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PROPERTIES OF ALUMINIUM/ELECTROLESS Ni-COATED SiC COMPOSITES - A REVIEW

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ABSTRACT

The combination of properties of Al/SiC composites make them very attractive materials for applications in automotive and aerospace industries. Several techniques are used in developing Al/SiC composites but stir casting process is most commonly used because it is the simplest and cost effective technique. However, composites produced via stir casting suffer from limitations such as low wettability and inadequate bonding between the molten Al & SiC particulates and the formation of degrading interfacial products like aluminum carbide (Al_4C_3) which degrades the mechanical properties of the composite. Some of the techniques to improve Al-SiC wettability include addition of surface active elements such as magnesium, heat treatment of particles and application of metallic coating on the reinforcements before addition to the melt. Wetting agents alter the composition of the matrix alloy, while heat treatment of the reinforcement does not completely prevent the formation of Al_4C_3 when utilized. To reduce the direct interaction and promote wetting between reinforcements and molten aluminum during processing, the surface of SiC particulates can be modified by coating via oxidation, sol-gel and electroless processes. Of all these methods, electroless nickel deposition produces the best coatings with uniform thickness and adequate strength. In the present study, influence of electroless nickel-coating of SiC on the mechanical, corrosion and microstructural properties of Al/SiC composite has been evaluated. Finally, it can be concluded that the Ni and Ni_3P intermetallic phases produced via electroless coating improves the wettability between the SiC and molten aluminium leading to enhanced properties of the composite.

Keywords: Aluminium, silicon carbide, electroless nickel, coating, composites.

INTRODUCTION

Aluminium alloys have been the primary material of choice for structural components over the years (Abdulwahab *et al.*, 2016) but these aluminium alloys fail to meet the rising demand for high performance structural applications due to their low strength and low wear resistance properties (Moses *et al.*, 2016). In the last few decades, the use of ceramic particles in the strengthening of aluminium has gained significant attention by researchers (Alten *et al.*, 2019). Ceramic particulates like SiC, B_4C, TiC, WC, ZrO_2 and Al_2O_3 are the most commonly used reinforcements to fabricate aluminium matrix composites (Nagaral *et al.*, 2016).

Silicon carbide (SiC) is among the most commonly used ceramic material for composite reinforcement. Its usage is due to its excellent thermal properties, high modulus and strength, good corrosion resistance, low cost, availability and suitable compatibility with aluminium alloys. They have emerged the most preferred materials for composite production (as indicated in Figure 1) because they have superior plastic forming capability than that of the whisker or fibre reinforced composites. They are as well identified for excellent heat and wear resistance applications (Adebisi *et al.*, 2016).

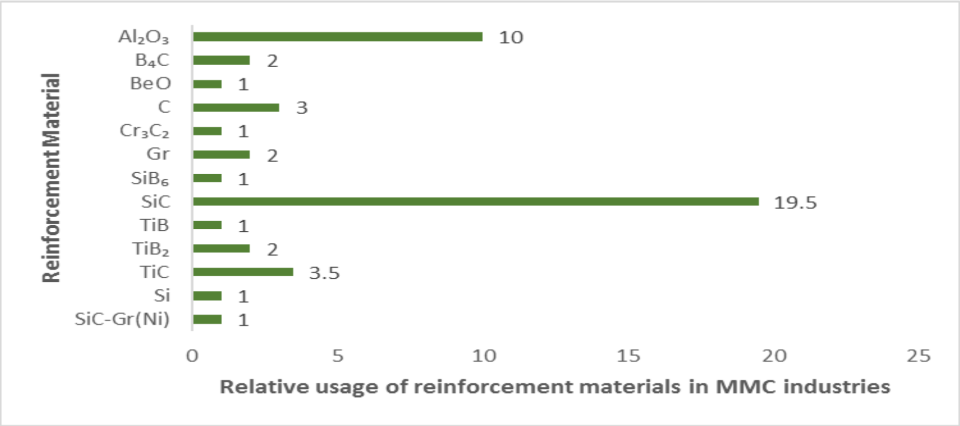


Figure 1: Industrial usage of reinforcement materials (Evans *et al.*, 2013)

Aluminium matrix composites reinforced with ceramics have improved resistance to wear, superior strength and lower coefficient of thermal expansion compared to monolithic aluminium alloys when used for the production of brake drums, cylinder liners, pistons, cylinder blocks, connecting rods, etc. and this has increased its usage in the automotive, military, aerospace and electrical industries (Rao & Das, 2011; Bharath *et al.*, 2014 and Moses *et al.*, 2016).

Many techniques are available for the fabrication of aluminium matrix composites (AMCs) such as spray deposition, powder metallurgy, infiltration technique, squeeze casting and stir casting. The powder metallurgy processing method cannot be used for bulk production of large and complex structural AMCs components because the process is time-consuming, expensive and energy intensive. Stir casting is one of the most commonly used method instead due to its simplicity, ease of production of complex casting, mass production possibility and it is an economical process (Nagaral *et al.*, 2016; Ramesh *et al.*, 2010). However, it is reported that poor wettability of hard ceramic particles such as silicon carbide particles (SiCp) in molten aluminium alloys poses a limitation in the development of metal-ceramic reinforced composites (Ramesh *et al*., 2010).

The poor wetting of SiC ceramic particles by the molten aluminium matrix could be attributed to inadequate interfacial contact, poor interfacial reaction and weak bonding between the matrix and the reinforcement (Hashim *et al.*, 2001; Xie *et al.*, 2019). These effects lead to uneven dispersion of the SiC ceramic particles in the molten aluminium matrix, lower mechanical properties of the developed composites and high porosity in the composite (Kumar *et al.*, 2016).

Effective treatments such as preheating the ceramic particles, adding some surface active elements such as magnesium and coating of the ceramic particles prior to addition into the molten matrix are some ways of improving the wettability and making the mixing and retention of the ceramics particles easier (Sahoo and Das, 2019; Xie *et al.*, 2019). Among these treatments, coating of the ceramic reinforcement using a simple, low-cost and easy to use electroless nickel (EN) process has been successfully applied to promote the wettability and prevent undesired interfacial reactions by increasing the overall surface energy of the reinforcement (Dikici *et al.*, 2011; Khosroshahi *et al.*, 2014).

In the present study, a review of the influence of electroless nickel coating of SiC on the mechanical, corrosion and microstructural properties of Al/SiC composite is evaluated. This review will make a brief discussion on electroless coating, components of electroless nickel plating bath, electroless nickel coating of ceramic particles, aluminium matrix composite reinforced with electroless Ni-coated SiC particles, influence of Ni-coated SiC particles on the mechanical and corrosion of AMCs and finally, the microstructure of AMCs reinforced with Ni-coated SiC particles.

ELECTROLESS NICKEL (EN) COATING

In 1946, Brenner and Riddel developed the electroless coating technology by successfully depositing a metallic coating on a surface via aqueous solution without the passage of electric current through the solution (Agarwala and Agarwala, 2003). Since then, electroless coating has been actively used in applications where the adjustments of mechanical (hardness), tribological (wear, friction), chemical (corrosion, permeation, temperature insulation, biocompatibility, wettability) and electrical (conductivity) properties of surfaces are required (Bewilogua *et al.*, 2009). Electrically conductive materials as well as fabrics and insulators like ceramics, plastics, rubber etc. can be coated using this process (Kundu *et al.*, 2014; Faraji *et al.*, 2015). Extended properties of electroless nickel coatings and the primary uses of electroless deposition are shown in Table 1 and Figure 2 respectively.

Electroless plating process is also called autocatalytic deposition. Uniform coatings onto catalytic surfaces regardless of the complexity of shape of the components are achieved through this process. Once a primary layer of metal has been formed on the substrate, that layer of metal as well as each subsequent layer becomes the catalyst that causes the deposition to continue.

Table 1: Properties of electroless nickel coatings (Sahoo and Das, 2011).

Feature	Benefit
Excellent corrosion resistant	Good coating durability
High hardness	Low wear characteristics
Low friction co-deposits available	Self-lubricating coating
Deposit uniformity	Eliminates post plate finish
Good brightness	Attractive finish
Fast plating rate	High production output
Good chemical resistance	Acts as protective coating
Solderability/weldability/brazeability	Functional in many applications
Non-magnetic/magnetic	Magnetic property selectivity

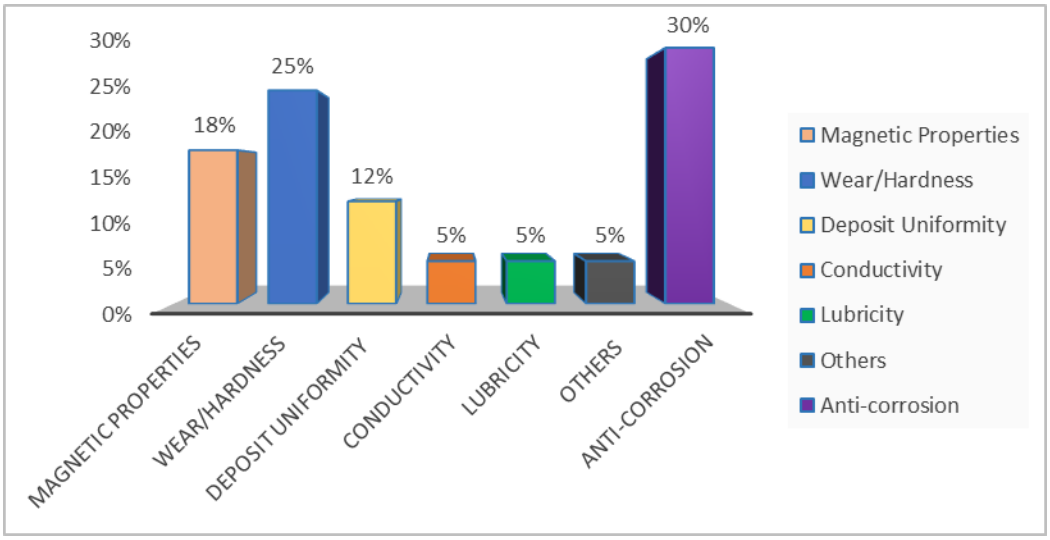


Figure 2: Primary uses for electroless nickel deposits (Sahoo and Das, 2011).

Electroless plating in contrast to conventional electrolytic plating, does not require the use external electric current to produce deposit on a substrate. Deposition is a chemical process which occurs in an aqueous bath which can either be acidic or alkaline depending on the pH and temperature of the bath (Bestetti and Da Forno, 2013).

In the aqueous bath, the process requires the metal to be deposited to be reduced onto the surface of the substrate by receiving electrons from the surface of the metal substrate or from the surface of the catalysts used to initiate the deposition. The reductant in turn delivers electrons to this surface and is thereby oxidized. (Kundu *et al.*, 2013). Even though it may be similar to immersion plating since they are both chemical deposition process, electroless coating differs from immersion plating with which a base material is coated by the reduction of metallic ions from a solution onto its surface after the base material has been dissolved in it. That mechanism differs from autocatalytic deposition because it does not require reducing agents to convert metal ions to metal as the base material acts as a reducing agent, and these processes have not gained widespread acceptance due to poor plating adherence and properties (Sudagar *et al.*, 2013).

The electroless coating process is used to deposit a variety of metals, including nickel, copper, gold, silver, cobalt, and palladium, but nickel is the most commonly deposited element (DiGiampaolo *et al.*, 1997). During electroless nickel coating process, phosphorus may be co-deposited alongside nickel (Ni-P) and the phosphorus content may range from 2 to 14% depending on the reducing agent and the type of bath (acid or alkaline) used for the deposition (DiBari and Stapleton, 1998). The novelty of electroless coating process is in its ability to coat irregularly shaped objects, holes or the inside of tubes regardless of size with a deposit of uniform thickness (Bello *et al.*, 2015).

Agarwala and Agarwala, (2003); Sahoo and Das, (2011) and Sudagar *et al.* (2013) outlined that there are four major types of electroless nickel coatings, as described below:

1. Coatings of pure nickel and black nickel.
2. Coatings of nickel alloys.
    a. Ni–P alloy coatings with 3–5 % (Low), 6–9 % (Medium) and 10–14 % (High) phosphorus content in acid deposition baths.
    b. Ni–P alloy coatings in alkaline deposition bath.
    c. Ni–B alloy coatings with 0.1–2 % (Low), 2–5 % (Medium) and 5–10 % (High) boron content in acid deposition baths.
    d. Poly alloys and Ni–B alloy coatings in an alkaline bath.

3. Composite coatings. e.g, Ni-P-PTFE, Ni-P-Al_2O_3.
4. Nanocoatings.

COMPONENTS OF ELECTROLESS NICKEL PLATING BATH

The components of an electroless nickel plating bath includes, a source of metal ion, a reducing agent, a wetting agent, a buffering agent, a complexing agent, and a stabilizer. Operating conditions of the bath such temperature and pH are very important in EN plating (Faraji *et al.*, 2015).

Reducing Agent

Amino boranes, hydrazine, sodium borohydride and sodium hypophosphite are the reducing agents reported to have been used for electroless coatings but over 70 percent of electroless nickel deposits are reduced using sodium hypophosphite because of better process control, better corrosion resistance properties and lower cost. (Agarwala and Agarwala, 2003).

The chemical reactions that occur in hypophosphite reduced electroless nickel plating solutions have multiple deposition mechanisms proposed, but the most commonly accepted mechanisms, as illustrated by Sahoo and Das (2011) are:

I. Electrochemical mechanism, where nickel and hydrogen ions are reduced onto the catalytic surface as a result of the catalytic oxidation of the hypophosphite ions in the electroless bath. It is illustrated as thus;

$$H_2PO_2^- + H_2O \rightarrow H_2PO_3^- + 2H^+ + 2e^- \tag{1}$$

$$Ni^{2+} + 2e^- \rightarrow Ni \tag{2}$$

$$2H^+ + 2e^- \rightarrow H_2 \tag{3}$$

$$H_2PO_2^- + 2H^+ + e^- \rightarrow P + 2H_2O \tag{4}$$

II. Atomic hydrogen mechanism, where hypophosphite molecule is absorbed at the surface of a substrate as a result of the catalytic dehydrogenation of the hypophosphite molecule leading to the release of hydrogen atom. It is illustrated below:

$$H_2PO_2^- + H_2O \rightarrow HPO_3^{2-} + H^+2H_{ads} \tag{5}$$

$$2H_{ads} + Ni^{2+} \rightarrow Ni + 2H^+ \tag{6}$$

$$H_2PO_2 + H_{ads} \rightarrow H_2O + OH^- + P \tag{7}$$

The adsorbed active hydrogen, equation (6), then reduces nickel at the surface of the catalyst.

$$(H_2PO_2)^{2-} + H_2O \rightarrow H^+ + (HPO_3)^{2-} + H_2 \tag{8}$$

Stabilizers

These are substances added into the electroless plating bath to shield the catalytically active depositions from breakdown during electroless plating. They also increase the deposition rate and the brightness of the deposits when added in the adequate quantity (Sudagar *et al*, 2013).

Complexing Agent

These are compounds that are applied to regulate the reaction in the electroless bath so that reaction takes place only on the catalytic surface. They also prevent solution decomposition during the plating process. It also buffer the solution and retard the precipitation of nickel phosphite. Ammonia, hydroxides and carbonates are some of the common complexants (Sahoo and Das, 2011).

Temperature

The reaction mechanism that regulates the charge transfer to the substrate and the ionization process in the solution is initiated by temperature (Fajari *et al.*, 2015). It has considerable influence on the rate of the deposition process by increasing the rate of the process with its increase and attains a maximum deposition at about 92°C. Maintaining the pH of the solution at higher temperatures is very difficult, leading to the deterioration of the coating quality. (Agarwala and Agarwala, 2003). Acidic hypophosphite baths operate between 85 and 95 °C. The same is true for alkaline borohydride and hydrazine baths. Only a few alkaline to neutral hypophosphite baths are capable of operating over a wide range at temperatures from ambient up to 70 °C (Alten *et al.* 2019). A summary of the function of the components of electroless nickel plating bath is highlighted Table 2.

Table 2: Components of an Electroless Plating Bath and Their Functions (Sudagar *et al*, 2013).

COMPONENT	FUNCTION
Metal Ion	Source of Metal.
Reducing Agents	Reduces metal ions through the supply of electrons.
Complexants	Prevents the concentration of free metal ions from being too high.
Accelerators	Increases deposition by speeding up the reducing agent.
Stabilizers	Protects the bath from decomposition by shielding the catalytically active depositions.
Buffers	Stabilizes the pH for a long time.
pH Regulators	Regulates the pH of the solution.
Temperature	Supplies the needed energy for the deposition.

Electroless Nickel Coating of Ceramic Particles

The limitations in obtaining composite materials with excellent properties when SiC and other ceramic particles are used as reinforcement is due to poor wetting, unwanted interfacial reactions and weak interfacial bonding between the SiC particulates and the molten metal when the particles are dispersed into the metal matrix during fabrication (Zou *et al.*, 2006). Because of these limitations, an intermediate layer between the surface of the SiC particulates and the molten metal is needed to improve the cohesive properties of the interface. The development of metal-coated ceramic particles which are composite powders with a ceramic core and metallic shell have been reported to have improved wettability when compared to non-coated particles. They are also more suitable for processing composites at high temperatures where property degrading reactions can occur. In addition, the coated ceramic particles have better magnetic, chemical and electrical properties (Khosroshahi *et al.*, 2014). Electroless nickel deposition can be used to make metallic coatings on the surface of SiC and other ceramic particles so as to improve their wettability in composite fabrication (Kang *et al.*, 2002).

Nickel cannot be plated directly on the surface of SiC and other ceramic materials and plastics during electroless coating because they do not have conductive surfaces. In order for the SiC particles surface to become conductive, they are subjected to some pretreatment before electroless deposition (Pazman *et al.*, 2010). The pretreatment sequence includes cleaning with acetone, etching with hydrofluoric acid, sensitization with acidic solution of stannous chloride and then activation using acidic solution of palladium chloride. Electroless plating comes afterwards. The particles are rinsed multiple times with deionized water after each step (Davidson *et al.*, 2000). The complete details of the pretreatments as highlighted by Chen *et al.* (2003), Pazman *et al.* (2010), Khosroshahi et al. (2014) and Bello et al., (2015) are:

i. The SiC particles are cleaned with acetone for 15mins and then washed with distilled water.

ii. Micro-roughening (etching) of the SiC powder surfaces are achieved by dispersing the cleaned powder in a strong oxidizing acid solution containing 40 ml/L hydrofluoric acid (HF), 80 ml/L nitric acid (HNO_3), 2 g/L ammonium fluoride (NH_4F) and distilled water. The operation are carried out using the magnetic stirrer hot plate for 15 min at 25 °C.

iii. Sensitization is done by immersion of the cleaned SiCp into an aqueous solution containing 10g/L of stannous chloride ($SnCl_2$) and 30ml/L of concentrated hydrochloric acid (HCl) for 15mins. The SiCp are then washed with distilled water afterwards.

iv. After sensitization, activation of the SiC particles achieved by immersion of the sensitized SiC particles into the aqueous solution of 0.25 g/L palladium chloride ($PdCl_2$) and 3 ml/L concentrated HCl for 15 minutes. The particles are washed with distilled water and dried in air for 2 hours.

After the pretreatment is completed, the activated SiC particles are then coated by immersion into the electroless coating bath using the formulations given by Ramesh *et al.* (2010), Khosroshahi *et al*. (2014), Bello *et al.* (2015) and Alten *et al.* (2019). The flow chart of the pretreatment processes for electroless Ni-P coating for ceramics is shown in Figure 3.

One of the major problems encountered during the pretreatment is the high cost of palladium chloride which is needed to activate the surface of the substrate before initiating the electroless process and to enhance adequate bonding between the coating and the substrate. This has led to more researches on palladium-free electroless plating in recent years (Nobari *et al.*, 2016). Pazman *et al*. (2010) coated SiC particles using electroless nickel after three different surface pretreatment methods (acidic pre-treatment, palladium chloride activation and surface oxidation) were utilized and observed that the palladium chloride activated pretreated particles had strongest bond between the SiC particles and the Ni coatings, while the acidic pretreated particles had the lowest adhesion.

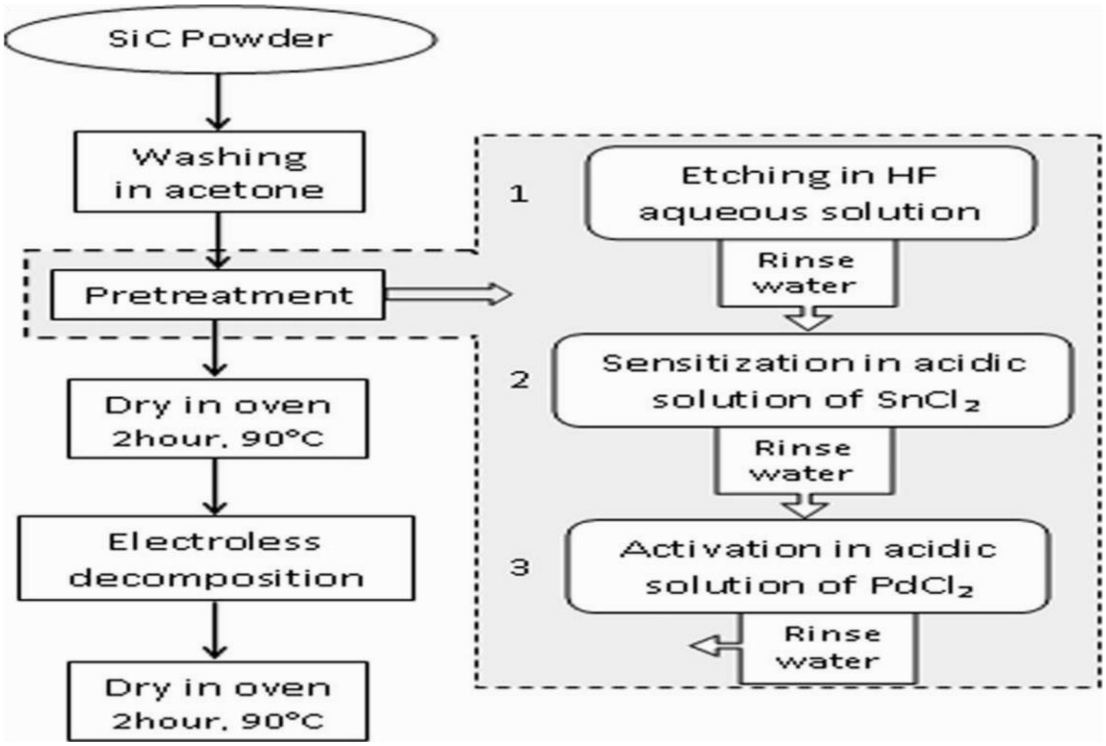


Figure 3: Flow chart of electroless Ni–P coating procedure of SiC particles (Khosroshahi *et al.*, 2014).

After successfully activating a catalytic layer on the surface of the SiC or other ceramic particles, researchers have investigated and documented their observation on EN coating of SiC and other ceramic particles. Sateesh *et al.*, (2015) studied the interface influence of Ni-P coated SiC as reinforcements in metal matrix composite development via Direct Metal Laser Sintering (DMLS) additive manufacturing process. They reported complete encapsulation of the irregular shaped SiC particles by Ni-P coating with a thickness of 1 to 2 µm. The surface morphology of coated SiC particles were observed to be more spherical and smoother than the uncoated SiC particles.

Khosroshahi *et al.* (2014) coated SiC particles of 80 µm and 10 µm using electroless Ni-P coating and reported that the SiC particles with average particle size of 80 µm had better coating uniformity and mechanical bonding than those of 10 µm.

Dikici *et al.* (2011) observed that the electroless nickel coating of homogenous and uniform thickness of about 1 µm was deposited on SiC particles used as reinforcement for aluminium matrix composite production via squeeze casting.

Pazman *et al.* (2010) subjected SiC particles to electroless nickel deposition using three independent pretreatment methods to evaluate which gives the best deposition. The EN plated SiC particles were used as reinforcements to produce Al/SiC composites by compression and sintering. Different Al-Ni phases were observed at the Al/SiC interface of the composites. The quantity of Al_3Ni_2, Al_3Ni, $AlNi_3$ intermetallic phases was low but the AlNi phase (> 5%) was an indication of higher nickel content in composite as a result of pretreatment of the SiC using palladium chloride.

Zou *et al.* (2006) performed a low temperature electroless-plating surface modification on SiC particles and reported the formation of agglomerated nickel coating on the SiCp. Also, improved dielectric loss and dielectric permittivity of the nickel-coated SiCp were observed when compared to the uncoated SiCp.

Leon and Drew (2000) coated alumina and silicon carbide particles using electroless coating process and utilized the coated particles as reinforcements in composite production. The final composition of the deposited metallic nickel on the particles was at 8 – 21wt%, while that of the phosphorus was 1.6 - 1.9wt%. XRD analysis of the coated particles showed that the Ni-P deposit was initially amorphous which was later transformed into crystalline structures of Ni and Ni_3P after the coated particles were heat treated. The surface morphologies of Ni-coated and uncoated SiC powders are shown in Figure 4. While the as-received powders show a clean, deposit-free surface (Figure 4a), the plated powders show a uniformly distributed nickel coating (Figure 4b).

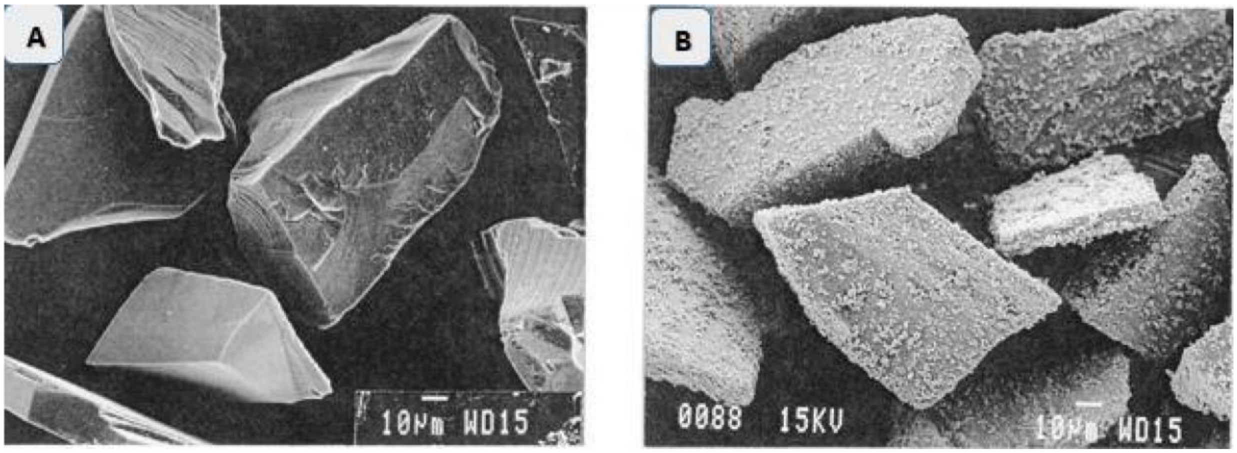


Figure 4: Surface morphologies of (a) uncoated and (b) electroless Ni-coated silicon carbide powders (Leon and Drew, 2000)

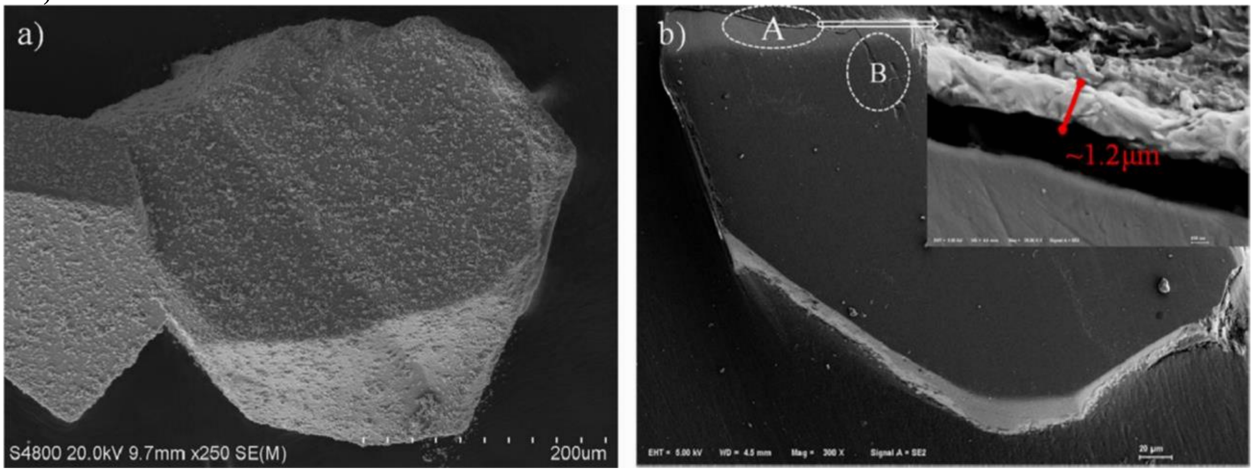


Figure 5: SEM micrographs of (a) EN coated SiC particles and (b) cross section of the EN coated SiC particles (He *et al.*, 2014).

He *et al*. (2014) deposited a continuous and uniform layer of Ni-P on SiC particles using EN plating. The as-received coating had an amorphous structure which became crystalline with Ni and Ni_3P phases when the coating was heat treated at 650K for 4 hours. The thermal stability of the SiC particles was enhanced by the Ni–P alloy coatings. Figure 5 shows the morphologies of the coated SiC. In Figure 5(a), the SiC particles are totally covered with Ni-P alloy coatings which have extensive distribution of globular nodules. Figure 5(b) represents the cross-sectional SEM micrograph of an EN coated SiC particles with an approximate coating thickness of 1.2 μm.

Aluminium Matrix Composites Reinforced by Electroless Nickel Coated SiC Particles

Aluminum matrix composites (AMCs) reinforced by silicon carbide particulates have gained a lot of interest from researchers in recent years because they combine the properties of the aluminum alloys and the silicon carbide particulates. However, the poor wetting of SiC ceramic particles by the molten aluminium matrix which causes inadequate interfacial contact and weak bonding as well as poor interfacial reaction between the matrix and the reinforcement has been a major setback in the use of AMCs (Hashim *et al.*, 2001; Xie *et al.*, 2019). Researchers have reported that the interfacial reaction between SiC particles and aluminium lead to formation of deleterious compounds such as aluminium carbide which weakens the mechanical and wear properties of the composite. The chemical reaction is:

$$3SiC\ (s) + 4Al\ (l) \rightarrow Al_4C_3\ (s) + 3Si\ (s) \tag{9}$$

The Al_4C_3 and Si in composites are in the form of flakes and bulk material (Davidson and Regener, 2000).

The modification of the surface of silicon carbide particles via electroless nickel coating has been reported to have yielded appreciable results against the formation of aluminium carbide (Al_4C_3) interfacial products and weak wettability in MMCs resulting in products of better properties in comparison to those with uncoated SiC particles (He *et al.*, 2014). Figure 6(a) and 6(b) shows how the dispersion of the Ni-P coated and uncoated SiC particles affect the mechanisms of grain refinement of developed Al/SiC composites. Figure 6(c) and 6(d) illustrates the effect of interfacial products formed on the strucures of Al/SiC composites.

Influence of electroless Ni-Coated SiC$_p$ on the Mechanical Properties of AMCs

Xie *et al.* (2019) reported that Ni-coated SiCp / Al-Cu composite has lower lattice mismatch and excellent wettability because of the presence of the intermetallic phase, Al_3Ni, on the interface of the developed composite. This intermetallic phase helps in facilitating uniform distribution of the Ni-P coated SiC particles in the aluminium alloy matrix. At room temperature, the yield strength and ultimate tensile strength of the Ni-coated SiC /Al composite increased by 39.8% and 21.5%, respectively when compared to those of the Al–Cu alloys. An increase of 30.1% and 41.3% were obtained for the yield strength and ultimate tensile strength respectively at 220 °C when the composite with Ni-coated SiC was compared to the Al alloy.

Farayibi *et al.* (2018) developed Al4043/Ni-coated SiC composite via stir casting and investigated the mechanical and wear properties of the composites. The Ni-coated SiC reinforcement particles were varied between 5 wt.% - 20 wt.% in 5% intervals during composite production. The tensile strength, yield strength and elastic modulus were found to increase with increasing SiC reinforcement fraction and highest values obtained for composite with 25 wt% SiC were 350 MPa, 254 MPa and 13.4 GPa respectively. The hardness and wear resistance properties of the composites improved with increasing reinforcement content with the highest hardness and lowest wear rate recorded at 75 HB and 3×10^{-11} m^3/s respectively.

Umasankar *et al*. (2014) observed an increase in hardness with increasing reinforcement weight percentage when the interface strength and microhardness of aluminium composite reinforced with coated SiC and uncoated SiC paticulates was investigated. The ultimate breaking load of composite reinforced with Ni-coated SiC particulate increased by 40% when compared with the uncoated SiC particulates reinforced composites. AMCs with coated SiC particulate also had higher hardness values than the uncoated SiC reinforced composites.

Kretz *et al*. (2004) studied the influence of Ni-coated SiC particles on the hardness and surface morphologies of Ni-coated SiC reinforced aluminium matrix composites and reported an increase in the joining strength at the interface of Al-base metal matrix composite when Ni-coated SiC particles are utilized as reinforcements when compared to those AMCs reinforced with uncoated SiC particles. They further reported better hardness value for the composites with coated SiC particles. Also, the microstructure of composites reinforced with Ni-coated SiC particulates was observed to have better surface finish and closer surface contact with the Al matrix than those made with uncoated SiC particles.

Davidson and Regener (2000) reinforced AA6061 matrix composite with uncoated and electroless-copper coated particulates and investigated the tensile properties of the developed composites using in-situ SEM tensile testing. They observed that AMC reinforced with electroless-coated Cu particulates had enhanced failure strains in comparison to those with uncoated copper particulates. The larger strain-to-failure values of the Cu-coated/AA6061 composites was as a result of better and efficient load transfer from the AA6061 alloy to the Cu-coated particulates.

Influence of electroless Ni-Coated SiC$_p$ on the Corrosion of AMCs

Zakaulla *et al.* (2014) studied the corrosion behaviours of uncoated and Cu-coated SiC/Al composites in marine environment using gravimetric weight loss method and revealed that corrosion rate increased with increasing weight fraction of uncoated and Cu coated SiC particles. Aluminium matrix composite with Cu-coated 8% SiC particles had the highest corrosion rate in 3.5 wt. % NaCl solution.

Also, Dikici *et al.* (2011) investigated corrosion behavior of electroless Ni-coated SiC particle reinforced aluminum composite in chloride solutions. It was observed that despite improving the wettability, the addition of 20 wt. % of electroless Ni-coated of SiC particles is not effective when the corrosion resistance property of AMCs in 3.5 wt. % NaCl solution is to be improved.

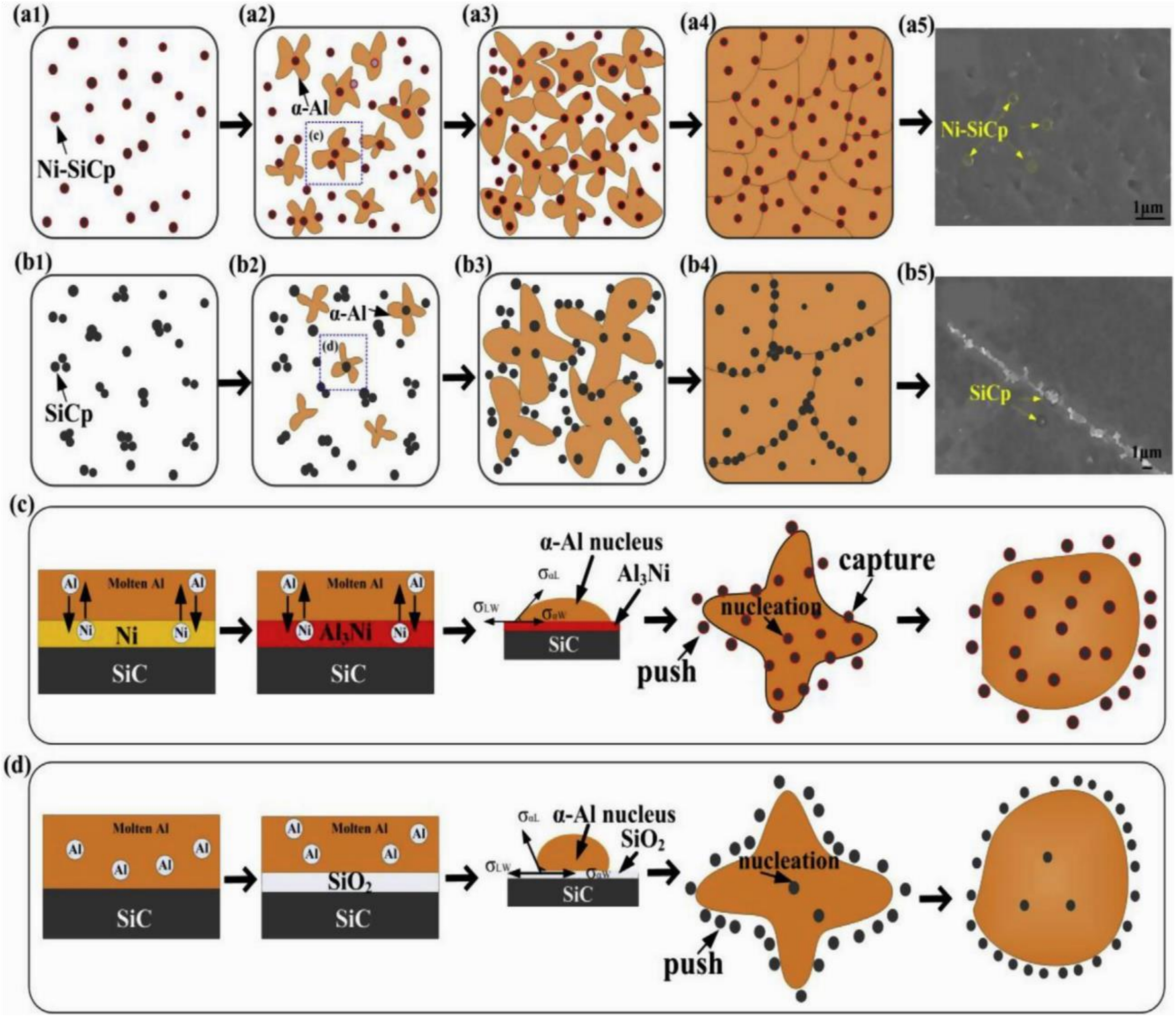


Figure 6: Grain refinement mechanisms of (a) Al/Ni-coated SiC composite, (b) Al/uncoated SiC composite, (c) interfacial Al_3Ni intermetallic phase of Al/Ni-coated SiC composite, and (d) interfacial SiO_2 phase of AMC reinforced with SiCp coated via surface oxidation (Xie *et al.*, 2019).

Microstructure of AMCs reinforced with Electroless Ni-coated SiC_p

The TEM micrographs of Al–Cu/Ni-coated 3wt% SiCp composites are shown in Figure 7 as illustrated by Xie *et al.* (2019). In Figure 7(a), many SiCp particulates could be observed to be evenly distributed in the Al-Cu matrix. These SiC nanoparticles were further confirmed using the selected area electron diffraction (SAED) image in Figure 7(b). Figure 7(c) is a 200 nm micrograph of the Al–Cu/Ni-coated 3wt% SiCp composites while a magnified 5 nm image of the composite clearly showing the interfaces between the Al-Cu matrix and the SiC_p is shown in Figure 7(d). The isolation of the Al-Cu alloy and SiC nanoparticulates by the nickel-coating prevented the formation of degrading interfacial phases such as Al_4C_3 because the chemical reaction occurred directly at the interface of the aluminium and nickel-coating resulting in the formation of Al_3Ni intermetallic phase.

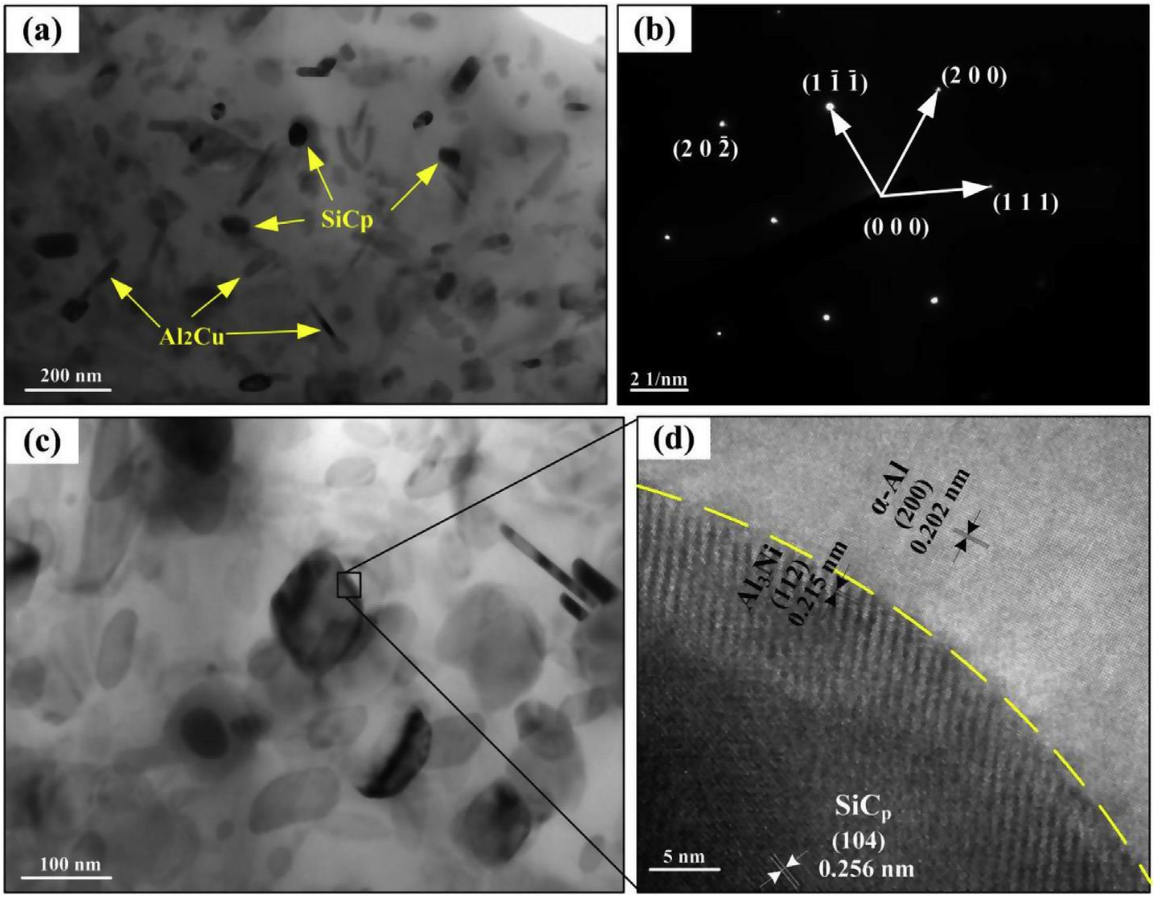


Figure 7: (a) TEM micrograph of Al–Cu/Ni-coated 3wt% SiCp composites, (b) SAED image of SiC_p, (c) magnified micrograph of (a), and (d) HRTEM image of the Al–Cu/Ni-coated 3wt% SiCp composite interface (Xie *et al.*, 2019).

Farayibi *et al*. (2018) studied microstructure of cast Al4043/15 wt.% SiC composite in Figure 8 and it was observed at 100 µm magnification that the SiC particles were uniformly distributed in the composite. The microstructure of the composite matrix was characterized by Al-SiC eutectics. The SiC solid solution precipitates were seen as the filament-like or whisker structures which were randomly oriented to reinforce the Al solid solution matrix. The formation of Al_4C_3 phase was not observed and this suggested that the Ni coating prepared on the SiC particles before casting had prevented the formation of this deleterious phase.

Pazman *et al.* (2010) studied the microstructures of AMCs developed with coated SiC particles pretreated using three different methods prior to electroless coating and then came to the conclusion that electroless coating prevented the direct contact between the aluminium alloy and the SiC particles. They further illustrated using SEM and XRD that the direct contact between the aluminium and the Ni surface led to the formation of various Al_xNi_y intermetallics at the reinforcement-matrix interface. This is seen in Figure 9 (a) & (b). The intermetallic phases present in the composite samples as observed (Figure 9c) via XRD were Al_3Ni_2, Al_3Ni, $AlNi_3$ and AlNi.

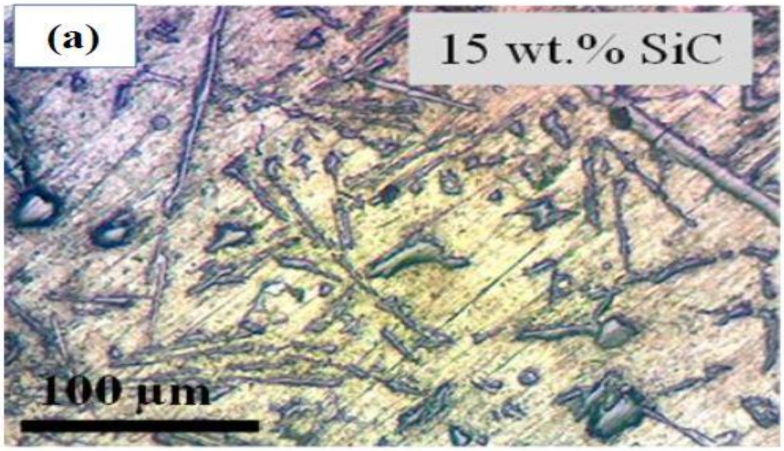


Figure 8: Optical micrograph of cast Al4043/15 wt.% SiC composite (Farayibi *et al.*, 2018).

Other researchers used either a different matrix other than aluminium or a different Ni-coated ceramic reinforcements other than SiC to produce and evaluate the properties of MMCs.

Ramesh *et al.* (2010) outlined that not only was the nickel-coated silicon nitride particles uniformly distributed throughout the matrix of Al6061 alloy, but also, the Al6061–Ni–P–Si_3N_4 composite had higher hardness and ultimate tensile strength and lower wear rate and coefficient of friction as the reinforcement weights increase when compared to the matrix alloy. Table 3 and Figure 10 illustrates the mechanical properties and wear rate of the Al6061 alloy and Al6061–Ni–P–Si_3N_4 composites respectively.

The mechanical properties and microstructure of IN625 alloy reinforced with varied weight percent of Ni-coated SiC particles was investigated by Sateesh *et al.*, (2003). They concluded that increase in weight percent addition of the Ni-coated SiC particles resulted in more refined microstructure of IN625 matrix. The tensile properties and hardness of the composite increased with increasing percentage of Ni-coated SiC particles as a result of the grain refinement. The highest hardness of the composite was recorded to be 33 % over that of the base IN625 material.

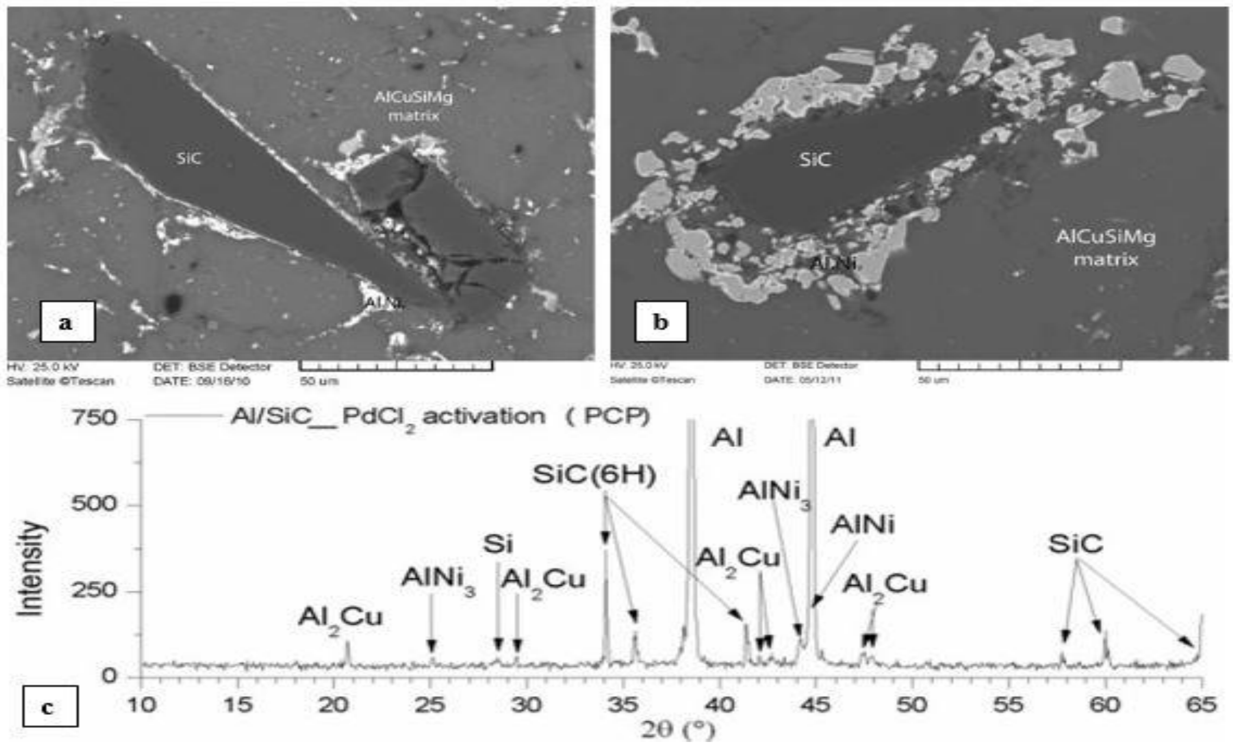
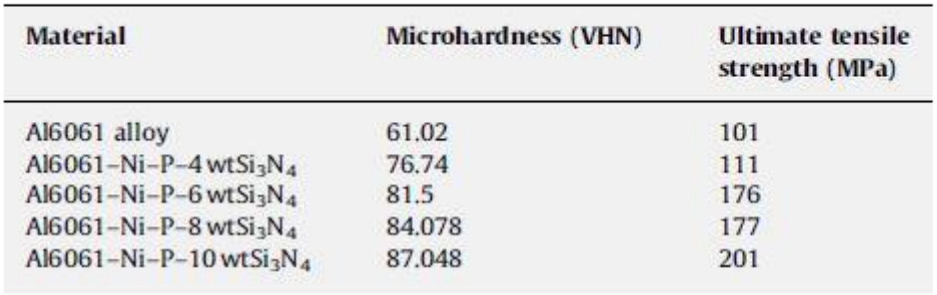


Figure 9: (a & b) SEM of composites with SiC pretreated using $SnCl_2$ & $PdCl_2$ and surface oxidation respectively and (c) XRD of Al/coated SiC composites with Aluminium nitride intermetallics (Pazman *et al.*, 2010)

Table 3: Mechanical properties of Al6061 alloy and Al6061–Ni–P–Si_3N_4 composites (Ramesh et al., 2010)



Material	Microhardness (VHN)	Ultimate tensile strength (MPa)
Al6061 alloy	61.02	101
Al6061–Ni–P–4 wtSi_3N_4	76.74	111
Al6061–Ni–P–6 wtSi_3N_4	81.5	176
Al6061–Ni–P–8 wtSi_3N_4	84.078	177
Al6061–Ni–P–10 wtSi_3N_4	87.048	201

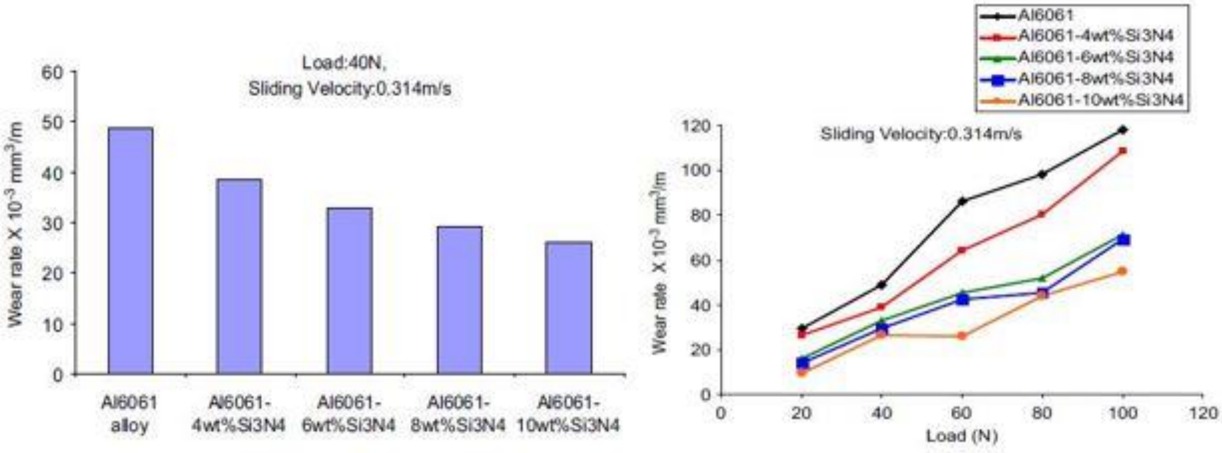


Figure 10: Shows (a) Effect of reinforcement on wear rate of Al6061 alloy and Al6061–Ni–P–Si_3N_4 composites and (b) Variation of wear rate of Al6061 alloy and Al6061–Ni–P–Si_3N_4 composite with load (Ramesh et al., 2010).

Also, Zhan and Zhang (2003) used copper matrix instead of aluminium and then investigated the effects of nickel-coating on the mechanical and wear properties of silicon carbide particle reinforced copper matrix composites. They observed that the nickel coating modified the interface structure and was effective in transfer of load between the matrix and the reinforcement. The coating reduced the extent of interfacial de-bonding and therefore improved the mechanical properties and wear resistance.

Finally, Ramesh et al. studied the corrosion behaviour of hot extruded aluminium 6061-silicon nitride- carbon fiber hybrid composite in 3.5% NaCl solution and reported that the Si_3N_4 reinforced Al6061 composites exhibited superior corrosion resistance in 3.5% NaCl solution when compared with matrix alloy and hybrid composite.

CONCLUSION

An overview of the influence of electroless Ni-coated SiC particles on the mechanical, corrosion and microstructure of Al/SiC composite has been carried out with the following conclusion. Electroless Ni-coating when deposited on SiC particles used as reinforcements for Al/SiC composites has resulted in aluminium-silicon carbide composites with better mechanical, corrosion resistance and microstructural properties. Uniform distribution of the Ni-coated SiC particles in the matrix has been observed because the Ni-P coating promote better wetting between the reinforcement and matrix and also prevents formation of degrading interfacial compounds such as aluminium carbide. XRD analysis show that formation of Ni and Ni_3P intermetallic phases on the SiC particulates produced via electroless coating improves the wettability between the SiC and molten aluminium leading to enhanced properties of the composites. The intermetallic phases present in the composite samples as observed via XRD were Al_3Ni_2, Al_3Ni, $AlNi_3$ and AlNi.

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CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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