was confirmed that the formed galvanic corrosion potential matched relatively well with the position where the anodic polarization behavior of AA4045 and the cathodic polarization behavior of AA3003 intersect in the mixed potential theory.

Fig. 3a shows the polarization behavior of AA7072 and AA3003. The polarization behavior of the two alloys shows that the corrosion potential of AA3003 is noble than that of AA7072. If the two alloys are connected as a galvanic couple and exposed to the above environment, AA3003 acts as a cathode and AA7072 acts as an anode, and galvanic corrosion is expected to occur. AA7072 is connected to the working electrode and AA3003 is

connected to the counter electrode to form a galvanic cell, and the galvanic current density and galvanic corrosion potential were evaluated in the same environment as the environment in which the polarization behavior was evaluated, and these are shown in Figs. 3b and 3c. As expected, the galvanic current density is positive, and the positive current density increases with time. AA7072 is more active than AA3003. The observed galvanic corrosion potential was slightly higher than the intersection of the anodic polarization behavior of AA7072 and the cathodic polarization behavior of AA3003.

To evaluate the galvanic corrosion behavior between AA4045 and AA7072 used as clad material, a polarization test was performed in the same environment for both alloys, and the polarization behavior results are shown in Fig. 4a. The corrosion potential of AA4045 was higher than that of AA7072 in the clad material. It is expected that the two alloys are connected as a galvanic couple when galvanic corrosion proceeds, AA7072 is expected to act as an anode and corrosion will proceed. This galvanic corrosion behavior is shown in Figs. 4b and 4c. The galvanic current density in Fig. 4b shows a positive value. And as shown in Fig. 4c, the galvanic corrosion potentials formed in both alloys were slightly higher than the potential where AA7072's anodic polarization behavior intersected with AA4045's cathodic polarization behavior.

The polarization behavior of the three alloys shows that when the three alloys are exposed to a corrosive environment at the same time, the corrosion potential decreases in the order of AA3003, AA4045, and AA7072. Which means that the possibility of acting as a cathode in the formation of a galvanic cell is also likely to follow the above order. Therefore, clad applied to delay the occurrence of pin-holes in the tube (AA3003) will be effective in terms of galvanic corrosion for both AA4045 and AA7072. Additionally, according to the galvanic corrosion test results in Figs. 2 to 4, the galvanic corrosion current density was in the order of size: AA7072-AA3003 > AA4045-AA3003 > AA7072-AA4045. As shown in Fig. 1, when the materials clad in the tube and fin are different, AA4045 and AA7072, respectively, the combination of alloys exposed to the initial corrosive environment and connected as a galvanic couple is

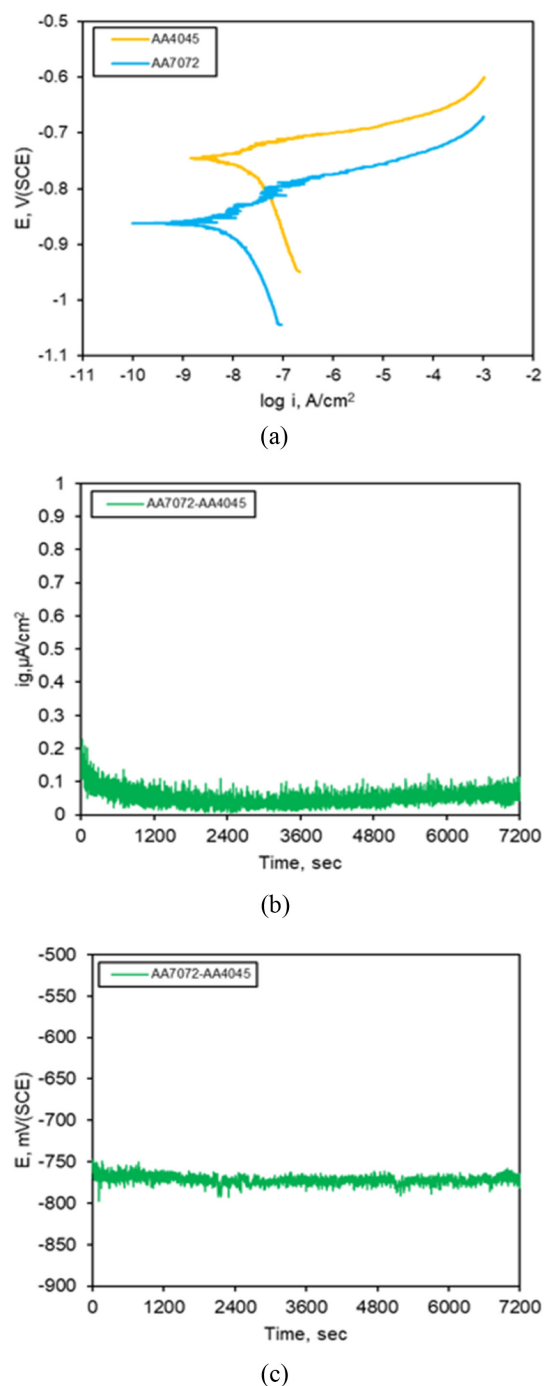


Fig. 4. (a) Polarization curves of AA4045 and AA7072, (b) galvanic current density of AA7072 (working electrode) and AA4045 (counter electrode), (c) its galvanic potential (test solution: deaerated 1% NaCl at 20 °C)

AA4045 and AA7072. Although the potential difference between the two alloys is not large, AA7072 is evaluated as the anode. Therefore, if the above two materials are to be clad on the tubes and fins, it is preferable to clad AA7072 on the fins and AA4045 on the tubes, which

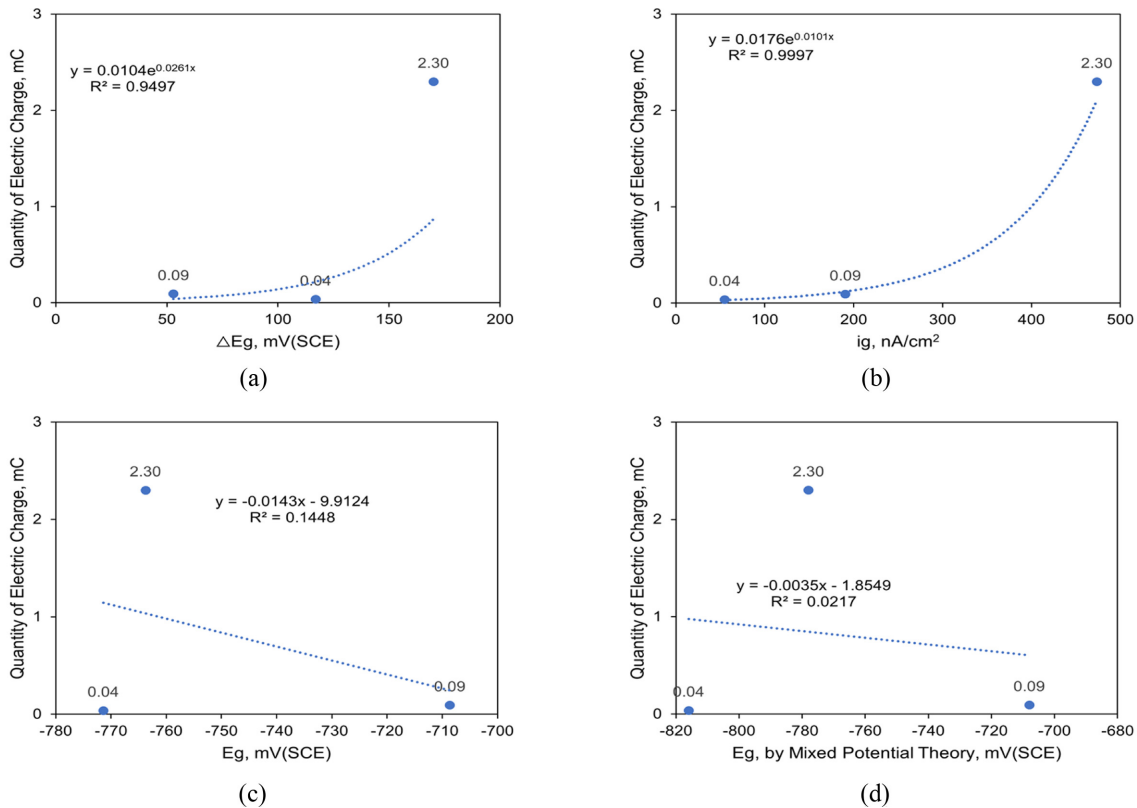


Fig. 5. Relationship between electrochemical factors (from the polarization curves and the galvanic corrosion behavior) and electric charge during galvanic corrosion test; (a) corrosion potential difference, (b) galvanic current density, (c) galvanic corrosion potential, (d) galvanic corrosion potential by the mixed potential theory

should be subjected to corrosion first.

This galvanic corrosion evaluation is based on the polarization behavior of materials, assessing the possibility of their acting as either anodes or cathodes in galvanic pairs. Therefore, the influence of electrochemical factors on galvanic corrosion for these galvanic pairs was investigated.

Fig. 5 is a graph showing the relationship between electrochemical factors (from the polarization curves and the galvanic corrosion behavior) and electric charge during galvanic corrosion test. Fig. 5a compares the corrosion potential difference between the alloys in polarization behavior with amount of electric charge during the test. It shows that as the corrosion potential difference increases as the corrosion potential difference increases. Fig. 5b shows the effect of galvanic current density on the electric charge during the galvanic corrosion test, which tends to increase exponentially as the galvanic current density increases. The correlation between the three couple of galvanic potential and charge

amount is shown in Fig. 5c. The relationship between the galvanic potentials and the electric charge amount is low as the galvanic potential increases and decreases. And this trend is also shown in Fig. 5d. Fig. 5d shows the relationship between the galvanic potential by the mixed potential theory and electric charge amount, and the effect of the galvanic potential on the amount of electric charge and dissolution according to the mixed potential theory was evaluated as having a low correlation, like the galvanic potential. Therefore, when each alloy is exposed to a corrosive environment and a galvanic corrosion is occurred, the difference between the corrosion potentials of the alloys in the galvanic couple combination and the galvanic current density are judged to affect the galvanic corrosion behavior.

4. Conclusions

There are various methods to reduce the external corrosion of heat exchangers. Among them, this study

investigated the galvanic corrosion of aluminum alloys used in the tubes and fins of heat exchangers, which can cause external damage. The following conclusions were drawn:

1. From the perspective of protecting the tube AA3003, both AA4045 and AA7072 exhibited excellent sacrificial galvanic effects when used as cladding materials. When the material of the tube and the fin are the same AA3003, AA7072 which is relatively active than AA4045 should be applied as the cladding material for the fins, because the fin corrodes preferentially and protects the tube. In the case of AA7072 cladded fin, AA4045 is suitable as the cladding material for the tube, because this among three alloys is the most effective clad design to delay the occurrence of pinhole in the tube.

2. Based on the galvanic corrosion between three aluminum alloys for heat exchangers, the main factors influencing galvanic corrosion dissolution were determined to be galvanic corrosion potential difference and galvanic corrosion current density. These findings provide insights into mitigating the effects of galvanic corrosion on aluminum heat exchangers, which can help in improving their durability and performance.

Acknowledgments

This research was supported by a grant from the 2023-2024 Research funds of Andong National University, and Korea Institute for Advancement of Technology (KIAT) grant funded by the Korea Government (MOTIE) (P0008458, HRD Program for Industrial Innovation).

References

1. J. M. Kim, J. P. Lee, C. E. Lee, and S. M. Kum, Characteristics of thermal efficiency with changing distances between tubes for heat exchanger, *Journal of Energy Engineering*, **19**, 177 (2010).
2. W. S. Miller, L. Zhuang, and J. Bottema, Recent development in aluminum alloys for the automotive industry, *Materials Science and Engineering: A*, **280**, 37 (2000). Doi: [https://doi.org/10.1016/S0921-5093\(99\)00653-X](https://doi.org/10.1016/S0921-5093(99)00653-X)
3. P. D. Srivyas and M. S. Charoo, Application of hybrid aluminum matrix composite in automotive industry, *Materials today: Proceedings*, **18**, 3189 (2019). Doi: <https://doi.org/10.1016/j.matpr.2019.07.195>
4. M. Asadikiya and M. Ghorbani, Effect of inhibitors on the corrosion of automotive aluminum alloy in ethylene glycol-water mixture, *Corrosion*, **67**, 126001 (2011). Doi: <https://doi.org/10.5006/1.3666860>
5. Y. Liu and Y. F. Cheng, Effects of coolant chemistry on corrosion of 3003 aluminum alloy in automotive cooling system, *Materials and Corrosion*, **61**, 574 (2010). Doi: <https://doi.org/10.1002/maco.200905323>
6. C. W. Kang, T. J. Kim, and C. W. Lee, Numerical analysis on the characteristics of thermal flow in an automobile radiator, *Journal of the Korean Society of Manufacturing Process Engineers*, **18**, 55 (2019). Doi: <https://doi.org/10.14775/ksmpe.2019.18.6.055>
7. S. B. Kwak, Ph.D. Thesis, pp. 1 - 2, Hanyang University, Seoul (2011).
8. A. S. Fitrianto, C. Caing, H. A. Notonegoro, and B. Soegijono, Effect of titanium on corrosion behavior of aluminum alloy 3104 as a candidate material for radiator combustion engines, *Flywheel*, **7**, 12 (2021). Doi: <http://dx.doi.org/10.36055/fwl.v0i0.10855>
9. H. M. Ali, H. Ali, H. Liaquat, H. T. B. Maqsood, and M. A. Nadir, Experimental investigation of convective heat transfer augmentation for car radiator using ZnO-water nanofluids, *Energy*, **84**, 317 (2015). Doi: <https://doi.org/10.1016/j.energy.2015.02.103>
10. O. K. Abiola and J.O.E. Otaigbe, Effect of common water contaminants on the corrosion of aluminum alloys in ethylene glycol-water solution, *Corrosion Science*, **50**, 242 (2008). Doi: <https://doi.org/10.1016/j.corsci.2007.06.013>
11. J. Zaharieva, M. Milanova, M. Mitov, L. Lutov, S. Manev, and D. Todorovsky, Corrosion of aluminum and aluminum alloy in ethylene glycol-water mixtures, *Journal of Alloys and Compounds*, **470**, 397 (2009). Doi: <https://doi.org/10.1016/j.jallcom.2008.02.079>
12. G. L. F. Mendonça, S. N. Costa, V. N. Freire, P. N. S. Casciano, A. N. Correia, and P. Lima-Neto, Understanding the corrosion inhibition of carbon steel and copper in sulphuric acid medium by amino acids using electrochemical techniques allied to molecular modeling methods, *Corrosion Science*, **115**, 41 (2017). Doi: <https://doi.org/10.1016/j.corsci.2016.11.012>
13. B. Jegdić, B. Bobić, and S. Linić, Corrosion behavior of AA2024 aluminium alloy in different temperatures in NaCl solution and with the CeCl₃ corrosion inhibitor, *Materials and Corrosion*, **71**, 352 (2020). Doi: <https://doi.org/10.1002/maco.201911219>
14. S. Liu J. Dong W. W. Guan J. M. Duan R. Y. Jiang Z. P.

- Feng, and W. J. Song, The synergistic effect of Na_3PO_4 and benzotriazole on the inhibition of copper corrosion in tetra-n-butylammonium bromide aerated aqueous solution, *Materials and Corrosion*, **63**, 1017 (2012). Doi: <https://doi.org/10.1002/maco.201106346>
15. L. Niu, Y. F. Cheng, and J. Mater, Electrochemical characterization of metastable pitting of 3003 aluminum alloy in ethylene glycol-water solution, *Journal of Materials Science*, **42**, 8613 (2007). Doi: <https://doi.org/10.1007/s10853-007-1841-1>
 16. S. Y. Cho, J. J. Kim, and H. J. Jang, Effects of Zn Coating and Heat Treatment on the Corrosion of Aluminum Heat Exchanger Tubes, *Corrosion Science and Technology*, **18**, 24 (2019) Doi: <https://doi.org/10.14773/cst.2019.18.1.24>
 17. Y. R. Yoo, Y. I. Son, G. T. Shim, Y. H. Kwon, and Y. S. Kim, Influence of Graphite Epoxy Composite Material on the Electrochemical Galvanic Corrosion of Metals, *Corrosion Science and Technology*, **8**, 27 (2009)
 18. S. Y. Hur, K. T. Kim, Y. R. Yoo, and Y. S. Kim, Effects of NaCl Concentration and Solution Temperature on the Galvanic Corrosion between CFRP and AA7075T6, *Corrosion Science and Technology*, **19**, 75 (2020) Doi: <https://doi.org/10.14773/cst.2020.19.2.75>
 19. J. S. Yoon, S. H. Lee, and M. S. Kim, Fabrication and brazability of a three-layer 4343/3003/4343 aluminum clad sheet by rolling, *Journal of Materials Processing Technology*, **111**, 85 (2001). Doi: [https://doi.org/10.1016/S0924-0136\(01\)00517-9](https://doi.org/10.1016/S0924-0136(01)00517-9)
 20. J. Lacaze and S. Tierce, Study of the microstructure resulting from brazed aluminum materials used in heat exchangers, *Materials Science and Engineering: A*, **413**, 317 (2005). Doi: <https://doi.org/10.1016/j.msea.2005.08.187>
 21. X. X. Yao, R. Sandstrom, and T. Stenqvist, Strain-controlled fatigue of a brazed Al-Mn-Mg alloy at room temperature and at 75 and 180°C, *Materials Science and Engineering: A*, **267**, 1 (1999). Doi: [https://doi.org/10.1016/s0921-5093\(99\)00062-3](https://doi.org/10.1016/s0921-5093(99)00062-3)
 22. D. P. Sekulic, P. K. Galenko, M. D. Krivilyov, L. Walker, and F. Gao, *International Journal of Heat and Mass Transfer*, **48**, 2372 (2005). Doi: <https://doi.org/10.1016/j.ijheatmasstransfer.2005.01.034>
 23. D. Laougli and F. Beniere, Evaluation of inhibitor efficiency on corrosion of the aluminum heat exchangers and radiators in central heating, *Journal of Materials and Environmental Science*, **3**, 34 (2012). <https://www.jmaterenvironsci.com/Document/vol3/3-JMES-66-2011-Laouali.pdf>