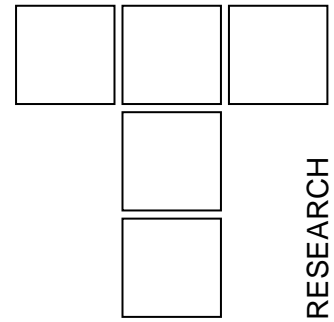


# Corrosion of Metal-Matrix Composites with Aluminium Alloy Substrate



The corrosion behaviour of MMCs with aluminium alloy matrix was presented. The corrosion characteristics of boron-, graphite-, silicon carbide-, alumina- and mica- reinforced aluminium MMCs were reviewed. The reinforcing phase influence on MMCs corrosion rate as well as on various corrosion forms (galvanic, pitting, stress corrosion cracking, corrosion fatigue, tribocorrosion) was discussed. Some corrosion protection methods of aluminium based MMCs were described.

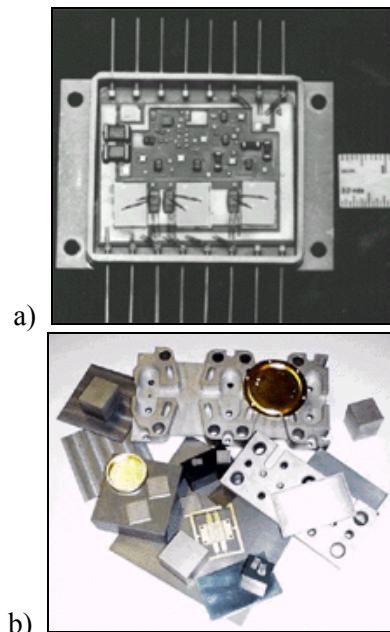
**Keywords:** metal-matrix composites, aluminium alloys, aluminium based MMCs, corrosion, pitting corrosion, corrosion protection

## 1. INTRODUCTION

Advanced metal-matrix composites (MMCs) represent a new class of structural materials as conventional metals and alloys approach their developmental limits. With proper processing, the reinforcement of a metal matrix with various particulate or fiber reinforcements can yield MMC with significantly improved properties (e.g. lower density, higher specific modulus and higher specific yield strength) ideal for many potential automotive and aerospace applications [1]. For example, discontinuously reinforced aluminium composites (DRA) are especially advantageous for electronic packages and thermal-management applications because of their combination of high thermal conductivity and low density. Several SiC<sub>p</sub>/Al and Gr<sub>p</sub>/Al electronic packages (Fig. 1a and 1b) have been space-qualified and are now flown on communication satellites [1].

MMCs have also begun to substitute for conventional materials in household appliances, computers, audio and video equipment, as well as in sport appliances. Compressive and tensile strength, as well as the hardness at room and

elevated temperatures, are also increased significantly, resulting in an improvement in the wear resistance of the composite material. However, the addition of the reinforcement particles could significantly alter the corrosion behaviour of these materials [2]. While physical-mechanical properties of MMCs have been extensively studied, relatively little information is available about the MMCs corrosion behaviour. In general, the composites are more susceptible to corrosion attack than the matrix alloy.



**Figure 1.** Discontinuously reinforced aluminium MMCs for electronic packaging applications: a) SiC<sub>p</sub>/Al electronic package for a remote power controller and b) cast Gr<sub>p</sub>/Al components [1].

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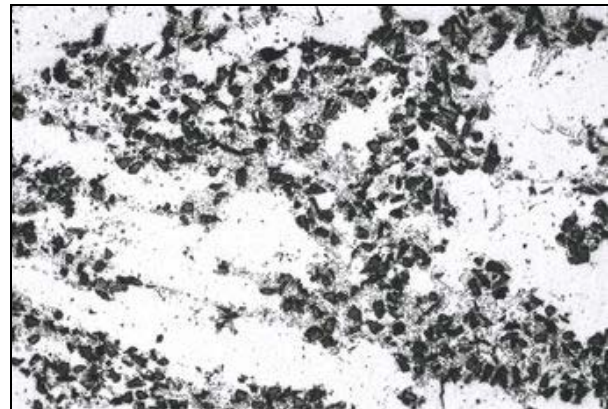
Although MMCs offer greatly improved performance, they also can suffer from problems that are absent in bulk matrix materials. Since composite processing typically requires a high-temperature environment, interfacial reactions between the matrix and the reinforcement can take place. The resulting interfacial region plays a dominant role in the mechanical behaviour and environmental stability of the composite and generally can provide preferential sites for composite failure [2].

Aluminium is potentially an important material for tribological applications because of its low density and high thermal conductivity. However, aluminium and aluminium alloys exhibit poor resistance to seizure and galling [3]. Reinforcement of aluminium alloys with ceramic particles, short fibers and whiskers provide satisfactory improvements of tribological properties [3]. The wear resistance of aluminium composites has received much attention in the literature. Deius et al. [4] showed that aluminium based MMCs containing hard particles offered superior operating performance and resistance to wear and abrasion compared to iron or nickel based alloys. It has been shown recently that composite materials (produced by compocasting process) with Al-Si alloy (A356) substrate reinforced with  $Al_2O_3$  particles provide better mechanical and tribological properties, compared to matrix alloy [5].

Most of the commercial work on MMCs has focused on aluminium as the matrix metal. The combination of light weight, environmental resistance and favourable mechanical properties has made aluminium alloys very popular for use as a matrix metal [6]. In general, for aluminium-based matrices the choice of the matrix alloy is made according to the processing steps used downstream of composite production [7]. If the composite is to be used in the as-cast condition (as with  $SiC_p/Al$  brake rotors, for example), casting matrix alloys are used; typically A356 or other Al-Si alloys, for  $SiC$  particulate reinforcements. The microstructure of  $SiC_p/A356$  composite (with 10 wt %  $SiC$  particles) is shown in Fig. 2. If the composite is to be deformed after being produced, wrought alloys, of lower solute content and often age-hardenable, are used; the usual wrought aluminium alloys 6061 and 2024 are classical examples.

Aluminium and its alloys have been used as a matrix for a variety of reinforcements: continuous boron,  $Al_2O_3$ ,  $SiC$  and graphite fibers, various particles, short fibers and whiskers. Also, the melting point of aluminium is high enough to

satisfy many application requirements, yet low enough to render composite processing reasonably convenient [7].



**Figure 2.** Microstructure of  $SiC_p/A356$  composite, OM, polished, x 100.

The reinforcing particles or fibers introduce inhomogeneities on the surfaces exposed to aggressive environments. This is particularly evident when the matrix is an active metal, such as aluminium and its alloys, and the reinforcement has electrical conductivity or semiconductivity, as in the case of graphite or silicon carbide. For example, the corrosion rate for an Al-matrix coupled to graphite is 30 times higher than for Al coupled to silicon carbide ( $SiC$ ) or titanium boride ( $TiB_2$ ), as a result of galvanic corrosion and the higher rate of oxygen reduction on cathodic (graphite) sites [8]. In these cases, the presence of galvanic cells stimulates the corrosion process on the matrix. Alumina is an insulator and alumina particles or fibres can be used to reinforce aluminium alloys without inducing galvanic corrosion [2].

Corrosion of aluminium MMCs has been studied extensively, but the published literature on the corrosion of aluminium-based composites is often contradictory. This is due to the fact that there is a variety of aluminium alloy matrix and reinforcement type combinations which may exhibit a completely different corrosion behaviour. In addition, processing parameters can heavily influence composite microstructure and, consequently, their corrosion behaviour.

## **2. CORROSION OF ALUMINIUM ALLOYS BASED METAL-MATRIX COMPOSITES**

One of the main obstacles to the use of MMCs is the influence of reinforcement on MMCs corrosion resistance. This is particularly important in

aluminium alloy based composites, where a protective oxide film imparts corrosion resistance. The corrosion resistance of aluminium and Al-alloys can be attributed to the natural protective oxide layer (passive film) that forms on their surface. This protective oxide film is subject to localized breakdown, allowing pitting and crevice corrosion of the underlying substrate. The addition of a reinforcing phase could lead to further discontinuities in the film, increasing the number of sites where corrosion can be initiated and rendering the composite liable to severe attack.

Accelerated MMCs corrosion may originate from electrochemical and chemical interaction between composite constituents, microstructural effects and from problems related to processing [2]. The presence of the reinforcing fibers and particles and the processing associated with aluminium MMCs fabrication can cause accelerated corrosion of the metal matrix compared to corrosion of the unreinforced matrix alloy [2].

Corrosion studies have been conducted on aluminium MMCs reinforced with SiC (particles, whiskers, fibers etc.), Al<sub>2</sub>O<sub>3</sub> (particles, fibers etc.), graphite fibers or particles, boron monofilaments and mica particles.

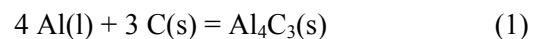
**Boron/aluminium MMCs** experience severe corrosion in chloride environments and are significantly less corrosion resistant than unreinforced aluminium alloys [9]. The boron/aluminium MMCs have been usually fabricated by diffusion bonding of boron monofilaments with aluminium foils. It has been found that corrosion in these composites takes place at fiber/matrix interfaces and at the bonds between foils [2, 9]. Corrosion at the fiber/matrix interfaces has been attributed to the presence of aluminium borides (AlB<sub>12</sub> and AlB<sub>2</sub>) formed during fabrication [2]. The corrosion rate of B<sub>MF</sub>/Al MMCs increases when the boron-monofilament content is increased. Preferential sites of attack have been also documented as diffusion-bonded B<sub>MF</sub>-foil and foil-foil interface regions. The accelerated corrosion at these sites has been attributed to imperfect bonding and fissures in the composite and emphasizes the need for eliminating fabrication flaws to reduce corrosion of boron/aluminium MMCs in chloride environments [9].

**Graphite/aluminium MMCs** with continuous fiber graphite are known to have high specific tensile strength and stiffness in the direction of the fiber axis. High thermal conductivity, negative coefficient of thermal expansion and high stiffness

of graphite have made Gr/Al MMCs ideal for thermally stable space structures [1]. Particulate Gr/Al MMCs have also been developed for potential use in tribological applications due to good resistance to wear and seizure.

Under normal conditions of temperature and pressure, graphite is relatively stable in water. Graphite is also an electrical conductor and efficient cathode for oxygen reduction in aerated solutions, promoting galvanic corrosion in Gr/Al MMCs. Galvanic corrosion has been identified as a primary corrosion mechanism for graphite reinforced aluminium matrices in aerated solutions [10].

Another cause of degradation in Gr/Al MMCs is the presence of the Al<sub>4</sub>C<sub>3</sub> interphase, which can form by the reaction of aluminium and carbon during processing [2]:



On exposure to moisture Al<sub>4</sub>C<sub>3</sub> hydrolyzes, liberating methane gas by the reaction:

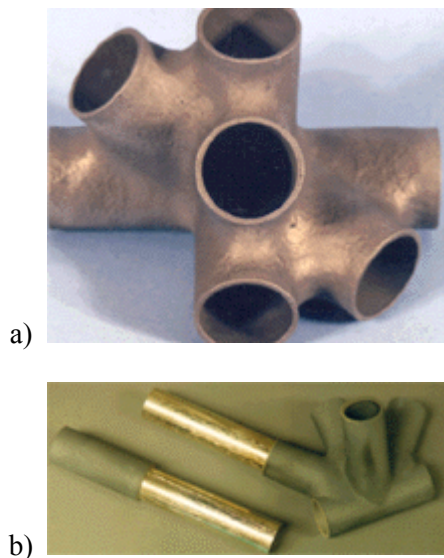


The hydrolysis of Al<sub>4</sub>C<sub>3</sub> in Gr/Al MMCs leaves fissures at fiber-matrix interfaces. There is a possibility that these fissures may also lead to other secondary corrosion problems, such as pitting and crevice corrosion [2].

**Silicon carbide/aluminium MMCs** have attracted a growing interest from the automotive, aeronautical and aerospace industry [1], due to their advantageous toughness to weight ratios, combined with the possibility of employing conventional casting technologies. Silicon carbide/aluminium MMCs are reinforced with SiC particles, whiskers, fibers or monofilaments. Potential applications include joints and attachment fittings for truss structures, longerons, electronic packages, thermal planes, mechanism housings and bushings. Figures 3a and 3b show multi-inlet SiC<sub>p</sub>/Al truss node produced by a near net-shape casting process. The SiC<sub>p</sub>/Al MMCs have been also used in drive shafts, brake rotors and brake drums in automobiles, for ventral fins and fuel access covers in aircraft and a variety of bicycle components [2].

Experimental results have generally indicated that the corrosion rate of particulate and whisker SiC/Al MMCs is higher than the corrosion rate of monolithic-matrix alloy [11,12] and increases with SiC content in aerated chloride containing

environments. The composite containing SiC fibers showed higher corrosion rate than the one with SiC particles reinforcement. Weight loss data of SiC<sub>p</sub>/6092-T6 aluminium MMCs have shown an enhancement in the corrosion rate as the SiC<sub>p</sub> content increases from 5, 10, 20 and 40 to 50 vol %, for 90 day humidity chamber test [13]. At the 50 vol % SiC<sub>p</sub> content level, the corrosion rate for MMC reinforced with high purity, high resistivity green SiC, was noticeably lower than that of the MMC reinforced with low resistivity black SiC [13].



**Figure 3.** Cast SiC<sub>p</sub>/Al attachment fittings:  
a) multi-inlet fitting for a truss node and  
b) cast fitting brazed to a Gr/Al tube [1].

In aqueous solutions silicon carbide can serve as an inert electrode for proton or oxygen reduction. Depending on the SiC type, galvanic corrosion with aluminium is possible. The degree of galvanic corrosion is strongly dependent on the type of SiC reinforcement. The electrical resistivity of SiC depends on its purity. It ranges from approximately  $10^{-5}$  to  $10^{13}$   $\Omega\text{cm}$ . The resistivity range of SiC (depending on the type of SiC reinforcement) may be the cause for conflicting results in the literature concerning the corrosion resistance of silicon carbide/aluminium MMCs [2].

Pitting attack is reported to be the major form of corrosion in SiC<sub>p</sub>/aluminium MMCs [14]. Studies on aluminium alloys based MMCs have shown that more pits are formed on composites than on unreinforced alloys [15]. Pits in the SiC/aluminium composites were deeper than those in the Al<sub>2</sub>O<sub>3</sub>/aluminium composites, probably because the SiC particles acted as efficient cathodic sites. Investigations to date have focused on the effect of SiC reinforcement and intermetallic cathodic

phases on pitting behaviour [16]. According to some authors, preferential attack occurs at the reinforcement/matrix interface [17]. Furthermore, pores, matrix second phases and interfacial reaction products can all influence corrosion behaviour of an SiC/Al composite in a significant way.

Other data [18], however, suggest that reinforcement additions such as SiC do not substantially affect pitting attack on some aluminium alloys. In these cases, although, pits were more numerous on the composite, they were smaller and shallower than those on the unreinforced alloy [18]. Nevertheless, it is generally agreed that SiC reinforcement can affect corrosion less directly, modifying the microstructure of the matrix alloy during manufacture of the MMC by altering the size and distribution of intermetallic phases or introducing residual stresses between reinforcement and matrix.

The presence of SiC particles does not have a significant effect on aluminium passive current densities and pitting potentials, indicating that the presence of SiC particles does not degrade the pitting resistance of passive film on aluminium [19]. Pit morphology, however, is indirectly affected by the presence of SiC particles. SiC whiskers and particles enhance the precipitation of intermetallic phases. The pits nucleate at intermetallic particles (not SiC), which are smaller and more numerous in the MMCs than in the monolithic–matrix alloys. Pitting has also been observed at dendrite cores of SiC<sub>p</sub>/2024 aluminium alloy composites [20] and at the FeSiAl<sub>5</sub>/aluminium interphase of SiC<sub>p</sub>/A356 composites [21], in chloride media.

In summary, SiC/aluminium MMCs are susceptible to localized corrosion in chloride solutions, that is in marine environments. Generally, the susceptibility to pit initiation is similar for composites and unreinforced alloys; however, the rate of pit propagation is higher for composites [9].

Due to the influence of microstructure, the corrosion behavior of particulate SiC/aluminium MMCs is also sensitive to processing. Processing conditions and the presence of SiC particles can affect void content, dislocation density and the precipitation of active phases in aluminium matrices [2]. Certain solution heat treatments improved corrosion resistance of a 20 vol % SiC<sub>p</sub>/7091 aluminium alloy MMC, while extrusion improved the corrosion resistance of cast MMCs reducing the amount of pores and agglomerates of SiC particles. Corrosion resistance was also

improved by a finer, more homogenous distribution of secondary phases at the T4 temper in comparison to the O and F tempers [22].

Stress-corrosion cracking studies for alternate exposure and immersion in NaCl solutions have been conducted on aluminium MMCs reinforced with SiC particles [23, 24] and whiskers [23]. It was shown that 6061 aluminium alloy composites (reinforced with SiC<sub>p</sub> and SiC<sub>w</sub>) were not susceptible to stress-corrosion cracking [21]. Similarly, SiC<sub>p</sub>/2024 aluminium alloy MMCs were not prone to stress-corrosion cracking under constant strain while exposed to an aerated NaCl solution [24].

Corrosion fatigue has been studied in aluminium MMCs reinforced with SiC whiskers [25, 26] and particles [26]. Processing conditions and type of reinforcement affect corrosion-fatigue behavior. It was shown that the MMCs reinforced with whiskers are more resistant to stress-corrosion and corrosion fatigue than those reinforced with particles [26]. It has been suggested that the improved corrosion fatigue properties of silicon carbide/aluminium MMCs are due to an increased resistance to crack initiation.

Functionally graded metal-matrix composites (FGMMCs) are attractive materials for a broad range of engineering applications whenever a superior combination of surface and bulk mechanical properties is required. Through an adequate control of the ceramic particles distribution from the part surface down to its core, the conventional MMC may become a functionally graded metal matrix composite. In general, these materials are developed for the production of high wear resistant components. These components frequently operate in the presence of aggressive environments, such as marine atmospheres, and the interaction of mechanical loading and chemical reactions between elements of a tribosystem takes place. Despite the fact that corrosion studies and wear behaviour of SiC/aluminium based MMCs are separately available in the literature, published works dealing with wear corrosion are rather limited in number. Tribocorrosion studies in aluminium-matrix SiC<sub>p</sub> reinforced functionally graded composites, have been carried out recently [27]. It was shown that water lubrication significantly increased wear of FGMMCs, by facilitating catastrophic SiC particle pull-out, thus obviating the load carrying and anchoring role of the reinforcements [27]. The results of tribocorrosion studies have shown an increase in material loss for the water-lubricated cases,

although variations are registered depending on reinforcing particle volume fraction. Under water-lubricated conditions, an increase in reinforcing particles content led to poorer FGMMC wear performance [27].

Sliding wear, slurry erosive wear and corrosive wear of an aluminium based metal matrix reinforced with SiC particles were studied [28]. It was found that sliding wear and slurry erosive wear resistance were considerably improved with the addition of SiC particles, whereas composite corrosion resistance was decreased [28].

**Alumina/aluminium MMCs** are characterized by low weight, high temperature tensile and fatigue strength, low thermal conductivity and superior wear resistance. In automotive industry short-fiber Al<sub>2</sub>O<sub>3</sub>/aluminium MMCs have been used to replace cast iron components such as pistons, engine blocks, cylinder heads and brake calipers and rotors [2].

Galvanic corrosion between Al<sub>2</sub>O<sub>3</sub> fibers (or particles) and aluminium is unlikely, because resistivity of Al<sub>2</sub>O<sub>3</sub> (99,7 wt %) is greater than 10<sup>14</sup> Ωcm. The Al<sub>2</sub>O<sub>3</sub>/pure aluminium MMCs possess excellent corrosion resistance due to a lack of galvanic action with the Al<sub>2</sub>O<sub>3</sub> fibers.

Corrosion evaluations of Al<sub>2</sub>O<sub>3</sub>/Al-2Mg MMCs identified pitting at the fiber/matrix interfaces, presumably due to the Mg<sub>5</sub>Al<sub>8</sub> precipitated there during fabrication [9]. Research on Al<sub>2</sub>O<sub>3</sub>/6061 aluminium alloy MMCs also reported preferential corrosion at the fiber/matrix interface. These findings suggest that the corrosion resistance of aluminium oxide/aluminium composites is highly dependent on the bonding compound formed at the fiber/matrix interface. The corrosion rate of the MMCs (based on weight loss measurements) was only slightly higher than for aluminium alloy 6061-T6 [9].

Corrosion behaviour of Al<sub>2</sub>O<sub>3</sub>/aluminium MMCs has been investigated by prolonged immersion test and anodic polarization measurements in sodium chloride solution [19]. The influence of particle characteristics (size, volume fraction and pretreatment) on the aqueous corrosion behaviour of the composites were studied. Immersion test data revealed significant weight loss for the composites, resulting from pits or microcrevices formation in the matrix near the particle-matrix interface and from particle dropout. Pit initiation and propagation occurred at weak spots in the air-formed film, corresponding to phase discontinuities and second

phase particles and to oxygen reduction at the particles or precipitates [19].

Corrosion behaviour of aluminium alloy 6061-T6 matrix reinforced with 10 vol % alumina particles has been studied [29]. Corrosion attack occurs preferentially in the vicinity of the reinforcing particles. Extrusion or forging treatment did not affect corrosion behaviour of the composite material significantly.

The stress corrosion behaviour of some Al<sub>2</sub>O<sub>3</sub> reinforced aluminium alloys (AA 6061 and AA 2014) was studied, under the combined action of a sustained elastic tensile stress and a corrosive environment (3,5 wt % NaCl). The onset of SCC on both the aluminium alloy 6061 matrix and the Al<sub>2</sub>O<sub>3</sub>/2014 aluminium alloy composite was detected after the alternate exposure to 3,5 wt % NaCl salt spray or 3,5 wt % NaCl solution. It was shown that [23] the Al<sub>2</sub>O<sub>3</sub>/2014 composite was susceptible to stress-corrosion cracking while subjected to three-point beam bending and alternate exposure and continuous immersion in a NaCl solution [23].

Synergistic effects of wear and corrosion for Al<sub>2</sub>O<sub>3</sub> particulate reinforced aluminium alloy matrix 6061 [30] and 7075 aluminium alloy matrix composites [31] have been recently examined. Experimental results indicated that the wear rate was reduced by adding alumina reinforcements. However, the effect of volume fraction on wear rate is only minor in dry wear, while it is significant in the case of wear corrosion. Wear corrosion tests showed that although the incorporation of reinforcement in these aluminium matrix composites was detrimental to their corrosion resistance, the influence on wear corrosion rate was favorable [31].

Microbial corrosion was also reported for Al<sub>2</sub>O<sub>3</sub>/aluminium alloy MMCs, more significant in comparison to the monolithic alloy, indicating that Al<sub>2</sub>O<sub>3</sub>/aluminium interface or Al<sub>2</sub>O<sub>3</sub> particles may have aided biofilm formation [32].

**Mica/aluminium MMCs** have been developed for potential use in applications where good antifriction characteristics, seizure resistance and high damping capacity are required [33]. Muscovite [KAl<sub>3</sub>Si<sub>3</sub>O<sub>10</sub>(OH)<sub>2</sub>] mica particles (less than approximately 70 µm) are used in mica/aluminium MMCs. Galvanic corrosion between aluminium and muscovite should not be a problem because muscovite is an insulator with resistivity range from 10<sup>13</sup> to 10<sup>17</sup> Ωcm. Pits around and away from mica particles, interfacial corrosion of the mica-matrix

interface, and exfoliation of mica particles were observed [33]. It has been also reported that muscovite particles have a tendency to absorb moisture and then swell causing MMC exfoliation [34].

The characterization of corrosion on outdoor-exposed aluminium MMCs as a function of reinforcement species and volume fraction has been performed most recently [35]. The experimental matrix involved variations in particulate volume fraction and particulate reinforcement species (higher purity green and less pure black SiC, B<sub>4</sub>C and Al<sub>2</sub>O<sub>3</sub>). The observed variations in corrosion behaviour of these sets of MMCs could be related to the crystallographic and morphological characteristics of the resulting corrosion products. Compared to the monolithic aluminium control specimens, the measured corrosion rates for these MMCs were considerably accelerated (by at least an order of magnitude) by the presence and relative amount of the second-phase particulates. Higher values of corrosion rates for these MMCs were nominally proportional to the volume fraction of the particulate phase. Other differentials in gravimetric corrosion rates and corrosion product characteristics were related to the type of reinforcement phase present [35].

### **3. CORROSION PROTECTION OF ALUMINIUM ALLOYS BASED METAL-MATRIX COMPOSITES**

For long-term use of aluminium alloys based MMCs components in service, effective corrosion protection must be considered. Aluminium is a very reactive metal, but forms a protective oxide film when exposed to air. This film provides protection from general corrosion in neutral solutions. Aluminium is susceptible to localized corrosion, such as pitting and crevice corrosion, in solutions containing aggressive anions, such as chlorides. To protect aluminium and its alloys, a number of different protection methods are used. In contrast to aluminium alloys protection methods, relatively little is known about the corrosion protection of aluminium alloys based MMCs and the effectiveness of standard corrosion protection methods [36]. A proven coating system for an aluminium alloy may not be suitable for a MMC of that alloy however. Poor adhesion and wettability between the coating and reinforcement or differences in the electrochemical properties of the alloy and MMC may render a proven system ineffective for the MMC [2]. Other protection techniques, such as anodization, could also be

ineffective or even deleterious to the MMC. Anodization, which is frequently used for aluminium alloys protection could destroy a graphite/aluminium MMC by oxidizing the graphite fibers to CO<sub>2</sub> [2].

In order to achieve an effective corrosion protection, MMCs corrosion design should take into consideration the ease of particular coating application as well as coating maintenance [9]. A simple component design is optimum for ensuring effective coating application. Areas such as sharp edges and corners, overlaps, rivets, fasteners and welds should be eliminated as much as possible during design. Also, recesses or low spots should be avoided, because these areas will collect water and lessen the corrosion resistance of the coating [9].

The inhomogeneous structure of an MMC must be considered in designing a corrosion protection system. Surface treatments applied to MMCs encounter reinforcement particles that may disrupt any protective coatings and hinder effectiveness of passive coatings. It was established that simply transferring protection methods routinely used for an aluminium alloy wouldn't be effective without considering the nature of the MMC surface [36].

Effects of reinforcement type, volume fraction and matrix alloy on effectiveness of corrosion protection methods of aluminium alloys based MMCs were investigated in detail by Greene [37], while results obtained by anodizing, chemical passivation and application of polymer coatings have been summarized in [38].

Greene and Mansfeld [36] have evaluated MMCs corrosion resistance resulting from application of standard protection methods for aluminium alloys when applied to aluminium based MMCs. The MMCs used were commercially available discontinuously reinforced aluminium MMCs with various reinforcement concentrations, reinforcement types and different matrix aluminium alloys (AA): SiC<sub>p</sub>/AA 6061, Al<sub>2</sub>O<sub>3</sub>/AA 6061, SiC<sub>p</sub>/AA 2009, SiC<sub>w</sub>/AA 2009, SiC<sub>p</sub>/A356 and Al<sub>2</sub>O<sub>3</sub>/AA 2014. Anodizing, conversion coatings and polymer coatings were chosen as protection methods because of their frequent commercial use. The corrosion behaviour of MMCs was studied using electrochemical polarization measurements. The results obtained have shown that H<sub>2</sub>SO<sub>4</sub> anodizing of aluminium alloys based MMCs was not as effective as for aluminium alloys [36]. The barrier layer typical of anodized aluminium was disrupted by reinforcement particles. The interface

between the reinforcement particles and the matrix lowered resistance of the barrier layer and acted as a cathodic site [36].

In general, the corrosion resistance of surface modified, aluminium based MMCs has been found inferior to that of the corresponding matrix alloys [36-38]. This result has been attributed to intermetallic precipitates that preferentially segregate to matrix-reinforcement interfaces in composites [12].

Standard corrosion protection methods for aluminium alloys were less effective for aluminium based MMCs. The effectiveness of all anodizing methods studied decreased with increasing reinforcement concentration. Effectiveness of the protection methods also was a function of the matrix alloy composition, but not a function of reinforcement composition. The effectiveness of the protection depended on the matrix alloy rather than on the reinforcement type [36].

Organic coatings have been identified as providing excellent corrosion protection for graphite/aluminium MMCs [9]. These coatings provide only barrier protection. Noble metal coatings, such as nickel and titanium, also provide barrier protection; however corrosion at coating flaw sites is much worse for these coatings than for an organic coating due to highly unfavourable anodic (aluminium) to cathodic (noble coating) area ratio at a flaw site. Consequently, noble metal coatings are not recommended for protection aluminium based MMCs.

MMCs corrosion can be also prevented using corrosion inhibitors. A study of the corrosion behaviour and corrosion inhibition of AA 6061 and AA 2014 based MMCs reinforced with alumina particles during exposure to neutral chloride solutions was performed [39]. Many tungsten and molybdenum-containing inorganic salts were tested as corrosion inhibitors, but only ammonium tetrathionate afforded good inhibiting properties [39]. Generally, inhibitors intended for monolithic alloys should be used with MMCs only after ample examination.

#### 4. CONCLUSION

Most of the commercial work on MMCs has focused on aluminium and aluminium alloys as the matrix metals. The combination of light weight, environmental resistance and favorable mechanical properties has made aluminium alloys very popular

for use as a matrix metal. However, the addition of the reinforcement particles could significantly alter the corrosion behaviour of these materials. The presence of the reinforcing fibers and particles and the processing associated with aluminium MMCs fabrication can cause accelerated corrosion of the metal matrix compared to corrosion of the unreinforced matrix alloy. Accelerated corrosion may originate from electrochemical and chemical interaction between MMC constituents, microstructural effects and from problems related to processing.

Corrosion studies have been conducted on aluminium MMCs reinforced with graphite, silicon carbide, alumina, boron and mica in the form of particles, fibers, whiskers or monofilaments. The published literature on the corrosion of aluminium-based composites is often contradictory. This is due to the fact that there is a variety of aluminium alloy matrices and reinforcement type combinations which may exhibit completely different corrosion behaviour. In general, the composites are more susceptible to corrosion attack than the matrix alloy.

In contrast to aluminium alloys, relatively little is known about the effectiveness of standard corrosion protection when applied to aluminium based MMCs. Standard corrosion protection methods for aluminium alloys were less effective for aluminium MMCs. The effectiveness of all anodizing methods studied decreases with increasing reinforcement concentration. In general, corrosion resistance of surface-modified, aluminium based MMCs has been found inferior to that of the corresponding matrix alloys. Simply transferring protection methods routinely used for an aluminium alloy will not be effective without considering the nature of that aluminium alloy based MMC surface. The inhomogeneous structure of an MMC must be considered in designing a corrosion protection system. Surface treatments applied to MMCs will encounter reinforcement particles that may disrupt any protective coatings and hinder effectiveness of passive coatings.

There are many additional concerns regarding the corrosion of aluminium based MMCs in comparison to their monolithic matrix alloys. Prudence should be used, however, when making generalities about corrosion behavior for a specific MMCs group, such as for example SiC/Al composites, because MMCs corrosion behaviour may vary significantly due to the quality of the reinforcement and matrix alloy, the manufacturing technique, post thermomechanical processing and

other factors. Hence, it will be difficult to obtain a corrosion data base of corrosion behavior for a specific MMCs group until standards are developed for the manufacture and processing of metal-matrix composites.

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