

## Comparative Study of Corrosion Behavior of AA2014/15 Vol% Al<sub>2</sub>O<sub>3</sub>p and AA2009/20 Vol% SiCw

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### Abstract

The influence of heat treatment on the corrosion behavior of two aluminium matrix composites (AA2014/15 vol% Al<sub>2</sub>O<sub>3</sub>p - composite A and AA2009/20 vol% SiCw - composite B) was analyzed in 3.5% sodium chloride solution. The kinetic of the corrosion process was studied based on the gravimetric measurements. The corrosion damage and pit shape were analyzed by Image Analyzer. The corrosion damage in both composites was caused by the pitting attack on the surface. Pit shape of the composite A is different to the composite B. The corrosion rate of composite A is higher than composite B because the voids or gap between reinforcement particles and matrix are larger than in the composite B. The main attack of nucleation sites was at the interface region of the matrix and the reinforcement.

**Keywords:** aluminum matrix composite, corrosion, heat treatment.

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### Introduction

Aluminum matrix composites (AMCs) that contain particle reinforcement have their advantages such as isotropic distribution of the particles to be used in the engineering applications. This distribution is generated during the fabrication processes by powder metallurgy, compo-casting, squeeze casting, pressure-less infiltration, hot rolled extrusion, etc. Another consideration of AMCs is the influence of reinforcement particles on the corrosion behavior. The high-strength, high-specific modulus and low-density aluminum alloy-based composites with silicon carbide reinforcement have guaranteed significant interest in the aerospace, defense and car industries. The combination of lightweight, environmental resistance and useful mechanical properties such as modulus,

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strength, toughness and impact resistance, has made aluminium alloys well suited for use as matrix materials. Several previous studies on properties of aluminium matrix composite which have been reported in the literature were focusing on either comparative study between monolithic alloy and reinforced alloy in terms of influence of similar type of reinforcement [1], or comparative study between different reinforced alloys in terms of similar type of reinforcement [2]. Furthermore, several studies have focused on the properties of aluminium matrix composites from the same fabrication route such as casting [1, 3, 4] and powder metallurgy [2]. Some researchers studied the influence of heat treatment based on single aluminium matrix composite without comparison [3, 4].

Corrosion resistance of metal matrix composites (MMCs) is also a subject of study to be discussed in order to compare their corrosion resistance towards corrosive environment and some studies have reported based on the effect of heat treatment to the corrosion behavior. Some works on the mechanical properties and corrosion behavior of AA2009/20SiCw [6-10] and AA2014/15Al<sub>2</sub>O<sub>3</sub>p [3, 4] were reported.

None of the studies carried out focusing on the corrosion behavior between two different aluminum matrix composites in terms of different type of reinforcement and fabrication route. Comparative study between different composites is required in order to develop information for all metal matrix composites. This information is very important for the user to select the best material for engineering applications with different properties required, including its corrosion resistance [5]. This present paper deals with the study of the corrosion behavior of AA2009 and AA2014 aluminium alloys as matrices, under the corrosive environment (3.5% NaCl solution). Both matrices are having similar alloying elements content based on 2XXX series of Al-Cu alloys. The purpose of this study is to compare the corrosion behavior between AA2009/SiCw and AA2014/ Al<sub>2</sub>O<sub>3</sub>p after artificial aging.

### **Experimental procedure**

The composites studied were AA2014 (Al-Cu) matrix reinforced with 15 vol. % of Al<sub>2</sub>O<sub>3</sub> particles (indicated as composite A) and AA2009 (Al-Cu) matrix reinforced with 20 vol. % SiC whisker (indicated as composite B). Both composites have similar working process, i.e., hot extrusion. The chemical composition of both composites was given by the supplier and it is indicated in Table 1. Instead of similar series alloys, there is a difference in both composites such as the fabrication technique, the type, size and percentage of reinforcement shown in Table 2.

Composite A was supplied by Duralcan Inc., San Diego, California, USA, and produced by casting method followed by hot extrusion process to form rectangular bar with 77 mm wide and 19 mm thickness (Fig. 1). Composite B was supplied by Advanced Composite Materials Corporation (ACMC), USA. Composite B was fabricated by powder metallurgy method followed by hot extrusion process to form a rectangular fillet bar with 90 mm wide and 21 mm thickness (Fig. 1).

**Table 1.** Typical chemical composition of AA2009 and AA2014.

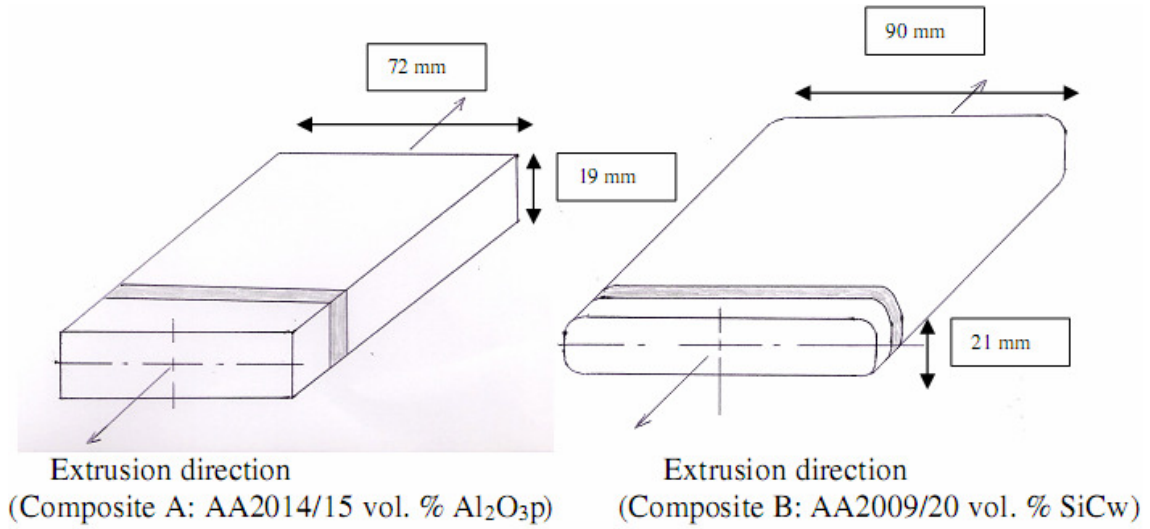
composition	percentage	
	AA2014 (A)	AA2009 (B)
Silicon	0.50 – 1.2	0.25 max
Iron	0.7 max	0.20 max
Copper	3.9 – 5.0	3.2 – 4.4
Manganese	0.4 – 1.2	-
Magnesium	0.2 – 0.80	1.0 – 1.6
Chromium	1.10 max	-
Zink	0.25 max	0.1
Oxygen	-	0.10 max
Titanium	0.15 max	0.6 max
Others	0.05 max	0.05 max
Others	-	0.15 max
Aluminium	Remainder	Remainder

**Table 2.** Information of the composites.

Aluminum Matrix Alloy	Type of reinforcement	Size of reinforcement	Percentage of reinforcement	Route of fabrication	Working process
Al2014	Alumina particles	9 – 13 $\mu\text{m}$	15 vol %	Casting	Hot extrusion
Al2009	Silicon Carbide Whiskers	0.45 – 0.65 $\mu\text{m}$ (d) 5 – 80 $\mu\text{m}$ (l)	20 vol %	Powder Metallurgy	Hot extrusion

Samples were cut into small pieces followed by wet grinding technique using silicon carbide paper (240, 400, 600, 800, 1200 grit). Finally, the samples were polished by using alumina 0.05 micron in order to reveal the microstructure. The microstructures of the composites were observed by scanning electron microscopy JOEL-JSM-6460LA. The samples were subsequently solution treated at 510 °C for 4 hours in the furnace followed by quenching in water and then artificially aged at 165 °C for 2 – 12 hrs.

The solution treated samples were kept in the refrigerator prior to aging. Immersion test in 3.5 % NaCl solution was used to study the corrosion behavior on the samples before and after aging. Concentration of 3.5% NaCl was selected in this work because it accelerated corrosion test similar to the marine environment. This test has been done to observe the corrosion damage and the effect of aging condition on the corrosion rate. Before immersion test, sample was cleaned from dust and contamination. Solution preparation has been prepared by dissolving 7 g NaCl in 200 mL distilled water. Before immersion test, the weight of sample was measured after polished. Sample was immersed in the solution for 28 days. The weight gain was measured for each week. Image Analyzer NIKKON was used for microstructure observation. Every time before measuring the weight of samples, they were immersed in 10 % HNO<sub>3</sub>, for 10 minutes followed by washing with distilled water and then dried. Table 3 indicates the specimen's description during ageing treatment.



**Figure 1.** Schematic diagram of as-received bar of the composites from the suppliers.

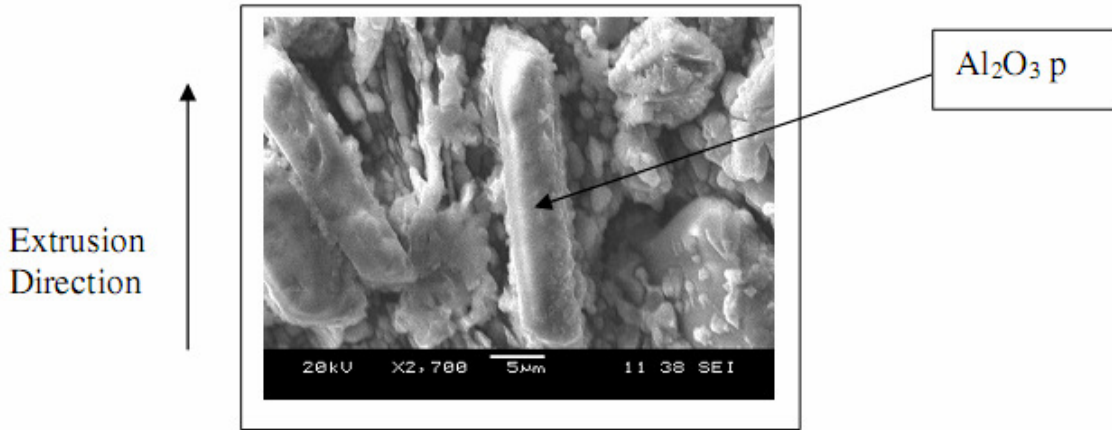
**Table 3.** Samples description.

Time of aging	Composite A	Composite B
As received	A0	B0
2 hours	A2	B2
4 hours	A4	B4
6 hours	A6	B6
8 hours	A8	B8
10 hours	A10	B10
12 hours	A12	B12

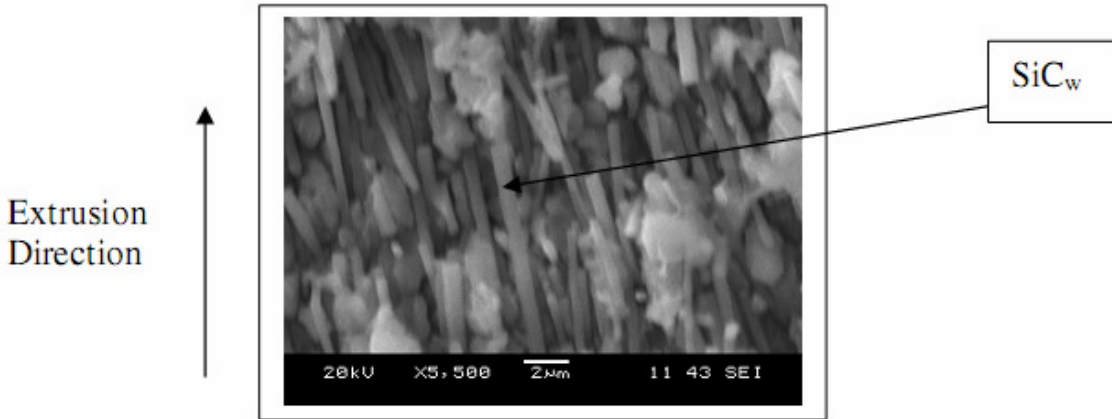
## Results and discussion

### *Microstructure*

Fig. 2 shows the microstructure of composite A: AA2014/15%Al<sub>2</sub>O<sub>3</sub>p, parallel to the extrusion direction. Etching with an acid solution (HCl/HNO<sub>3</sub>=1:1) reveals the grain boundaries in the matrix. The particles are moderately aligned to the extrusion direction and homogeneously distributed. Fig. 3 shows the microstructure of composite B: AA2009/20%SiCw parallel to the extrusion direction. Etching with an acid solution (HCl/HNO<sub>3</sub>=1:1) reveals the whiskers in the matrix. The whiskers are moderately aligned to the extrusion direction and homogeneously distributed.



**Figure 2.** SEM micrograph of composite A: A2014/15%Al<sub>2</sub>O<sub>3p</sub>, parallel to the extrusion direction.



**Figure 3.** SEM micrograph of composite B: Al2009/20%SiC<sub>w</sub> parallel to the extrusion direction.

**Gravimetric results after immersion test**

Tables 4 and 5 show the gravimetric corrosion rate of composites A and B after the immersion test in 3.5% NaCl solution. Samples consist of unaged and after aged at 165 °C.

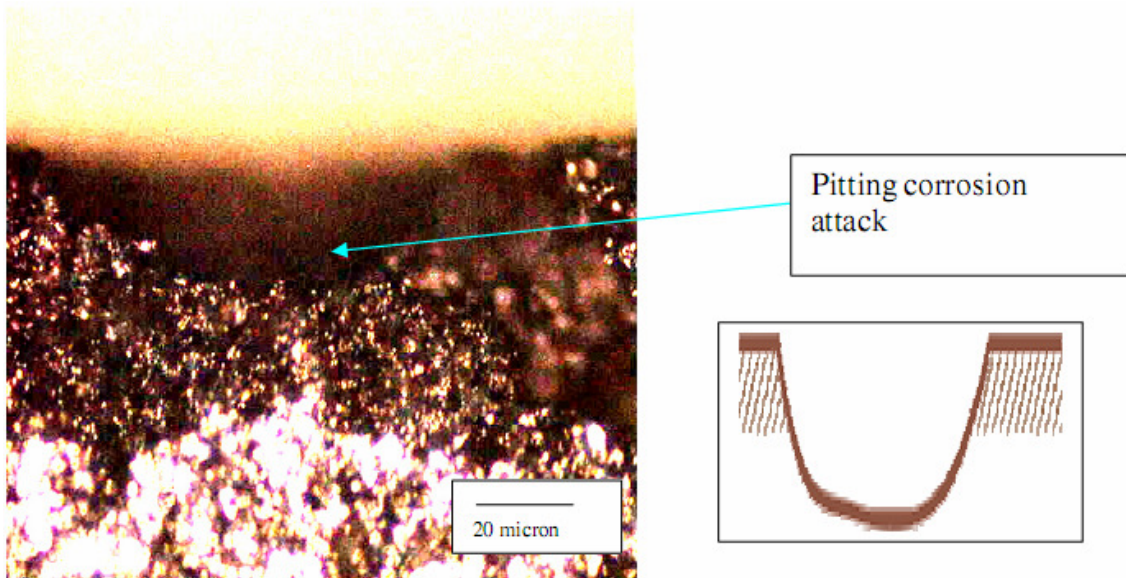
**Table 4.** Composite A (AA2014/Al<sub>2</sub>O<sub>3p</sub>) aging at 165 °C.

Time(day)		0	3	7	14	21	28
Corrosion Rate (mg/cm <sup>2</sup> /day)	A0	0	2.09	4.31	7.39	10.60	14.10
	A2	0	2.37	4.56	8.03	11.50	15.70
	A4	0	2.20	3.85	7.89	11.01	15.05
	A6	0	2.19	4.39	7.43	10.80	14.70
	A8	0	2.33	4.51	7.47	11.20	14.93
	A10	0	2.46	4.30	7.59	10.87	14.56
	A12	0	2.45	4.56	7.90	11.41	14.75

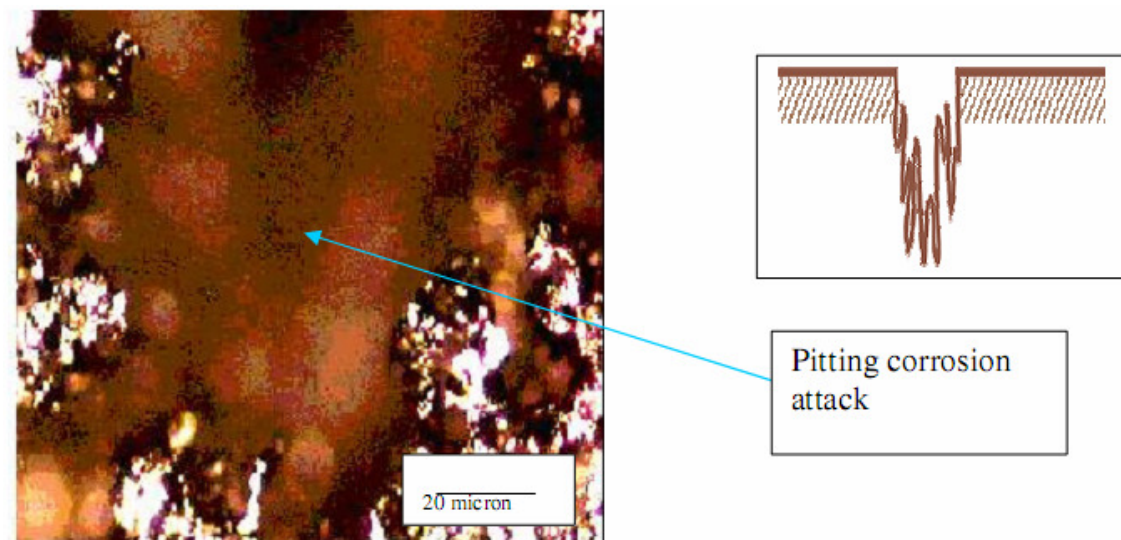
**Table 5.** Composite B (AA2009/SiC<sub>w</sub>) aging at 165 °C.

Time (day)		0	3	7	14	21	28
Corrosion rate (mg/cm <sup>2</sup> )	B0	0	2.20	4.00	6.80	9.72	13.00
	B2	0	2.35	4.53	7.40	10.91	14.80
	B4	0	1.60	3.60	6.70	10.30	14.24
	B6	0	2.22	4.58	7.72	11.24	14.90
	B8	0	2.07	4.00	6.70	10.00	13.53
	B10	0	2.12	4.25	7.31	10.36	14.35
	B12	0	2.15	4.18	6.93	10.28	14.20

From Tables 4 and 5, the corrosion rate increases with the increment of immersion time. This trend of the corrosion rate is due to the development of pitting. Corrosion rate (CR) is expressed in milligrams (weight loss, W) per square centimeter (immersed area, A) per day (immersion time, T) according to Fontana [5]. It can be seen from the table that the corrosion rate of composites A is slightly higher than composite B with increasing ageing time and increasing immersion time. For short immersion times, composites A and B indicate mass loss associated with pitting attack. Both composites exhibit severe damage due to metal dissolution and pitting at the interface of reinforcement and matrix. This phenomenon is explained by the action of both the Cl<sup>-</sup> ion and the galvanic couple Cu-Al. The presence of Cu in the matrix has favored to the degradation. The process of degradation is accelerated by the Cu-Al galvanic couple [11]. Intermetallic of Al-Cu compound is strongly cathodic against the metallic matrix and act as cathodic site, facilitating dissolution of the protective Al<sub>2</sub>O<sub>3</sub> and enhancing pitting corrosion. Several researchers found that there is no evidence to suggest that the corrosion of AMCs was accelerated by the presence of reinforcement, but the presence of reinforcement had played a secondary role in modifying the microstructure of matrix [13-15]. However, a possible reason of pitting susceptibility in the metal matrix composite is small voids at the reinforcement/matrix interface, which may be found after processing. It can be seen in composite A (Fig. 2), the voids or gap between reinforcement particles and matrix are larger than in the composite B (Fig. 3). The nature of SiC whiskers morphology has made gap or voids are closer between the whiskers reinforcement and the matrix. As a consequence, pitting corrosion is more slightly intense in composite A compared with composite B. Overall, corrosion rate of the overaged samples A12 and B12 is slightly higher than unaged samples A0 and B0, respectively, due to the increasing and growing of Al<sub>2</sub>Cu and Al<sub>2</sub>CuMg phases.



**Figure 4(a).** Pitting corrosion attack in the matrix through the interface  $\text{Al}_2\text{O}_3\text{p}$  /matrix in composite A (AA2014/  $\text{Al}_2\text{O}_3\text{p}$  /15% (T6) MMC) in shallow wide pit shape.



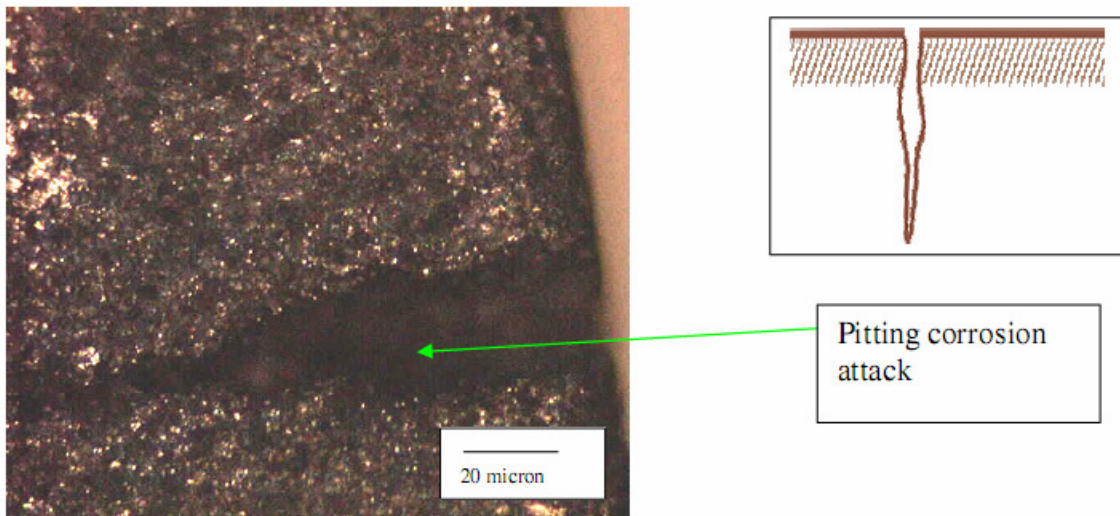
**Figure 4 (b).** Pitting corrosion attack in the matrix through the interface  $\text{Al}_2\text{O}_3\text{p}$  /matrix in composite A (AA2014/  $\text{Al}_2\text{O}_3\text{p}$  /15% (T6) MMC) in vertical grain attack pit shape.

***Microstructural observations after immersion test***

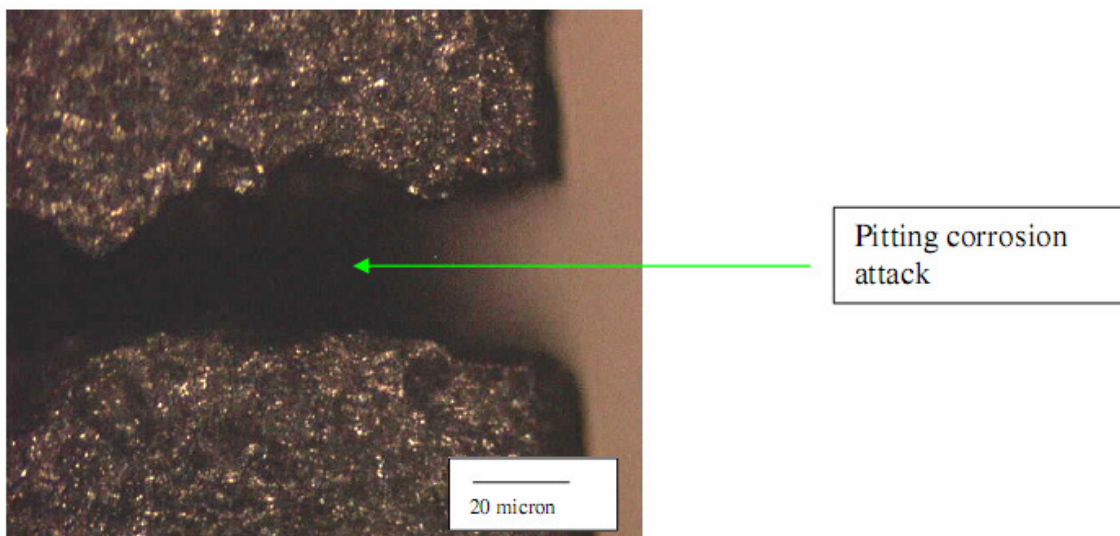
Figs. 4 to 5 show the pitting corrosion attack after 28 days immersion in 3.5% NaCl for both composites. The pitting corrosion attacks the matrix through the interface reinforcement/matrix in different pit shape. Figs. 4(a) and 4(b) indicate pitting corrosion attacks after 28 days immersion in the composite A. The pitting corrosion attacks the matrix through the interface  $\text{Al}_2\text{O}_3\text{p}$  /matrix indicating shallow wide pit shape and vertical grain attack pit shape. Figs. 5(a) and 5(b) indicate pitting corrosion attacks after 28 days immersion in the composite B through the interface SiCw/matrix and indicating shallow deep pit shape. It was



observed that the pitting processes were rapid with shallow wide pit shape and vertical grain attack pit shape compare to shallow deep pit shape.



**Figure 5(a).** Pitting corrosion attack in the matrix through the interface SiCw/matrix in composite B (AA2009/SiCw /20% (T6) MMC) in shallow deep pit shape.

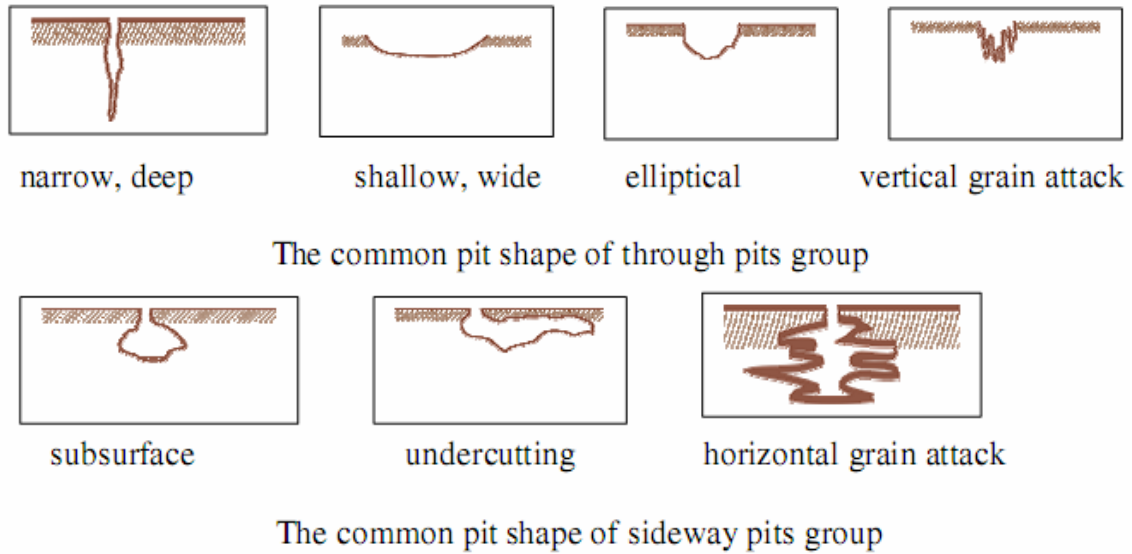


**Figure 5(b).** Pitting corrosion attack in the matrix through the interface SiC/matrix in composite B (AA2009/SiC w /20% (T6) MMC) in shallow deep pit shape.

Pitting corrosion can produce pits with their mouth open (uncovered) or covered with corrosion products. Different types of attack on the same surface of composites A and B that were exposed to a 3.5% NaCl solution for 28 days can be seen in all micrograph. Pits can be either hemispherical or cup-shape. In some cases, they are flat-walled, revealing the crystal structure of the metal, or they may have a completely irregular shape. Pitting corrosion occurs when discrete areas of material undergo rapid attack while most of the adjacent surface remains

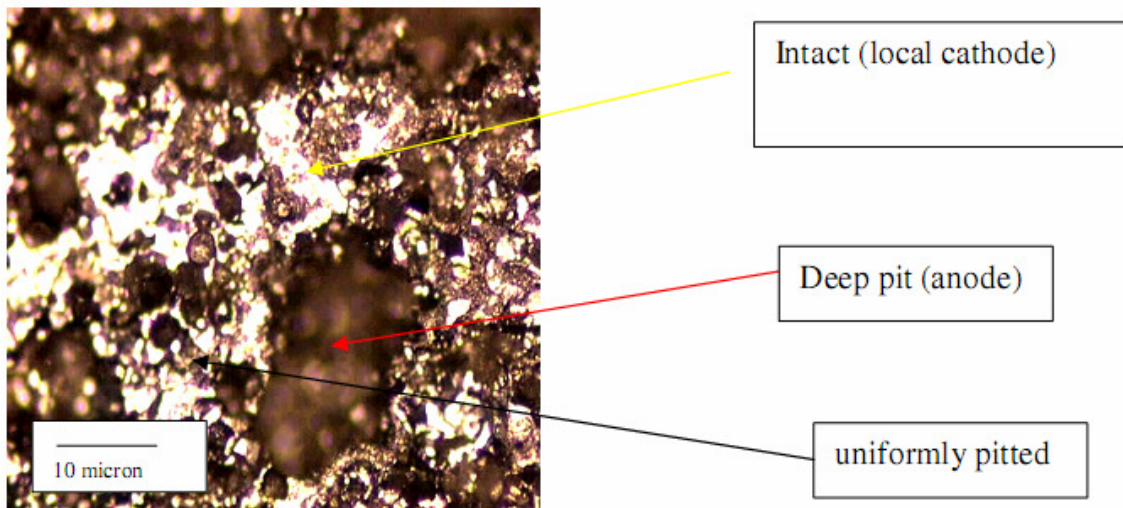


virtually unaffected. The following are common pits shape divided in two groups, as shown in Fig. 6.

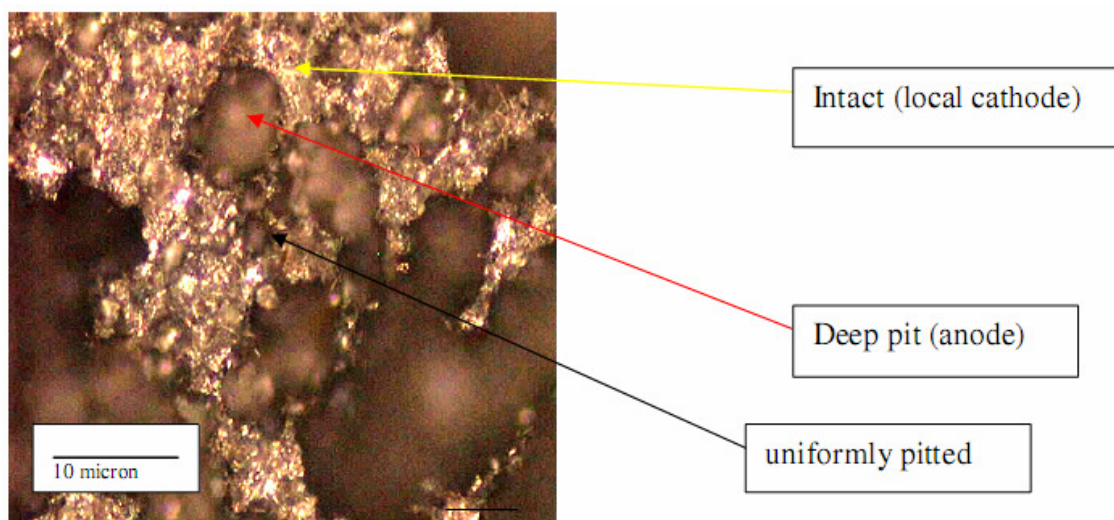


**Figure 6.** Common pit shape of through pits group and sideway pits group [17].

Figs. 7 and 8 show the holes due to the intensive matrix corrosion in the composites A and B. This example of a pitted surface was produced by exposing a sample to a 3.5% NaCl during 28 days. Most of the surface is uniformly pitted (black arrow), as both composites would do in similar conditions. It is seen the formation of deeper pits (red arrow) that are surrounded by un-attacked regions (yellow arrow). However, the main reason for their poor corrosion resistance is attributed to the crevices at the  $Al_2O_3/Al$  interface and  $SiCw/Al$  interface as preferential site of attack, as shown in Figs. 7 and 8.



**Figure 7.** Holes due to an intensive matrix corrosion in composite A (AA2014/  $Al_2O_3p$  /15%p (T6) MMC).



**Figure 8.** Holes due to an intensive matrix corrosion in composite B (AA2009/SiC/20%w (T6) MMC).

### Conclusions

Different reinforcement is found to affect the corrosion behaviour of composites. Corrosion rate of the composite AA2014/15 vol%  $\text{Al}_2\text{O}_3\text{p}$  is higher than AA2009/20 vol% SiCw composite because the voids or gap between reinforcement particles and matrix are larger in the first composite. The pitting corrosion attacks the matrix through the interface reinforcement/matrix in different pit shape. The pit shape in composite AA2014/15 vol%  $\text{Al}_2\text{O}_3\text{p}$  is shallow wide pit and vertical grain attack pit shape whereas in composite AA2009/20 vol% SiCw is shallow deep pit shape. The pitting process is rapid with shallow wide pit shape and vertical grain attack pit shape compared to shallow deep pit shape. The ageing process does not much influence the corrosion rate, however the corrosion rate for overaged samples shows slightly higher than unaged samples.

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