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The effect of porosity on the corrosion rate of aluminum foam as a sacrificial anode

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Abstract
The objective of this paper is to investigate the effect of porosity on the corrosion rate of aluminum foams as sacrificial anodes. An aluminum bar (6061 series) was cut to 19x19x13 mm. Then the aluminum was drilled to become an aluminum foam. A Carbon steel plate was cut to 40x 40x1 mm. The aluminum foam and the steel were connected by a bolt to become a galvanic couple. The galvanic couples were immersed in fresh water for variation times (32 hours, 168 hours, 335 hours, 504 hours and 672 hours). The temperature was 27 °C. The corrosion test was the weight loss method. The results. The corrosion rate of initial steel is 0.15 millimeter per year (mmy). The corrosion rate of steel decrease from 0.15 mmy to 0.015 + 0.02 mmy when using the aluminum foam as sacrificial anode. The corrosion rate of initial aluminum foam is 0.01 mmy. The corrosion rate of aluminum foam increases from 0.01 to 0.015 – 0.02 mm when used as sacrificial anode. Increasing the porosity of the anode will reduce the corrosion rate of the anode itself.

Keywords:
Aluminum Foam;
Corrosion;
Porosity;
Sacrificial Anode;

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INTRODUCTION

Many industries spend billions of dollars due to corrosion [1]. Corrosion is a reaction of the material especially the reaction of metals (metallic components) with the surroundings and causes many changes to the material (metallic components) [2]. Corrosion - induced component failure affect direct and indirect economic losses [3]. To protect the metal from corrosion, two main types of techniques are most popular which are coating methods (namely paint systems and metallic coating) and cathodic protection (CP) methods [4].

Non-alloy steel is usually coated with varnish or paint systems coatings. Paint systems are famous systems to steel structures. The paint acts as a physical barrier between the steel and any oxygen or water in the environment. Metallic coatings (e.g. based on zinc or zinc and aluminum). Metallic coatings are composed by non-ferrous metals, usually zinc (Zn), aluminum (Al) and their alloys. This protection system present corrosion protection by (i) barrier or physical protection of the metallic substrate against the environmental factors and (ii) galvanic actions (sacrificial protection of the steel at damaged areas) [5].

The CP technique is again two types: sacrificial anode cathodic protection (SACP) and impressed current cathodic protection (ICCP) methods. In cathodic protection methods, an external anode is used and the metal surface works (the protected metal) as the cathode. The external anode can be a galvanic anode or it can be impressed current. In the galvanic anode, the potential difference is the result of current flow and in the impressed current method, the current is supplied from an external dc power supply (rectified DC) [6].

A metal foam has high surface area per unit volume in open cell foams. The metallic foams have attracted considerable interest in recent years and have a variety of commercial applications such as electrodes, mechanical damping, vibration control, acoustic panels and cathode electrode [7, 8, 9]. Conventionally an aluminum sacrificial anode is solid [10] as shown in Figure 1. The corrosion rate of a solid sacrificial anode is 0.0349 - 0.04 mmy [11][12].

The corrosion rate of the anode is influenced by the surface area of cathode to surface area of anode. The anode corrosion rate will be higher if the anode area is smaller [13]. Since the surface area per unit volume compare of metal foam than solid foam. The objective of this paper is to investigate the effect of porosity on the corrosion rate of aluminum foams as sacrificial anodes.

METHOD

Material

The sacrificial anode was aluminum (6061 series) which Chemical composition (Wt %) are (Al: 95.8 - 98.6; Cr:0.04 - 0.35; Cu:0.15 - 0.4; Fe; Max 0.7; Mg: 0.8 - 1.2; Mn Max 0.15: Si:0.4 - 0.8. A cathode was medium carbon steel. Medium-carbon steel has approximately 0.3–0.6% carbon content. Media for corrosion was a fresh water.

Method

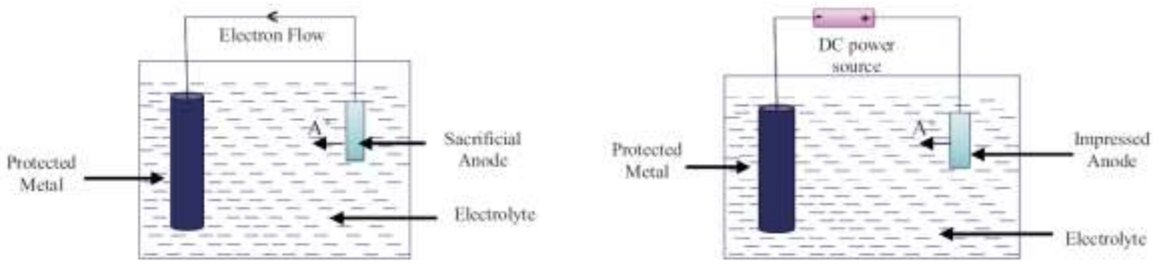
The research flow diagram is shown in Figure 2. The aluminum bar (6061 series) was cut into 19x19x13 mm and then the aluminum cutting was drilled to become aluminum foam. The carbon steel plate was cut to 40x40x1 mm. Aluminum foam and carbon steel were connected by bolts into a galvanic couple as presented in Figure 3. Steel was the cathode while aluminum foam was the sacrificial anode. The galvanic couples were immersed in fresh water for varying times of 36 hours (group 1), 168 hours (group 2), 335 hours (group 3), 504 hours (group 4), 672 hours (group 5). The temperature is 27 ºC. The method of measuring the corrosion rate is the weight loss method.

$$CR = \frac{k.W}{\rho.A.t} \quad (1)$$

Where *CR* is a Corrosion rate, *k* is Constant, *A* is Exposed Areas, and *t* is Time. Calculation of the porosity of aluminum foam is carried out using (2).

$$\text{Porosity (\%)} = (1- (\rho \text{ real}/\rho \text{ theory})) \times (100\%) \quad (2)$$

Where ρ is a real specific gravity, ρ aluminum theory is 2.7 grams/cm^3.



(a) (b)

Figure 1. Sacrificial anode cathodic protection method:
(a). Impressed anode cathodic (b) protection method [5]

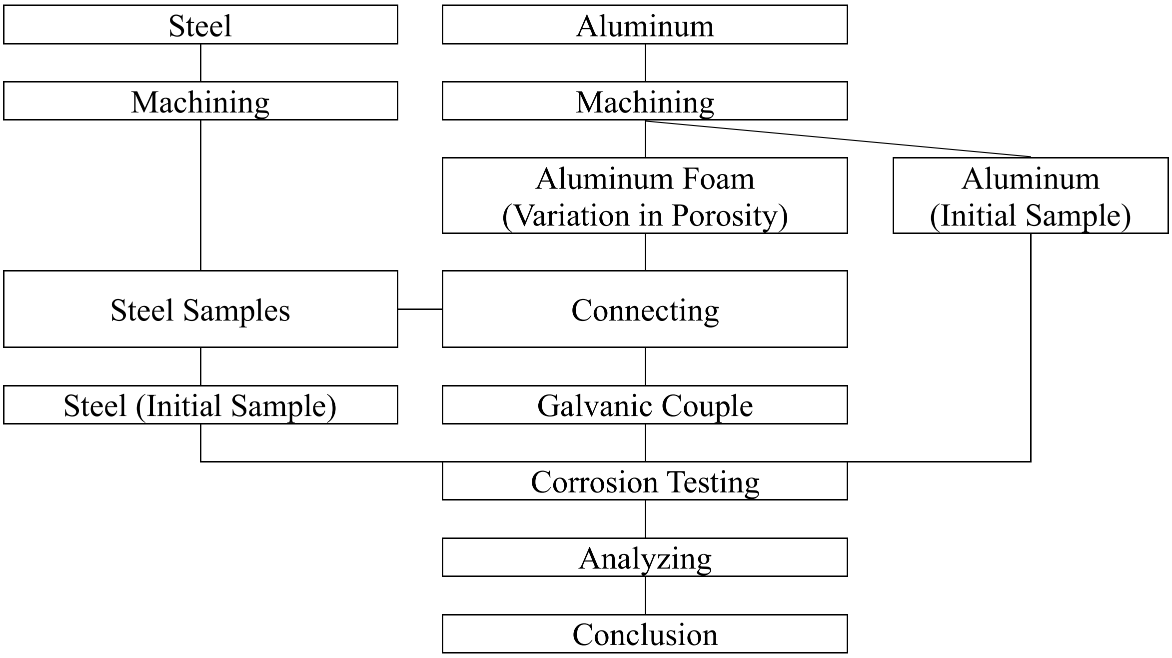


Figure 2. Research Flow Diagram

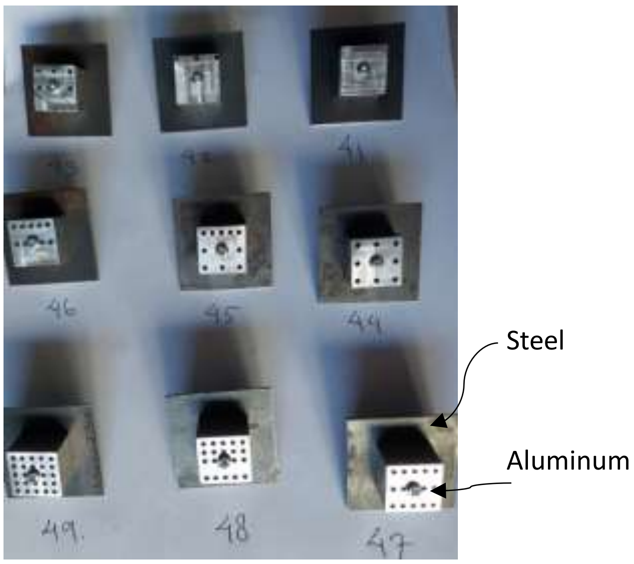


Figure 3. Galvanic Couple of cathode (steel)/anode (aluminum foam)

RESULTS AND DISCUSSION

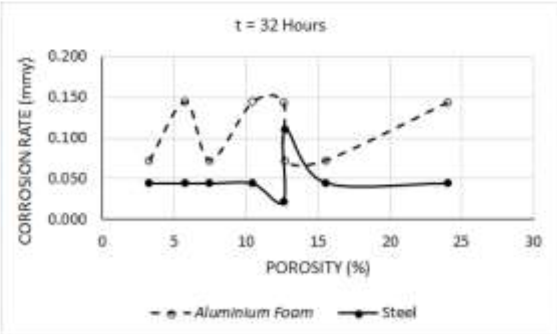
The initial aluminum foam corrosion rate is 0.01 millimeter per year (mmy) as listed in Table 1. Aluminum foam has a low corrosion rate because a layer of aluminum oxide forms on its surface [14]. The initial steel corrosion rate is 0.15 mmy. The electrochemical reaction in the initial steel is as follows:

$$\begin{array}{ll} \text{Cathodic} & O_2 + 4H^+ + 4e \rightarrow 2H_2O \\ \text{Anodic} & 2Fe \rightarrow 2Fe^{2+} + 4e \\ \hline & 2Fe + O_2 + 4H^+ \rightarrow 2H_2O + 2Fe^{2+} \end{array}$$

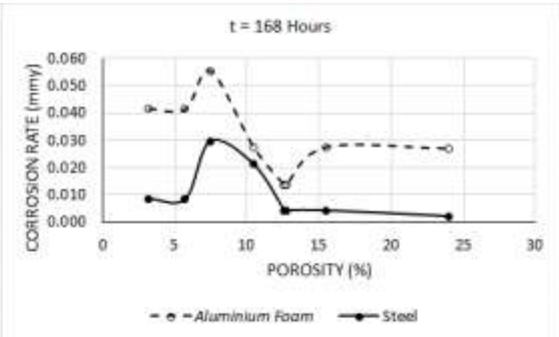
Table 1. Initial Sample Corrosion Rate

Material	Corrosion Rate (mmy)
Aluminum foam (initial)	0.01
Medium carbon steel (initial)	0.15

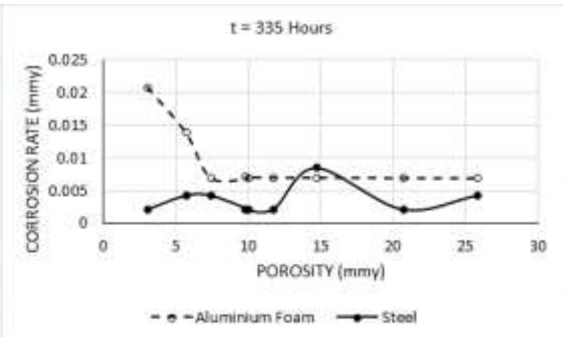
Figure 4 shows the corrosion rate values for steel and aluminum foam in the galvanic couple. Aluminum foam functions as a sacrificial anode used to protect steel from corrosion. The soaking time for galvanic couple varies from 35 hours, 168 hours, 335 hours, 504 hours and 672 hours. The corrosion rate of steel and the corrosion rate of aluminum foam as a galvanic pair of Fe-Al (foam) change with increasing percentage of porosity at each soaking time as shown in Figure 4. The corrosion rate of steel and the corrosion rate of aluminum foam are unsteady state when soaked 32 and 168 hours, due to the effect of the current density of the galvanic couple.



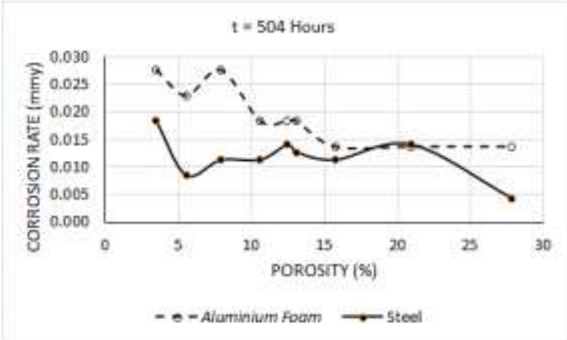
(a)



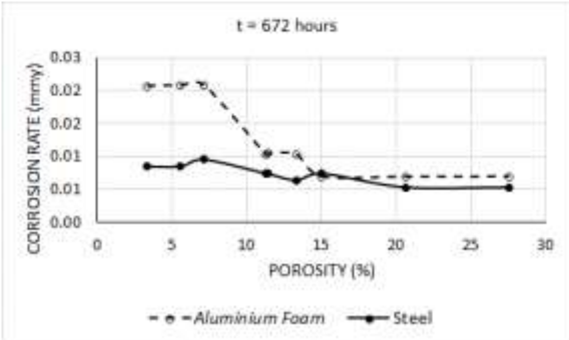
(b)



(c)



(d)



(e)

Figure 4. Corrosion rate of aluminum foam (sacrificial anode) and steel (cathode) with variations in immersion time:
(a) 32 hours, (b) 168 hours, (c) 335 hours, (d) 504 hours, (e) and 672 hours

Zhijian in his research show that the mean values of galvanic current densities generally attain their steady states after about 3 days immersion for all coupled pairs with different (Area of cathode/area of anode) [15]. At subsequent soaking times (335 hours, 504 hours and 672 hours) the steel corrosion rate steady states with increasing porosity percentage. Meanwhile, the corrosion rate of aluminum foam appears to decrease with increasing porosity.

The Effect of Porosities of Aluminum Foam on The Corrosion Rate of Steel.

The corrosion rate of steel appears to be constant with increasing porosity of aluminum foam. The average corrosion rate is 0.015 + 0.02 mmy. This corrosion rate value is smaller than the corrosion rate of the initial steel (0.15 mmy). This research proves that the aluminum foam can be used as a sacrificial anode. The electrochemical reaction in galvanic couple (Fe-Al foam) is as follows:

Cathodic	$3Fe^{2+} + 6e$	$\rightarrow$ Fe
Anodic	2Al	$\rightarrow 2Al^{3+} + 6e$
	$3Fe^{2e} + 2Al \rightarrow Fe + 2Al^{3+}$	

The Effect of Porosity on The Corrosion Rate of Aluminum Foam.

The corrosion rate of initial aluminum foam is 0.01 mmy. The corrosion rate of aluminum foam increases from 0.01 to 0.015 – 0.02 mm when used as sacrificial anode as shown in Figure 5. A relationship between the corrosion rate of anode (aluminum foam) with the porosity is shown in Figure 5 and porosity can be written in a mathematical using (3).

$$y = 0.03477\ x^{(-0,519)} \quad (3)$$

Figure 6 shows clearly that the decrease in the corrosion rate of anode is due to an increase in porosity. The decrease in corrosion rate is related to decrease the amount of weight loss of aluminum per surface area of anode as shown in Figure 7 researched earlier. It can be found obviously in Figure 7 that changes of porosity can cause a decrease ratio of (weight loss of aluminum/surface area). When the porosity is more 20%, the ratio of (weight loss of aluminum/surface area) stability around to 0.0030 (grams/cm^2). The results show that the ratio of (weight loss of aluminum/surface area) is no longer changes along with the increase of porosity, then it reaches limit. If the cathode surface area is constant, the ratio of cathode area to anode area will become smaller as porosity increases.

This experiment result is consistent with what Zhijian investigated earlier. Zhijian shows that the galvanic corrosion rate showed linear growth with ratio of (area cathode/area anode) due to the galvanic current along with the increase of (area cathode/area anode), and vice versa [15][16].

The relationship between the ratio (loss weight of aluminum/ surface area) and anode porosity can be written as follows:

$$y = 0.0131\ x^{(-0.46)} \tag{4}$$

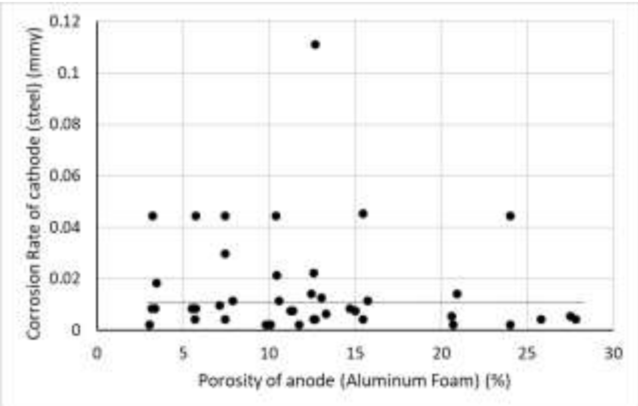


Figure 5. Corrosion rate of cathode (steel) vs porosity of anode (aluminum foam)

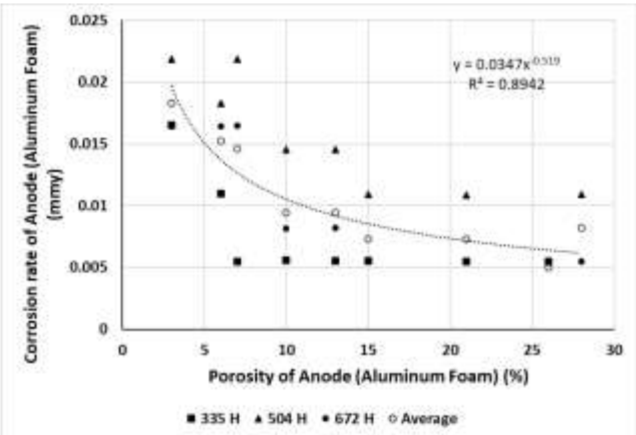


Figure 6. Corrosion rate anode versus porosity of anode (aluminum foam)

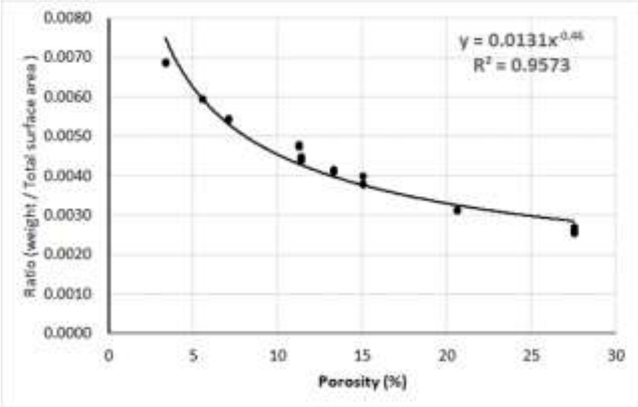


Figure 7. Ratio (weight loss/surface area) (grams/mm^2) versus porosity of anode (aluminum foam)

CONSCLUSION

Since the surface area per unit volume compare of metal foam than solid foam. The research investigated the effect of porosity on the corrosion rate of aluminum foams as sacrificial anodes. The research results show that aluminum foam can be applied as a sacrificial anode. The corrosion rate of aluminum foam increases from 0.01 to 0.015 – 0.02 mm when used as sacrificial anode. The results research also prove that increasing the porosity of the anode will reduce the corrosion rate of the anode itself.

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