Fabrication and Corrosion Behaviour of Aluminium Metal Matrix Composites – A Review

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Abstract.
Metal matrix composites (MMCs) corrosion nature is discussed with significance in regard to MMCs corrosion behavior with MMCs electrochemical and chemical properties. Galvanic corrosion between base metal and reinforcement influences the corrosion process in MMCs. The corrosion behaviour of Aluminium Metal Matrix Composites (AMMCs) reinforced with carbide and other solid waste is reviewed. AMMCs are capable of admitting the assault of corrosion over the base metal. AMMC's corrosion type of behaviour is localized with galvanic corrosion, the intermetallic phase between base alloy and reinforcement, micro cracks, voids, are the corrosion-influencing factors. The corrosive action of solid carbide-reinforced AMMCs (Aluminum Metal Matrix Composites) and other solid waste is analysed. The AMMCs have strong mechanical and tribological characteristics but no achievement in the effects of corrosion. Coatings methods are used to enhance the behaviour of AMMCs in corrosion.

Keywords: AMMCs, Stir Casting, Corrosion, Pitting, Potentiodynamic Polarization.

1. Introduction:
Metal Matrix Composite [MMC] consists of two or more constituent materials in which one acts as a matrix and other being reinforcement. During the fabrication of MMC, the stress applied over the matrix materials are distributed to the reinforcement materials. Subsequently, the required mechanical strength is provided to the composite in a preferential direction by the reinforcement materials. A good MMC should possess brittleness and ductility in the form of reinforcement and matrix respectively. MMCs have numerous advantages when compared to monolithic materials. They have lightweight, superior high-temperature properties, low coefficient of thermal expansion, better abrasion, improved strength and stiffness when compared with monolithic materials [1,2]. Nowadays, MMCs replace various conventional alloys in applications such as automobiles, marine, recreation industries and defense [3].

If a Metal Matrix Composite is made up of more than two constituent materials, it is termed as hybrid composites. Generally, metals such as Aluminum, Steel and Magnesium are used as matrix materials for composites. In MMCs, reinforcement materials are mostly used in the form of wires,
whiskers or particulates, continuous/discontinuous fibres in various volume fraction percentages. However particulate metal matrix composites were found to be having superior properties than their monolithic alloys. Callister found out that ceramic material such as carbides, nitrides and oxides when used as reinforcement’s exhibit improved stiffness and specific strength at both ambient and elevated temperatures.

MMCs can be fabricated through various production methods such as powder metallurgy, vacuum hot pressing, co-spray deposition and stir casting. The method of production of MMCs also plays an important role in the behaviour of the MMC as it influences the level of porosity, distribution of particles and matrix/reinforcement interfacial properties. It was reported that Stir Casting improves the strength and mechanical characteristics of fabricated composites [4]. Aluminium based metal matrix composites attract much attention in today’s world due to their potential to be used as top choice material in various engineering applications. They have good mechanical properties, good corrosion and wear resistance [5–7]. The production of Aluminium metal matrix composites is also cheaper when compared to other metal matrix composites. Nowadays, industrial wastes (fly ash, red mud) and agro based materials (rice husk ash, bagasse) are used as reinforcement materials in Aluminium metal matrix composites [8].

AMMCs suffer from corrosion in various environments due to the presence of the reinforcement phase. Generally, AMMCs exhibits poor corrosion resistance than the base metal. This is due to the reason that aluminium alloys have neutral strong oxide layers on its surface which when subjected to breakdown create a passive film which protects the aluminium alloys from corrosion initiation and crevice. However, in aluminium based metal matrix composites, the passive film gets breakdown due to the reinforcement phase which will make them more susceptible to corrosion. This article reviews various literature works done on the fabrication and corrosion behaviour of aluminium metal matrix composites.

2. Material Selection

2.1 Reinforcement Selection

The selection of reinforcements plays an important role in the fabrication of metal matrix composites. Among all the reinforcements, ceramic reinforcements provide MMCs with superior properties. The various factors which are considered for selecting ceramic reinforcements for MMC are

(i) Elastic modulus
(ii) Tensile strength
(iii) Density
(iv) Melting temperature
(v) Thermal stability
(vi) Coefficient of thermal expansion
(vii) Compatibility with a matrix material
(viii) Size, shape and cost

The thermal mismatch strain ($\varepsilon$) between matrix and reinforcement material are also one of the criteria considered mainly for MMCs that are subjected to thermal cycling.

$$\varepsilon=\Delta\alpha\Delta T$$

Where,

$\Delta\alpha$ = coefficient of thermal expansion,
$\Delta T$=change in Temperature.

In order to minimise the thermal mismatch strain ($\varepsilon$), the coefficient of thermal expansion should be minimal. It was also evident that the relaxation of these strains will alter the thermomechanical processing response of MMC significantly when compared to unreinforced alloys. The investigation done on the size ratio of SiC reinforcement particle to aluminium matrix powder in
the fabrication of MMCs during Powder Metallurgy (PM) has revealed that there is a relationship between the toughness of fabricated composite and the SiCp-Al powder size ratio.

2.2. Matrix Selection

There is a wide range of metallic alloys available which can be used as matrices in the fabrication of MMCs. However, low density, high thermal conductivity and other requirements promote the use of aluminium and magnesium as a predominant matrix element in fabrication of MMCs. For using the MMCs at elevated temperatures, the presence of thermodynamically stable dispersions is required. This can be achieved by using an alloy dispersoids system which minimises the coarsening and interfacial reactions. Several investigations have found out that low matrix alloying additions provide MMCs with superior properties.

2.3. Matrix Ceramic Interface

The interface between the matrix and the ceramic reinforcements plays an important role in the load transfer and deformation characteristics of MMCs during deformation. The studies which were done in the early 1960s revealed that the interfacial bond strength between the matrix and the reinforcements can be increased by promoting wetting and by minimizing the formation of oxides [9]. It was also found that the wetting occurs between the matrix and the reinforcements when the interfacial bonding strength between the matrix and the reinforcements exceeds the liquid’s surface tension. However, in molten metal-ceramic reinforcement MMC, it is difficult to achieve wetting. This is because the surface tension of molten MMCs is higher. This theory is justified by an investigation which revealed that the aluminium and its alloys exhibit a poor wetting effect on SiC, Al2O3, Carbon and B4C below 950°C.

The wetting behaviour of molten metal systems can be improved in the following ways.

(a) By alloying the matrix material with other reactive materials.
(b) By subjecting the ceramic particulates to heat treatment.
(c) By coating the ceramic particulates with metallic coatings [10].

2.4. Other Effects of Reinforcement in the Matrix

The ageing response of MMCs is different from the equivalent unreinforced alloys. This is due to the presence of Ceramic particulate reinforcements [11–13]. The age-hardening sequence of 6061 aluminium alloy reinforced with SiC and B4C particulates was similar to the age-hardening sequence of unreinforced Al6061 alloy. Researches also revealed that the formation of intermediate phase and precipitation, the GP zone formation and dissolution were increased in the presence of reinforcement materials. It was also found that the quench insensitive alloys such as Al6061 become quench sensitive alloys due to the effect of SiC particulates reinforcements. However, the quench sensitivity of more quench sensitive Al7475 alloy remains unaltered with reinforcement addition [14]. These findings reveal that the effect of reinforcement depends upon the nature of matrix material.

The presence of high diffusivity paths due to the thermal expansion that exists between the matrix and the reinforcement particulates was reported to be the main reasons for the acceleration of ageing and quench sensitivity in reinforced alloys. Quench sensitivity was also reported in PM monolithic materials but to a lesser degree [15]. Research done on segregation revealed that there is severe segregation of Magnesium and formation of MgO precipitates occurs at Al-SiC interfaces in Al2124-SiC MMCs [12].

3. Fabrication

The methods which are most commonly used for the fabrication of MMCs are Solid-phase processes and liquid-phase processes. The selection of the fabrication process for MMCs depends on
1) The temperature of the matrix during processing
2) The desired degree of microstructural integrity
3) Reinforcement loading

The solid-state process which is used for MMC fabrication is isostatic pressing (Powder Metallurgy (PM) Processing), diffusion bonding and spray deposition techniques. Melt stir casting, Spray Casting, melt infiltration and in situ processing are some of the liquid state processes used in MMC Fabrication.

3.1. Fabrication methods for Aluminium Composites

The uniform distribution of reinforcement particle within the matrix alloy is a major issue which is encountered in the fabrication of aluminium composites. In order to overcome this issue, proper selection of processing techniques and operating parameters are required. Powder Metallurgy (PM) and molten metal method are the two methods which are commonly used for the fabrication of aluminium composites [1,14]. Based on the operating parameters, both fabrication techniques have certain limitations.

3.2. Powder Metallurgy

The first step in the fabrication of aluminium composites through Powder Metallurgy (PM) is to blend the aluminium alloy powder with reinforcement particles in order to prepare a homogeneous mixture. The size of the aluminium powder and reinforcement particle should be selected properly. Otherwise, it will cause agglomeration at the end of the blending process [14]. It was also inferred from the studies that the selection of proper size ratio of alloy and reinforcement particle is essential to get uniform distribution in the final product [1]. For the Al/SiC composite, the appropriate size ratio was found to be of the order of 7:10. The hard reinforcement particle suffers from particle fracture during blending. Flaw density and aspect ratio are the two important factors which are responsible for particle fracture during blending. The appropriate aspect ratio for Al alloy and reinforcement powder should be less than 5:1 with a size range of Al alloy and reinforcement powder be 20-40 and 30-20 μm respectively [14]. In Powder metallurgy technique, the initial process involves a blending of matrix and reinforcement powders in order to produce a homogeneous mixture [1]. Then the homogeneous mixture which is obtained is subjected to compression. The compression is done at an isotactic pressure in room temperature. The water molecules present in the mixture may cause porosity during consolidation. So, these water molecules must be removed before the final consolidation process. Vacuum hot-pressing method can be used during the final consolidation process either below alloy’s solidus point or in a liquid-solid state to produce densified composites. Extrusion is the final process which is performed at the end of the PM technique to obtain the final product. The extrusion ratio should be greater than 20:1[14]. A high extrusion ratio is essential to obtain a uniform distribution of reinforcement particle in a matrix alloy and superior interfacial bonding between matrix and reinforcement particles.

Powder metallurgy has many advantages [1,14,15]. It allows the usage of any type of matrix alloy and reinforcement for composite fabrication. Through PM, we can also produce composites which contain higher reinforcement content. However, the requirement of long mixing time for obtaining a uniform distribution of particles is a major drawback of Powder Metallurgy (PM) technique [16,17].

3.3. Stir Casting

Stir casting is a liquid metallurgy technique which is most commonly used for the fabrication of particulate reinforced metal matrix composites. This process consists of melting the matrix alloy in the furnace of the stir casting machine. Then the reinforcement materials are added to the melt of the matrix alloy and the mixture is stirred by using a mechanical stirrer. The obtained molten metal mixture is transferred to a mould of the desired shape. After transferring the molten metal, the mould is allowed to cool. After solidification, the required composite is ejected from the mould and subjected
to various heat treatments. The major challenge in stir casting is the wettability of reinforcement material in the molten metal. It was found that the use of magnesium ribbons provides sufficient wettability while using ceramic materials as reinforcement.

3.4. Stir Casting of Aluminium Metal Matrix Composites

Aluminium metal matrix composites were fabricated using SiC as reinforcement material and magnesium as wettability agent. The findings revealed that the mechanical properties of the composites namely yield strength, hardness and tensile strength improved when the addition of reinforcement particle to the base alloy was less than 20 percentage [18]. A study was done on Aluminium metal matrix composites reinforced with SiC having 60µm particle size. Mechanical stirrer consisting of mild steel impeller was used to mix the alloy and reinforcement mixture in this study. The stirring was done with different stirrer speed (500 rpm, 600 rpm, 700 rpm) and different stirring time (5 min, 10 min, 15 min). It revealed that higher stirring speed and stirring time leads to the production of composites with homogeneous particle distribution and greater hardness [19]. Fabrication of Al-Al2O3 composites through Stir casting revealed that the ductility of the composites decreased with the addition of reinforcements to the base alloy. However other mechanical properties such as yield strength, tensile strength and hardness were considerably increased with reinforcement addition [20]. Preheated Borax was preheated to 250°C for 20 minutes and used as a wetting agent during the fabrication of Al6063-SiC Composite. It was found that composite containing SiC reinforcement between 9 to 12 percentage by volume exhibits improved strength. However, the ductility of MMC remains unchanged [21]. The microhardness and wear behaviour of the aluminium metal matrix composites improved with the addition of TiB2 reinforcements to the Al6061 base alloy [22]. A study done on the effect of stirrer parameters on the fabrication of metal matrix composites revealed that the formation of clusters can be prevented by modifying the stirrer design thereby the uniform distribution of base alloy and reinforcement can also be achieved. It was also found that changing the feeding mechanism in MMC productions provides a uniform spray of particulates [23]. The development of Al-SiC-Al2O3 hybrid metal matrix composite using an automatic agitator revealed that the reinforcements were distributed homogeneously in the Al6061 based alloy [24].

The strengthening derivable from load transfer in MMC from the matrix to the reinforcements can be decreased by using reinforcements such as rice husk which is softer when compared to SiC [25]. The use of argon gas as a protective covering for a furnace in which AZ91 was charged prevented the effects of agglomeration in the fabricated AZ91-SiC Composites [26]. The blending of reinforcement particle with a considerable amount of flux during stir casting removed slag from the molten mixture. As a result, wettability was increased [27].

4. Corrosion Behaviour

The major limitations in the applications of MMC are their corrosion behaviour. The heterogeneities in MMC tends to affect its corrosion characteristics. Galvanic Coupling, micro crevices, porosity, voids and high reactivity interfacial phases are some of the corrosion-related problems in MMC. The reported works on corrosion behaviour of MMCs is also less when compared to other behaviours of composites. Various reporters had used various tests namely Stress Corrosion Crack (SCC), immersion test and Potentiodynamic test to study the corrosion behaviour of MMCs.

4.1. Corrosion behaviour of Aluminium-based particulate metal matrix composites

The initiation of pitting on the PMMCs interface is considered to be the main reason for the corrosion of aluminium-based PMCs. Researchers reinforced Al2024, Al5466 and Al6061 with SiC through Powder metallurgy and studied their pitting potential and polarization behaviours in solutions containing 0.1 N and 0.8 N NaCl. The polarization behaviour of the fabricated composites was found to be in similar to their matrix alloys. Similarly, the pitting potentials of the fabricated MMCs were similar in accordance with the pitting potentials of respective alloys except in cases when Al2024 was used as a base alloy. The pitting potential value of Al2024-SiC composite was found to be more
negative than the base alloy. However, this doesn’t affect the matrix structure of the Al2024-SiC composites as well as the base alloy [28]. Studies also revealed that the SiC reinforced Al6061-T6 exhibits better corrosion resistance than Al6061-SiC composites [29]. The studies done on the corrosion behaviour of Al6061 reinforced with carbon fibres and alumina fibres or SiC whiskers revealed that the Al6061 based MMC and Al6061 exhibits similar pitting Potentials. It was also found that SiC whiskers reinforced Al6061 MMC showed greater pit initiation than the base alloy. It was also found that the cathodic current of Al6061-SiC whiskers was higher than base alloys due to the presence of interfacial layer [30]. The study done on the polarization behaviour of Al11050 reinforced with SiCp of particle size 3μm and 30 μm composite revealed that the pitting attacks on the composites are higher when compared to the base alloys. It was due to the presence of voids at the interface between matrix and reinforcement. However, polarization behaviour remains unaffected by the residual stress that exists between matrix and reinforcements. The author also concluded that the 20μm SiCp were found to be more prone to localized corrosion than the 60 μm SiCp [31]. The research done on the stress corrosion behaviour of Al2014-T6, Al6061-T6, Al6061-T6 reinforced with SiCp & SiCw and Al2014-T6 reinforced with Al2O3 revealed that the corrosion rate of Al6061 based MMCs in 3.5% NaCl was considerably lesser than the Al2014 alloy and its composites [32].

A study done on localized corrosion and its effect on the Al2024-SiCp MMC Containing SiCp of particle size 14 μm in varying volume fractions revealed that Al2024-SiCp MMCs exhibits less corrosion resistant when compared to the unreinforced base alloy. It also revealed that the increase in the addition of up to the base alloy decreases the pitting potential. At the same time, it increases the number of active sites on the composite’s surface [33]. Yue fabricated Al6013-SiCp composite through PM technique. He used Nd: YAG laser to change the surface microstructure of fabricated composite thereby improving the corrosion resistance of the composites. His findings revealed that the pitting resistance of the fabricated composites was improved by using Nd: YAG laser during PM technique. Researchers studied the corrosion characteristics of heat-treated Al6063 containing SiCp reinforcements in various weight percentage. They used a two-step stir casting process to fabricate the composites. They conducted the corrosion tests in 5% NaCl Solution. Their findings revealed that the addition of SiCp increases the corrosion rate of the composites [34]. A Study done on the corrosion behaviour of Pressure infiltrated Al-Mg alloy/SiCp reported that the corrosion attacks on pure Al matrix were three folds more when compared to Mg containing aluminium matrices. The corrosion resistance of the composites is shown in Figure 1 and Figure 2 was found to be increased with the presence of Mg content in the Al matrix [35]. The corrosion resistance of Al-SiC composites fabricated through PM technique revealed that the corrosion resistance increases with the increase in a volume fraction of SiCp reinforcement particles. However, the reduction in particle size of SiCp considerably improves the corrosion resistance of the fabricated composites [35].

![Figure 1. Polarization curves of pure Al, Al-2Mg, Al-4 Mg, Al-8 Mg in 3.5 wt.% NaCl for 1 hr [36]](image-url)
The fabrication of LM13-albite MMC by reinforcing LM13 with 2 to 6 wt.% of albites through liquid metallurgy revealed that the corrosion rates of both matrices and fabricated MMCs decreased with the increase in exposure time and increased linearly with increase in temperature [37]. A corrosion study was done on the Al2024-TiC MMC in 3.5% NaCl solution revealed that the size and number of pits in the composites decreases with increase in anodic current density [38]. The corrosion crack behaviour of Al7075-ZrP MMC fabricated through Stir casting was studied. The particle size of Zr ranges from 40-50 μm. Natural seawater was used as a corroding medium. Findings revealed that the corrosion characteristics of Al7075-ZrP and base alloys increase with the increase in temperature of seawater. This is due to an increase in the diffusion rate of hydrogen. A detailed report is done on the stress corrosion cracking (SCC) behaviour of pure Al/SiCw and Al2024/SiCw composites, treated annealing and fabrication by squeeze casting [39]. The sample was taken as a double cantilever specimen, which was immersed in simulated seawater i.e., 3.5% NaCl solution for evaluating SCC properties. Annealing temperature majorly affects the steady propagation rate of SCC for both composites. The dislocation density and stable propagation rates of SCC were found to be decreased, on an increase in annealing temperature, but the threshold stress intensity factor increases. Reports show that annealing at high temperature resists the SCC behaviour. Al 2009/SiCp composite was investigated based on its corrosion behaviour in de-aerated neutral 3.5% NaCl solution at 25ºC by Potentiodynamic polarization [40]. This polarization test showed that carbide turned sample had less resistance to corrosion when compared to WEDM and diamond-turned samples. A detailed report was done on the corrosion properties of Al-Si-Mg-SiCp composite, with addition of scandium in minimal amount, fabricated by powder process technique [41]. The Potentiodynamic polarization test was carried out at room temperature in electrolyte consisting of 0.1% and 3% NaCl with pH variation of 2, 7, 12. With addition of 1.5% Na2SO3 to 3% NaCl, the corrosion study was made. The study revealed that pitting behaviour was more observed in presence of 3% NaCl solution than 0.1% NaCl solution. Investigations done on the pitting phenomenon of aluminium MMC’s (A 360/10% SiCp, A360/20% SiCp, A380/10% SiCp, A380/20% SiCp) fabricated by pressurized die casting technique in 1-3.5 wt% NaCl solution at room temperature using Potentiodynamic polarization revealed that the corrosive attack in Al/SiCp composite materials was observed to be started at the interfacial layers of matrix/SiCp and matrix/intermetallic phases[42].

4.2. Corrosion Inhibitors

It is necessary to protect the aluminium based metal matrix composites from corrosion to prolong their usage period. Various studies done by researchers revealed that corrosion inhibitors such as polymer coating and anodizing help to protect the composites from corrosion attacks in a better
way. Researchers used rare-earth metal ions such as Ce3+, Y3+, La3+, Pr3+, Nd3+ for preventing pitting corrosion in composites [43].

Investigation performed on the action of anodizing coating on Al2024 alloy and SiCp/Al2024 PMMC as an inhibiting agent in 3.5% NaCl solution revealed that the anodizing coating Al2024 alloys possess good protection from corrosion when compared to Al2024/SiCp PMMC. It was due to the presence of SiC particulates in Al2024/SiCp [44]. A Study was performed using K2Cr2O7, Sodium molybdate and Cerium chloride as coatings for preventing corrosion in Al6013/SiCp Composites in 3.5% NaCl solution. The study concluded that cerium chloride treatment provides better protection to the composites than the other coatings. The anti-corrosion film prepared by using micro-arc oxidation (MAO) on Al2024/SiCp composite revealed that the MAO technique inhibits corrosion attacks on the samples in 3.5% NaCl Solution [45].

5. Conclusion

The above cited review for Aluminium metal matrix Composites gives the following Conclusion

❖ Aluminum alloys are more susceptible to localized pitting corrosion in chloride environment.
❖ Aluminium based MMCs reinforced with SiC, B4C and fly ash have more tendency to corrode when compared to TiC.
❖ The volume fraction and Size of the particulates influence the corrosion behaviour of the composites.
❖ The MMCs which are subjected to heat treatments after its fabrication exhibits improved corrosion resistance.

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