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Aluminum Alloys for Al/SiC Composites

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1. Introduction

Aluminum has played and continuous to play a key role in the development of metal matrix composites (MMCs) reinforced with a variety of ceramic materials including Al_2O_3, TiC, B_4C, and SiC. From the wide range of MMCs systems studied thus far and on account of the attractive properties of SiC, Al/SiC composites have drawn the attention of a plethora of research scientists and technologists. Like with any other composite material, the materials behavior lies much in the matrix characteristics as in the reinforcement properties. Several aspects are to be considered with regard to the metallic matrix, namely, composition, response to heat treatments, mechanical and corrosion behavior. And since aluminum offers flexibility in terms of these aspects, accordingly, a number of aluminum alloys have been used in studies intended for research and technological applications. The choice, however, for one or another alloy depends also on other factors as the composite processing route, which in turn can be dictated by the volume fraction of the reinforcement in the composite. For instance, the stir casting route is more suitable for low volume fractions (< 20%), whilst the infiltration routes are more appropriate for high volume fraction of the reinforcement (> 40%). Another important factor for selection of the aluminum alloy is the composites application and specific requirements in service. For instance, one composite may behave better under certain loads or in corrosive environments.

The aim of this chapter is to provide the readers with an insight into the factors that affect the properties of Al/SiC composites and the most important response parameters, associated to mechanical, heat-treatment, and corrosion behavior. The chapter is organized based on a hierarchical concept, starting with the role of alloy composition, followed by the resulting mechanical properties and its dependence in heat treatments, closing with the corrosion behavior. At the same time, this is derived from the central paradigm of materials science and engineering, based on the correlation: *processing → microstructure → properties → performance*. A review of the main findings in studies related to mechanical properties, heat treatments and corrosion behavior is presented. In view of that, the chapter is provided with references from earlier-to-the most recent studies on the behavior of Al/SiC composites, on the basis of the importance of aluminum alloy characteristics.

2. Factors and response variables related to Al alloys for Al/SiC composites

Aluminum alloy composition is one of the factors that most notoriously influence the properties of Al/SiC composites. Other factors are processing time and temperature,

atmosphere type, and reinforcement characteristics. The alloy chemistry impinges on the mechanical properties and corrosion behavior, and when applicable, on the composite response to solution treatment and age hardening. It is interesting to note, however, that the wide variety of Al/SiC composites reported thus far have been prepared both with commercial and experimental alloys.

2.1 Use of commercial and experimental aluminum alloys

Several reasons dictate the need for using one or another alloy, including final application, processing route, and with no doubt, availability and cost. As for final application, and according to the materials science and engineering standpoint, the clear establishment of stress level, temperature and environment (corrosion behavior) related aspects in service is paramount. Associated to all these requirements is the chemical composition of the aluminum alloy used for the manufacture of the composite. Table 1 shows the designations of a variety of aluminum alloys used in systematic studies on Al/SiC composites. They will be evoked in the following sections concerning mechanical property, heat treatments and corrosion response of Al-alloy/SiC composites.

Alloy designation	Related field of study	Reference(s)
2024	Aging behavior Deformation behavior	Ahmad et. el., 2000, Mousavi, 2010; Zhang, 2001
2124	Creep behavior	Li & Mohamed, 1997
2219	Fatigue and projectile penetration performance	Greasley et. al., 1995
A3xx.x A3xx.x	Corrosion in humid environment Pitting corrosion	Pardo, et. al., 2003 Pardo, et. al., 2005
5456 (UNS A95456)	Pit morphology	Ahmad et. al., 2000; Trzaskoma, 1990
6013-T4 and T6	Aging behavior	Guo and Yuan, 2009
6061 UNS(A6061) 6061-T6 6061-T6	Pitting corrosion Pit morphology Galvanic corrosion Residual fatigue life prediction	Ahmad et. al., 2000; Aylor et. al., 1985: Trzaskoma, 1990 Hihara & Latanison, 1992 Shan & Nayeb-Hashemi, 1999
Al-Li, Al-Cu	Fatigue and fracture	King & Bhattacharjee, 1995
7075	Fatigue and projectile penetration performance	Greasley, et. al.,1995
Al-9.42Si-0.36 Mg	Hardness	Sahin & Acilar, 2003
AS7G06	Hardening kinetics	Cottu el al., 1992
Al-4Mg	Corrosion behavior	Candan & Bilgic, 2004
Al-13.5 Si-9 Mg	Activity of SiC in Al MMCs (electrochemical studies)	Díaz-Ballote et. al., 2004
Al–15.52 Mg–13.62 Si	Microhardness and superficial hardness	Montoya-Dávila et. al., 2007
Al–13 Mg–1.8Si Al-Si-Mg (Si/Mg var.)	Pitting behavior The role of Mg_2Si in corrosion behavior	Montoya-Dávila et. al., 2009 Escalera-Lozano, et. al., 2010

Table 1. Commercial and experimental aluminum alloys used in Al/SiC composites

As regards to fabrication route, the alloy composition to be utilized – commercial or experimental – depends strongly on the manner used to incorporate the SiC reinforcement
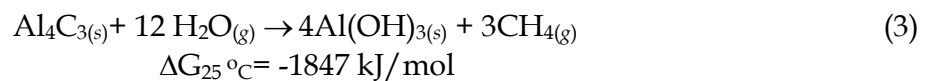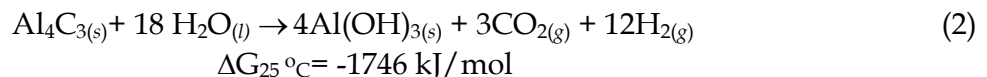
into the alloy matrix, and on other factors such as the SiC volume fraction and shape (fibers, whiskers or particles). In some cases, processing is made with the metal in the liquid state and in others, in solid state, as in the powder metallurgy route. Due to the inherent advantages of using the aluminum alloy in molten state, a copious number of researchers have used liquid aluminum in their work. Hence, this section revolves around the implications of using liquid aluminum for the processing and characterization of Al/SiC composites.

With the metal in liquid state, the SiC reinforcements can be incorporated by way of stirring or mixing, followed by casting into metallic molds to produce ingots, which are then remelted to produce parts by other routes, like squeeze casting. Alternatively, the alloy may be incorporated into a porous preform formed by the SiC reinforcements, via the infiltration route, which in turn can be conducted either under the application of forces or vacuum or by capillary action. The latter is the so-called non-assisted, spontaneous or pressureless infiltration. In both cases – mixing and infiltration – wettability of the SiC reinforcements by the aluminum alloy is a crucial prerequisite, in tandem with an optimum fluidity of the alloy.

One of the main problems faced when processing Al/SiC composites with the metal in molten state is that liquid aluminum tends to attack SiC according to the following reaction (Iseki et. al., 1984):

$$4Al_{(l)} + 3SiC_{(s)} \leftrightarrow Al_4C_{3(s)} + 3Si_{(in\ l\ Al)} \tag{1}$$

The Al_4C_3 compound has deleterious effects within the composite because, firstly, as a brittle phase degrades the mechanical properties, and secondly, it reacts with liquid water or with moisture in the ambient, debilitating even more the composite, according to the following reactions (Kosolapova, 1971; Park & Lucas, 1997):

$$Al_4C_{3(s)} + 18\ H_2O_{(l)} \rightarrow 4Al(OH)_{3(s)} + 3CO_{2(g)} + 12H_{2(g)} \tag{2}$$
$$\Delta G_{25\ ^oC} = -1746\ kJ/mol$$

$$Al_4C_{3(s)} + 12\ H_2O_{(g)} \rightarrow 4Al(OH)_{3(s)} + 3CH_{4(g)} \tag{3}$$
$$\Delta G_{25\ ^oC} = -1847\ kJ/mol$$

Several approaches have been proposed in the literature to prevent or retard aluminum carbide formation and overcome its harmful effect; these include: i) modifications to the aluminum alloys compositions, ii) coatings on the SiC reinforcements, iii) varying processing temperature and contact time, iv) artificial or intentional oxidation of the SiC reinforcements, and v) incorporation of silica (SiO_2) powders in the SiC preforms (Rodriguez-Reyes et.al., 2006).

One of the first and most successful approaches to avoid the attack of SiC by liquid aluminum and its consequences, and at the same time improve wetting, was the modification of alloy composition with silicon and magnesium. It is well established that silicon in the aluminum alloy plays a key role, as it lowers the melting point of the alloy and decreases the contact angle between the solid and the liquid, thus enhancing wettability (Pech-Canul et. al., 2000 (a)).

On the other hand, from equation (1) and in the light of Le Chatelier's principle it is simple to see the beneficial effect of silicon, since it will tend to reverse the direction of the reaction. However, an uncontrolled excess of silicon in the alloy may have an adverse effect because above a critical level –the eutectic point – it tends to increase the viscosity of the alloy. In the case of the Al-Si system it corresponds to 12.6 wt. % Si at the temperature of 577 °C.

It is clear, that long processing times and at high temperatures – like those used in SiC oxidation – turn out to be costly to the manufacture of Al/SiC composites. In this regard, within the author's research group, several approaches that prove to be successful have been tested. Initially, wettability studies – using four experimental aluminum alloys – were performed in order to establish the optimum parameters to lower contact angle and surface tension, and in parallel, avert Al_4C_3 formation (Pech-Canul et. al., 2000 (b)). Under optimized conditions, Al/SiC$_p$ composites were fabricated by pressureless infiltration and characterized physically and in mechanical tests, specifically, modulus of rupture and modulus of elasticity. It was shown that Al/SiC composites made with silicon rich aluminum alloys and siliconized SiC show properties that are significantly different from those of similar composites produced with unsiliconized SiC or with aluminum alloys that do not contain silicon. Under optimized infiltration conditions, metal matrix composites with less than 3% porosity, over 200 GPa modulus of elasticity, and about 300 MPa modulus of rupture were routinely produced (Pech-Canul & Makhlouf, 2000).

Another element with a prime importance as an alloying element for aluminum is magnesium. Various investigations have been devoted to study the effect of Mg on the microstructure characteristics and mechanical properties of SiC-reinforced aluminum alloys. A comprehensive review on the role of magnesium in the processing of Al-based composites reinforced with various ceramic materials has been reported by B. C. Pai and co-workers (B. C. Pai et al., 1995; Aguilar-Martínez et. al., 2004). One prominent outcome from wettability tests, studying the effect of magnesium in aluminum alloys for pressureless infiltration is that it lowers the surface tension of the liquid aluminum, thus, enhancing wettability (Pech-Canul et. al., 2000 (b)).

In another approach used by the author's research group, incorporation of SiO_2 powders into the SiC preforms also proved to be beneficial (Rodriguez-Reyes et.al., 2006) to prevent formation of the unwanted phase Al_4C_3. The use of 6 V. % SiO_2 either in the form of quartz or cristobalite powders of $\approx$ 5 μm average particle size, completely hindered formation of aluminum carbide. Later on, the same group tested a simple method by coating the SiC particles with 0.1 volume fraction of colloidal silica (0.02–0.06 μm particle size) (Montoya-Dávila et. al., 2007). With this method, aluminum carbide was prevented again. In each of these methodologies, several experimental aluminum alloys with unconventional levels of silicon and magnesium were used. A last but not least important factor is the atmosphere used during the infiltration operation. According to the optimization of processing parameters, a change in the atmosphere from argon-to-nitrogen during pressureless infiltration significantly improves the wetting of SiC by the liquid aluminum alloy and consequently, substantially enhances infiltration (Pech-Canul et. al., 2000(b)).

It should be no surprise that with modifications in the levels of Si and Mg in the aluminum alloy, alterations in the matrix microstructure should be observed. These changes are manifested as the appearance or disappearance of phases with specific composition and morphology. In this context, one main secondary phase responsible for the mechanical and corrosion of response Al/SiC composites is magnesium silicide (Mg_2Si). This intermetallic phase is responsible for hardness increase in many commercial and experimental alloys, but at the same time, it may sabotage the integrity of the composite because it may form galvanic couples with the aluminum matrix or with other phases (Wei et. al., 1998; Escalera-Lozano et. al., 2010). The role played by Mg_2Si becomes as important when it is formed in the alloy matrices only, as when it is present in aluminum-based metal matrix composites because although it may be dissolved during composite processing by the liquid state route, it is formed again during the solidification of the alloy as the composite matrix.

In summary, to some extent all factors involved in the processing of Al/SiC composites by the liquid state route influence the contact angle (θ) and liquid-vapor surface tension (γ_{lv}). In the case of composites processed by the infiltration route, the magnitude of θ and γ_{lv} will determine whether the liquid will incorporate with or without the use of external forces. Figure 1 summarizes the factors that affect the magnitude of θ and γ_{lv}.
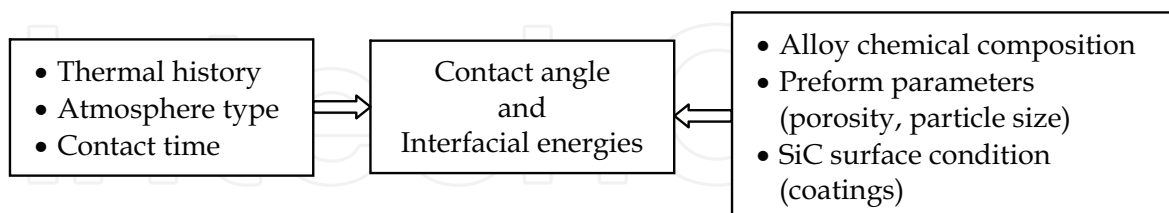

Fig. 1. Factors affecting the contact angle and interfacial energies in the Al/SiC system

From all the above factors, aluminum alloy composition plays a decisive role. However, it is possible to distinguish, chronologically speaking, between its effect *during* processing and *after* the fabrication stage. The resulting microstructure – embracing the matrix alloy and the matrix/reinforcement interface condition – is the first manifestation of the effect of alloy composition. Phase composition, amount and shape are dependent on the aluminum alloy. Then, after processing, they influence the mechanical properties, and when applicable, the heat treatments, and in the end, the corrosion behavior. As shown in Table 1, a broad variety of commercial and experimental aluminum alloys have been used in studies related to the processing and characterization of Al/SiC composites. Their particular effect on the composites' mechanical properties, heat treatment and corrosion behavior will be reviewed in the following sections (2.2, 2.3 and 2.4, respectively). An assessment of the SiC/Al-matrix interface microstructure condition is considered to be a prerequisite before evaluating the mechanical behavior of the composites. A sound interface is more likely to lead to reliable mechanical properties.

2.2 Mechanical behavior

Development of aluminum matrix composites reinforced with silicon carbide has been stimulated by the promise of improving the properties of aluminum alloys, and needless to say, mechanical properties were perhaps the first involved in systematic investigations. Several mechanical property related aspects, including deformation behavior (Zhang et. al., 2001), fatigue and fatigue-life predictions (Kumai et. al., 1991, King & Bhattacharjee 1995, Greasley et. al., 1995, Shan & Nayeb-Hashemi, 1999), fracture mechanisms predictions (Kumai et. al., 1991, King & Bhattacharjee 1995), hardness (Sahin & Acilar, 2003) and creep (Li & Mohamed, 1997) have been involved in earlier and recent studies, using both, theoretical and experimental approaches. Likewise, unconventional approaches have been proposed to strengthen Al/SiC composites (Tham et. al., 2001).

One of the first concerns was the effect of the difference in the coefficient of thermal expansion (CTE) of the matrix and that of the reinforcement on the mechanical behavior of the composite. This is because when a metal matrix composite is cooled down to room temperature from the fabrication or annealing temperature, residual stresses are induced in the composites due to the mismatch of the thermal expansion coefficients between the matrix and the reinforcements (either in the form of fibers or particles). And since alloy composition affects the CTE of the matrix, it is clear that the behavior of one Al-alloy/SiC system cannot be directly inferred from the behavior of any other given aluminum alloy.

Arsenault et. al. performed an investigation on the magnitude of the thermal residual stresses by determining the difference of the yield stress ($\Delta\sigma_y$) between tension and compression resulting from the thermal residual stresses (Arsenault et. al, 1987). A theoretical model based on the Eshelby's method was constructed to predict the thermal stresses and $\Delta\sigma_y$. A good agreement was observed between the theoretical prediction and the experimental results. In previous work, Arsenault and Shi (Arsenault and Shi, 1986) proposed a simple model based on prismatic punching to explain the relative dislocation density due to the differential thermal contraction. According to the model, the presence of SiC particles of platelet morphology in an aluminum metal matrix composite results in the generation of dislocations at the Al/SiC interface when the composite is cooled from the annealing temperature. The intensity of dislocation generation at the Al/SiC interface was found to be related to the size and shape of the SiC particles.

Kumai et. al. presented a review on the fatigue and crack growth behavior of SiC particulate aluminum alloy composite. It was concluded that the improved fatigue life reported in stress-controlled tests results from the higher stiffness of the composite; therefore, it is generally inferior to monolithic alloys at a constant strain level. The role of the particulate reinforcement was examined for fatigue and fatigue crack initiation, short crack-growth and long-crack growth. Crack initiation is observed to occur at the matrix-SiC interface or at the cracked SiC particles in powder metallurgy processed composites depending on particle size and morphology. The da/dN $vs.$ ΔK relationship in the composites is characterized by crack growth rates existing within a narrow range of ΔK and this is because of the lower fracture toughness and relatively high threshold values in composite compared with those in monolithic alloys. An enhanced Paris region slope attributed to the monotonic fracture contribution was reported and the extent of this contribution is found to depend on particle size (Kumai et. al., 1991).

King & Bhattacharjee studied the interfacial effects on fatigue and fracture in discontinuously reinforced metal matrix composites (DRMMCs), using Al-Li/SiC$_p$ and Al-Cu/SiC$_p$ systems. It was reported that the presence of weak interfaces leads to static modes of crack growth becoming important in fatigue crack growth resistance. However, whether this is deleterious to damage tolerance depends on the nature of the composite. In particles reinforced MMCs weak interfaces lead to void nucleation and growth, contributing to high m values and an early onset of stage 3 crack growth. In contrast, in whisker reinforced composites, crack deflection, associated with the presence of weak interfaces, can be beneficial in deflecting cracks and hence reducing growth rates. In order to exploit the benefits of crack deflection, it is essential to be able to predict both whether or not it will occur, and if so, the resulting path of the deflected crack. Mixed mode fracture testing approaches appear to offer some solutions in this area. However, when referring to the interface it is important to consider not just a two dimensional interface, but the whole interface zone (King & Bhattacharjee, 1995).

Greasley et. al. used either 2219 or 7075 Al alloys to study fatigue and projectile penetration performance of SiC particle reinforced aluminum matrix composite. It was found that the plastic deformation is the major energy absorption mechanism with a significant input from the melting phenomenon. However, these mechanisms can only be effective if spalling is prevented and the role of the reinforcement in this area is still important. Clearly fracture processes themselves do not absorb much energy and so reinforcement additions should not be made to promote fracture at the expense of enhancing spalling (Greasley et. al., 1995).

A study of the residual fatigue life prediction of 6061-T6 aluminum matrix composites reinforced with 15 vol. % SiC particulates (SiC$_p$) by using the acoustic emission (AE)

technique and the stress delay concept was carried out by Shan et. al. In their work, acoustic emission activity of a $6061/SiC_p$ composite was monitored during tensile tests in the as received condition and after the specimens were subjected to cycle fatigue loading for a number of cycles. It was found that the AE activity rises quickly once the material is well in the plastic regime. The activity was related to the particle/matrix debonding and linkage of voids. In the high cycle fatigue, the residual tensile strength of the composites was found not to be affected by the prior cyclic loading, since the crack initiation period dominated the life of the composite (Shan et. al, 1999).

Li and & Mohamed studied the creep behavior of Al 2124/SiC composites prepared by powder metallurgy. It was concluded that SiC particles are not directly responsible for the threshold stress behavior in the composite (Li & Mohamed, 1997).

Various attempts have been made to strengthen Al/SiC composites, including unconventional approaches. For instance, Tham et. al. proposed a strengthening approach in which the phase Al_4C_3 is made to form intentionally at the Al/SiC interface, varying the contact time between the SiC particles and the molten aluminum alloy during processing. A layer of aluminum carbide was found to increase the composite yield strength, ultimate tensile strength, work hardening rate, and work-to-fracture, and change the fracture pattern from one involving interfacial decohesion to one where particle breakage was dominant. These changes were attributed to a stronger interface bond, which is thought to result from the tendency of the Al_4C_3 reaction layer to form semicoherent interfaces and orientation relationships with the aluminum matrix and SiC particles and for it to be mechanically keyed-in to both phases. The stronger interface bond also enhanced the levels of plastic constraint which, when coupled with the greater work-hardening, promoted local matrix failure, thereby reducing the composite ductility (Tham et. al., 2001).

The deformation behavior below 0.2% offset yield stress in 2024 Al/SiC_p composites and its unreinforced matrix were investigated experimentally under three heat treatment conditions by Zhang et.al. In the case of annealing, incorporation of SiC particles into aluminum matrix can enhance the plastic flow stress (PFS) in the macroplastic stage, but almost has no effect on PFS in the microplastic stage, suggesting that the strengthening led by the SiC particulate is more effective in a larger stress (or strain) region. Quenching treatment would increase PFS in the microplastic both in micro- and microplastic stages for the unreinforced 2024 Al alloy while slightly lower PFS in the microplastic stage for the composite. Quenching followed by artificial aging shows the highest PFS both in the micro- and macroplastic stages for both materials, implying that like the conventional yield strength PFS in microplastic stage of the composite is also strongly controlled by the precipitates formed in the matrix during aging treatment. The results were attributed to the microstructure features such as the residual thermal stresses, dislocation density and matrix hardness (Zhang et. al., 2001).

The mechanical properties are also affected by processing type, like the extrusion and aging, with the net effect related to the production of dislocations. For instance, the effect of extrusion and sintering temperature on the mechanical properties of SiC/Al-Cu composites was discussed by C. Sun and co-workers (Sun et. al., 2011). The extrusion and increase of the sintering temperature can break up the oxide coating on the matrix powder surfaces, decrease the number of pores, accelerate the elements' diffusion and increase the density and particle interfacial bonding strength, thus significantly improving the mechanical properties of the composite. During aging, new precipitates nucleate and grow from the supersaturated matrix. The increase in the strength and decrease in the elongation at the under-aged stage are due to the increase in the volume fraction of the precipitates. A high number of volume-fractioned precipitates will effectively inhibit the movement of

dislocations, generate more geometrically necessary dislocations and reach the critical dislocation density for fracture earlier during deformation, and thus increase the strength and decrease the elongation.

It is well established that the volume fraction of reinforcement affects the mechanical and thermal properties of the metal matrix composites. Al MMCs with high volume fractions (40 > V_f < 70 %) are typically produced when high hardness and stiffness are sought after. This type of composites is usually produced by the infiltration technique. Composites with Young's modulus as high as 225 GPa and 405 MPa flexure strength were produced by Cui (Y. Cui, 2003) using the pressureless infiltration method. Sahin & Acilar studied the effect of SiC_p volume fraction on the physical properties and hardness of Al/SiC_p composites. Composites were produced by the vacuum infiltration technique using an alloy Al-9.42 %Si-0.36 % Mg (wt. %) and up to 55 vol. % SiC. Results showed that hardness and density of the composite increased with increasing load and increasing particle content (Sahin & Acilar, 2003). A different approach was used within the research group of the author in an endeavor to increase the Al/SiC composite's hardness (Montoya-Dávila et. al., 2007). The alloy Al–15.52 Mg–13.62 Si (wt. %) was employed to prepare composites in argon followed by nitrogen at 1100 °C for 60 min. The use of preforms with monomodal, bimodal and trimodal distribution of SiC particulates resulted in an increase of hardness with increase in the reinforcement particle size distribution. Superficial hardness behavior was explained by the combined effect of work-hardening in the alloy matrix and particle-to-particle impingement. As for hardness increase, a demonstrated and successful approach consists of the use of heat treatments, reviewed in the next section.

2.3 Heat treatments (solution and age-hardening)

In order to comply with the requirements for some specific applications, metals are not used as pure materials in the as-cast conditions, and aluminum is not the exception. The precipitation-strengthening (hardening) process is used to increase the strength of many aluminum and other metal alloys. The object of precipitation strengthening is to create in a heat treated alloy a dense and fine dispersion of precipitates in a matrix of deformable metal. The precipitate particles act as obstacles to dislocation movement and thereby strengthen the heat-treated alloy. The precipitation-strengthening process involves three basic steps: 1. Solution heat treatment, 2. Quenching, and 3. Aging (natural or artificial).

One prominent characteristic of age hardening is that the precipitate is *coherent* with the matrix, implying that certain matrix planes match specific planes of the precipitate quite closely in atom spacing and are continuous throughout the precipitate. This small difference in spacing produces a strain field around the precipitate particle, which causes blocking of dislocations for some distance from the actual precipitate. Usually the strain field can exist only while the precipitate is small. Precipitation hardening is commonly employed with high strength aluminum alloys. Although a large number of these alloys have different proportions and combination of alloying elements, the mechanism of hardening has perhaps been studied most extensively for the aluminum-copper alloys (Callister, 1997).

If many aluminum alloys are prone to age hardening and if those alloys are used for the manufacture of Al/SiC composites, then it is reasonable to think that precipitation-strengthening (hardening) processes might also occur in the composites, but with a slightly (or considerably) different mechanism due to the presence of the SiC reinforcement. One foreseeable difference is the solution treatment and/or aging response between the unreinforced alloy and the composite, including aging kinetics and peak hardness. In this particular discussion, it is postulated that the mechanism in the composites might be

influenced by one or more of the following factors: alloy composition, morphology, volume fraction, particle size and properties (physiochemical and thermal) of the reinforcements, and finally, the fabrication route and heat treatment given to the composites. Most of the work done is concerned with heat treatment parameters and alloy chemistry.

It is generally accepted that aging treatment can significantly increase the properties of some aluminum alloys and their respective composites, especially those alloys of the series 2xxx and 6xxx. However, some discrepancies are observed in the literature, because while some authors propose that the addition of reinforcing particles accelerates the aging kinetics, others suggest that it decreases or marginally affects it (Mosuavi & Seyed, 2010). As a result, the accelerated aging phenomenon aroused the interest of various researchers, stimulating both, theoretical and experimental studies to explain the operative mechanism.

For instance, Dutta & Bourell expounded that accelerated aging in metal matrix composites (MMCs) can be attributed to an increase in dislocation density in the vicinity of the reinforcements or to the matrix residual stress field near reinforcements (Dutta & Bourell, 1989). Both mechanisms aid the diffusion of solute atoms, thereby leading to more rapid precipitation. They studied experimentally the precipitation behavior of aluminum 6061 alloy reinforced with 10 vol. % SiC whiskers of variable aspect ratio and compared results with the precipitation behavior of a control aluminum alloy 6061 in the unstrained and plastically strained conditions. It was found that the strained control alloy, with approximately the same expanded plastic work as the composite, showed a similar β' precipitation rate and activation energy as the composite. On the contrary, the unstrained alloy had a much higher activation energy for precipitation. A theoretical model was developed to predict the rate of precipitation in the residual stress field of the matrix. This rate was compared with the rate of precipitation on a regular edge dislocation array. It was found that for realistic values of fiber radii and dislocation densities (about 0.25-1 μm and 10^{13}-10^{14} m^{-2}, respectively), both mechanisms give comparable precipitation rates. However, solute atoms flowing towards the matrix-fiber interface under the influence of residual stress field on encountering matrix dislocations are trapped, thereby lowering the activation energy to that of precipitation on dislocations. It was concluded that for MMCs with large fibers and high dislocation densities, dislocation generation is the principal contribution to accelerated aging while, in MMCs with small fibers and low dislocation densities, the residual stress mechanism predominates. For intermediate fiber radii and dislocation densities, both mechanisms could be important although, in real MMCs, dislocations seem to play the dominant role (Dutta & Bourell, 1989). Similar results were reported later on by Borrego and co-workers using the 6061 aluminum alloy, but with 15 vol. % SiC whiskers (Borrego et. al., 1996). They found that accelerated aging in composite materials with respect to the unreinforced alloy is more accentuated with increasing temperature, and attributed this behavior to the increasing dislocation density with extrusion temperature. The dislocation density of composites was calculated from the τ_{peak} values, observing that as the extrusion temperature goes up the dislocation density increases. This increment also accounts for the increasing hardness of the composite. It was suggested that the principal hardening mechanism of the composites is due to the residual dislocations (Taylor). Other contributions due to grain/subgrain structure (Petch/Hall), particle strengthening (Orowan) and/or initial work hardening would represent a factor of 0.3 (or smaller) that due to the residual dislocations (Borrego et. al., 1996). In a study conducted using the 2024 Al alloy in Al/SiC$_p$ composites, it was found that the presence of SiC particles led to increasing the peak hardness of the alloy. The aging behavior of the 2024 Al alloy and its composite reinforced with 20 vol. % SiC particles was studied after solution treatment at

495 °C for 1-3 h. The suitable solution treatment time was about 2 h for both, the unreinforced alloy and the composite that leads to the fastest aging kinetics and the maximum hardness. The composite reached its peak hardness in shorter time compared with the unreinforced alloy on solution treatment for 2 and 3 h, but reached it in longer time on solution heat treatment for 1 h (Mosuavi & Seyed, 2010). Using the same alloy type, 2124, Thomas and King studied the formation of phases during precipitation by differential scanning calorimetry (DSC) (Thomas & King, 1994).

Although most of the studies on precipitation hardening in aluminum alloys are related to the intermetallic phase Mg_2Si, not in all studies the precipitates responsible for age hardening correspond to Mg_2Si, as reported by Cottu et. al., who identified rod-shape precipitates (atomic ratio Mg/Si= 1) with chemical composition not consistent with Mg_2Si stoichiometry (Cottu et. al., 1992). They showed that age-hardening kinetics of Al-Cu-Mg alloy 10 wt. % SiC fiber composite was enhanced by the presence of the reinforcement during a T6 heat treatment, attributed to the plastic deformation induced during heat treatment due to the difference between coefficients of thermal expansion (CTE) of matrix and reinforcement. In addition to the works by Dutta & Bourell, and Guo & Yuan, Cottu et. el., (Cottu, et. al., 1992) concluded that the hardening kinetics is enhanced by the SiC reinforcement due to the fact that precipitation preferentially develops on dislocation lines. In a study with composites with the aluminum alloy AS7G06 reinforced with chopped SiC fibers (about 10-15 μm diameter and 3-6 mm long), they found that the high-temperature deformation strongly increases the precipitation rate as the material is reinforced.

In summary, several factors are expected to affect the aging behavior of Al/SiC composites, in addition to aluminum alloy composition. They include fabrication route and processing parameters comprising temperature, time, atmosphere, as well as SiC reinforcement size and shape. In the case of fibers, it has been reported that the length and radii play a significant role in the age hardening mechanism (Dutta & Bourell, 1989). Incorporation of a different phase also may play a significant role, like that observed in SiC/Gr/6013Al composites. In the work of Guo and Yuan (Guo & Yuan, 2009) it was reported that the aging behavior of the composites is similar to that of the 6013Al showing two peak hardness during artificial aging at 191 °C. The composite reaches its peak hardness in shorter time and exhibits a smaller increase of hardness. Moreover, during natural aging, the composite reaches stable hardness in longer time than does the matrix alloy, with lower increase of hardness. There was evidence that low fractions of graphite powders affect the aging behavior and mechanical properties of aluminum matrix composites with SiC particulate reinforcements.

Investigations comparing the effect of different aluminum alloys are scarce. It was recently stated that there is still a lack of information regarding the aging behavior of Al alloys and their corresponding composites (Mosuavi & Seyed, 2010). The author's research group is currently focused on studying the effect of silicon in the alloy (Al- 10.33 Si- 17.75 Mg *vs.* Al-21.85 Si- 16.21 Mg, wt. %) on the solution treatment and artificial age hardening of Al/SiC composites. SiC was protected with SiO_2 coatings. Preliminary results suggest that with the high Si alloy, hardness increases, but the peak hardness is not as sensitive – as in the alloy with low Si level – to aging time. With the latter, peak hardness was attained in aging for 3 h at 170 °C, after a solution treatment at 350 °C for 3 h.

2.4 Corrosion behavior

Numerous investigations have been devoted to the study of the corrosion behavior of Al/SiC composites (Ahmad et. al., 2000; Aylor & Moran, 1985; Candan & Bilgic, 2004;

Hihara & Latanison 1992; Pardo et. al., 2003; Pardo et. al., 2005; Kiourtsidis et. al. 1999; Shin et. al., 1997; Trzaskoma, 1990; Wei et. al., 1998). Several factors are known to affect the corrosion behavior of SiC-reinforced composites of aluminum alloys, namely, alloy composition, SiC physicochemical characteristics and volume fraction, and processing route. Factors related to processing are: porosity, the presence of intermetallic phases within the matrix, and the formation of reaction products at the interface between the metallic matrix and the reinforcing phases. The size and shape of the SiC reinforcement is also of great importance, as fine particles and short/thin fibers are more prone to the dissolution.

The intermetallic phases can already be present in the raw aluminum alloy or can be formed in situ during processing of the composite. For that reason, the corrosion behavior of the composites cannot be inferred directly from the response of their respective aluminum alloys. Both, in the aluminum alloy (before composite's processing) and in the composites, the intermetallic phases can form galvanic couples with the matrix or between them, and make the composites susceptible of corrosion. If the composites are manufactured with different aluminum alloys, then each type of Alloy/SiC system would require its own corrosion study. Magnesium silicide (Mg_2Si) is one of the intermetallics that play a dominant role in the corrosion behavior of the composites (Escalera-Lozano et. al., 2010). On the other hand, several corrosion parameters (pitting corrosion, corrosion potential, passivation potential, etc.) can be evaluated in the different studies using various experimental techniques (potentiodynamic polarization, double cyclic polarization, etc.).

Pitting corrosion is believed to be one of the main mechanisms for damage of high-strength aluminum alloys, and usually it initiates by the breakdown of the passive film of the metal surface. Accordingly, the effect of reinforcement on the pitting behavior of aluminum-base metal matrix composites was studied earlier (Aylor & Moran, 1985). Aylor & Moran studied the effect of processing type on the corrosion behavior, utilizing different 6061 Al processing forms (wrought vs. powder metallurgy) and SiC/Al composite heat-treating (as-fabricated vs T-6 temper). It was observed that processing type does not affect the anodic polarization characteristics of SiC/Al and Al and that the presence of SiC in the 6061 Al matrix does not alter the corrosion potential in aerated ocean water. Moreover, SiC does not increase the pitting susceptibility of the Al/SiC composite. The morphology and extent of pitting differs between the SiC/Al and Al materials. SiC/Al composites exhibit pitting concentrated predominantly at the SiC/Al interfaces, with the pitting being greater in number, smaller in size and more shallow in penetration depth, relative to the unreinforced aluminum alloys. The electrochemical behavior of Al/SiC composites was essentially identical to that of the powder metallurgy processed and wrought aluminum alloys; however, the pitting attack on the composites was distributed more uniformly across the surface, and the pits penetrated to significantly less depth. Pit morphology of aluminum alloy and Al/SiC composites was studied by Trzaskoma. Pit morphology of Al 5456 (UNS A95456), Al 6061 (UNS A6061), SiC_w/Al 5456, and SiC_w/Al 6061 was studied in order to compare pitting process of SiC_w/Al metal matrix composites and that corresponding unreinforced alloys. Pits on the composites are significantly more numerous, shallow, and widespread than on the monolithic materials. Studies of pit structure suggest that there are two stages in pit development. The first involves the initial dissolution of metal atoms and opening of the pit, and the second involves pit enlargement or growth. For both materials, pits initiate at secondary particles within the metal matrix. In the case of Al 5456 and SiC_w/Al 5456, it is shown that these particles are intermetallic phases composed of alloying elements Mg, Cr, Mn, and Al, as well as Fe, which is an impurity of the metal. Under equivalent conditions of

preparation and processing, a greater number of intermetallic phases form in the composite than the alloy and hence the composite has more pit initiation sites (Trzaskoma, 1990).

In a study of the influence of reinforcement proportion and matrix composition on the corrosion resistance of cast aluminum matrix composites (A3xx.x/SiC$_p$) in a humid environment, Pardo and co-workers found that the corrosion process was influenced more by the concentration of the alloy elements than by the proportion of the SiC particles (Pardo et. al., 2003). Later on, they confirmed this observation, but investigating the influence of reinforcement grade and matrix composition on pitting corrosion behavior of the same type of composites, using the potentiodynamic polarization technique and four aluminum alloys. The corrosion damage was caused by pitting attack and by nucleation and growth of $Al_2O_3.3H_2O$ on the material surface (Pardo et. al., 2005).

In a study using Al-4 Mg alloy matrix, Candan and Bilgic investigated the corrosion behavior of Al-60 vol.%/SiC in NaCl solution. Experimental results revealed that precipitation of Mg_2Si as a result of the reaction between the Al-Mg alloy and the SiC particles has a beneficial effect on corrosion resistance of Al-4Mg alloy matrix due to the interruption of the continuity of the matrix channels within the pressure infiltrated composite (Candan & Bilgic, 2004). Hihara and Latanison, studied the galvanic corrosion of aluminum matrix composites using ultrapure Al and 6061-T6 electrodes to study the galvanic corrosion current density (CD) of Al-matrix composites. Results indicated that the galvanic corrosion rate of Al is approximately 30 times less when coupled to SiC. Oxygen reduction was the primary cathodic reaction in the aerated solutions. In deaerated 0.5 M Na_2SO_4 and 3.15 wt.% NaCl, galvanic corrosion was negligible (Hihara & Latanison 1992).

Using the double cycle polarization technique Kiourtsidis et. al., conducted a study on the pitting behavior of AA2024/SiC$_p$ composite and found that pitting potential is unaffected by the presence and volume fraction of SiC particles in the composites (Kiourtsidis et. al. 1999).

In a different study, using four alloys (6013, 6061, 5456 and 2024 with heat treatments (T4 and T6)), it has been shown that pit initiation is dependent on the alloy type and heat treatment. Further, microscopic observations show that pit initiation sites are correlated with secondary phase particles, suggesting that secondary phases, rather than SiC particles, contribute to the pitting behavior of the composites (Ahmad et. el., 2000).

Related studies by the author's research group – using the Scanning electrochemical microscopy (SECM) technique in composites processed with the alloy Al-13.5% Si-9% Mg – allowed determining that SiC particles are electrochemically active (Díaz-Ballote, et. al., 2004). The data suggested that the electronic conductivity at these sites is higher than that of the Al_2O_3 film covering the alloy matrix surface. *In situ* SECM images of samples and current *vs.* tip-substrate distance curves were used to investigate the reduction of dissolved oxygen on the silicon carbide particles. Results with samples of SiCp/Al composites immersed in distilled water alone or in either 0.1 M NaCl or boric acid/borax buffer containing ferrocenemethanol as mediator demonstrate that the SiC particles are conductive and act as local cathodes for the reduction of oxygen. More recently, within the same group, the electrochemical behavior of the passive film of an alloy of the same type (Al–17Si–14Mg) was studied in anodic polarization tests and compared to that for pure Al. Results showed that for the alloy, the passive current density increased but the pitting susceptibility decreased. The first effect was ascribed to a significant electrochemical activity of the Mg_2Si intermetallics and the second to improved stability of the oxide film. X-ray photoelectron spectroscopy (XPS) analysis of potentiostatically formed passive film on the alloy showed that it consisted of aluminum oxyhydroxide with incorporation of silicon in its elemental

and two oxidized states (+3 and +4). Mott–Schottky analysis showed that trivalent silicon ion acted as an n-type dopant in the film (Coral-Escobar et. al., 2010).

Regarding the role of secondary phases, it has been reported that particles that contain Al, Cu and Mg tend to be anodic relative to the alloy matrix, while those that contain Al, Cu, Fe and Mn tend to be cathodic relative to the matrix (Wei et. al., 1998). It is generally accepted that Mg_2Si tends to be anodic with respect to the matrix and can act as initiation sites for corrosion. It is believed that this phase dissolves leaving behind a cavity, which can act as a nucleation site for pitting. Accordingly, a study of the role of Mg_2Si in the electrochemical behavior of Al-Si-Mg aluminum alloys was undertaken by the author´s group, using four experimental aluminum alloys with variations in the Si/Mg molar ratio (A1-0.12, A2-0.49, A3-0.89, A4-1.05)(Escalera-Lozano et. al., 2010). The corrosion potential in open circuit (Eoc) and polarization resistance (Rp) were measured. Results show that the augment in Si/Mg molar ratio increases the presence of Mg_2Si intermetallic phase. During immersion tests in neutral aerated chloride solutions the anodic activity of the Mg_2Si intermetallic decreased rapidly, as indicated by a fast ennoblement of open circuit potential. After the immersion period (7 days), higher Rp values for alloys A3 and A4 (21 and 26 KΩcm², respectively) as compared to those for alloys A1 and A2 (5 and 10 KΩcm², respectively), suggest a greater corrosion resistance in Cl- containing environments for alloys A3 and A4. Another major form of degradation of Al/SiC composites is via chemical corrosion, attributed to the aluminum carbide (Al_4C_3) phase, formed by the dissolution of the SiC reinforcement during processing with aluminum in liquid state. A study of the effect of processing methods on the formation of Al_4C_3 in Al 2024/SiC_p composites has been conducted by Shin et. al. (Shin et. al., 1997). In another recent investigation, the author´s group focused on the role of Al_4C_3 in the corrosion characteristics of Al-Si-Mg/SiCp composites with varying Si/Mg molar ratio in neutral chloride solutions (Escalera-Lozano et. al, 2009). Immersion tests in aerated 0.1 M NaCl showed that for composites with Si/Mg molar ratios of 0.12 and 0.49, chemical degradation by hydrolysis of Al_4C_3 was followed by intense anodic dissolution at the matrix reinforcement interface, while composites corresponding to Si/Mg molar ratios of 0.89 and 1.05 did not exhibit intense localized attack.

3. Conclusion

With all the valuable research work conducted thus far in the field, there can be no denying that aluminum plays a pivotal role in the development of composite materials reinforced with SiC. And perhaps, amongst all the Al/reinforcement systems, the Al-SiC one has become a benchmark. It turns out that alloy composition influences the processing route to be employed as well as the mechanical, heat-treatment and corrosion behavior of the composites. The use of aluminum in liquid state has serious implications because attack of SiC and the subsequent phenomena do compromise the integrity of the composite. In this regard, since the aluminum-matrix/reinforcement interface plays a critical role in transferring the load from the matrix to the reinforcing phase, the soundness of the interface is always a crucial aspect to take care of. What's more, wettability studies aimed at optimizing processing conditions are always wise. From heat treatment investigations, there is a consensus in that SiC in aluminum leads to an accelerated age hardening, compared to the unreinforced alloy. Being pitting one of the major concerns in the corrosion behavior of Al/SiC composites, the confluence of results suggest that in the composites, pitting is greater in number, smaller in size and shallower in penetration depth, relative to the

unreinforced aluminum alloys. Since pits initiate at secondary particles within the metal matrix, and as a greater number of intermetallic phases form in the composites, these have more pit initiation sites. It is suggested from this discussion that corrosion tests should precede mechanical evaluation involving hardness, creep and fatigue and fracture studies. A thoughtful consideration of the abovementioned factors and response variables involved increases the likelihood for Al/SiC composites to achieve their full potential in a safe and cost-effective way.

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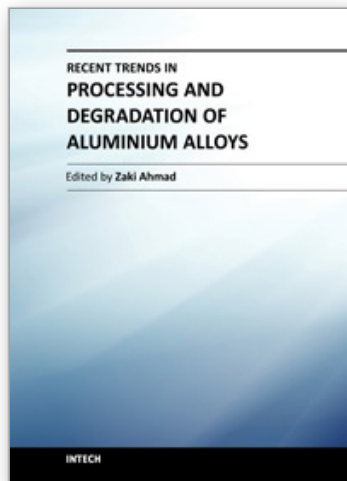
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