COATINGS ON REINFORCEMENTS IN ALUMINUM METAL MATRIX COMPOSITES

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Abstract

Aluminum metal matrix composites (AAMC) play a vital role in many fields due to their exceptional properties compared to monolithic aluminum alloys. While fabricating the AMMC, there are several problems including poor wettability between the matrix melt and reinforcements, low interfacial bond strength, and undesirable reactions in the interface. To overcome these problems, the surface of the reinforcements needs to be modified appropriately, often using coatings. This paper critically reviews the coatings used on reinforcements during the processing of aluminum-based composites. Nickel has been one of the most common coatings on reinforcements. Nickel coating promotes wetting between the melt and reinforcements, restricts unwanted interfacial reactions including carbide formation, and releases nickel in the matrix while dissolving with an exothermic reaction. Copper coating behaves similar to nickel, and in addition, avoids the initiation of fracture at the interface due to its ductile nature. Coating ceramics, including SiO_2, on reinforcements, improves the wetting with molten aluminum and increases the oxidation resistance of the composite. SiC-coated reinforcements avoid the formation of porosity and increase the wettability, enhancing the stability of the composite; however, the strength of the composite decreases if the thickness of the coating increases above a critical value. Coating nanocrystalline 5083 aluminum on reinforcement makes the composite more ductile than uncoated reinforcement. Mg coating on reinforcements promotes wetting but reduces the melting point of the matrix. While coatings on reinforcements have to lead to improved properties in aluminum composites, there is a need for further research on optimizing the composition and thickness of coatings, understanding how the coatings change during processing, and how they influence the properties of aluminum composites.

Keywords: *aluminum metal matrix composite, reinforcement coating, squeeze casting, interface, wettability*

Introduction

In the last ten years, the production of MMCs has increased exponentially and is in huge demand because of the enormous applications of MMC; the production revenue has increased by 170 million USD. The number of research papers published in various journals on MMCs is shown in Figure 1.[1]

The properties of the metal matrix composites depend upon the type of reinforcement used and the concentration of reinforcement in the matrix. The region of contact between matrix and reinforcement is known as the interface. The

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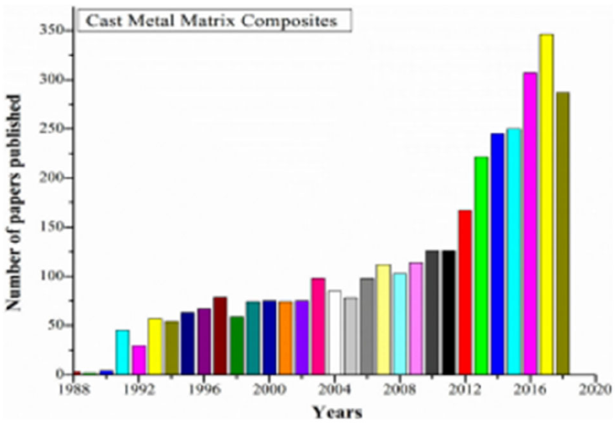

Figure 1. Papers published on MMC's in the years from 1988 to 2018.[1]

interfacial bond between interfaces plays a vital role in modifying the properties of the metal matrix composites.[2] The tough interfacial bond either by chemical interaction or by mechanical interlocking between metals and reinforcements leads to significant improvements in mechanical properties; likewise imperfect bonding, contaminants, cracks, detachments, voids, or any other undesired intermetallic compound at the interface may drastically deteriorate the final performance.[3] Wettability generally refers to the ability of the liquid or molten metal to remain in contact with the solid surface or the reinforcement; wettability is controlled by the force of balance between cohesive and adhesive intermolecular interactions. To obtain cast MMC with good strength, good wettability between the melt and the reinforcement is a necessary precondition (Figure 2).

Wettability mainly depends on the intermolecular forces between the matrix and the reinforcement phase in the

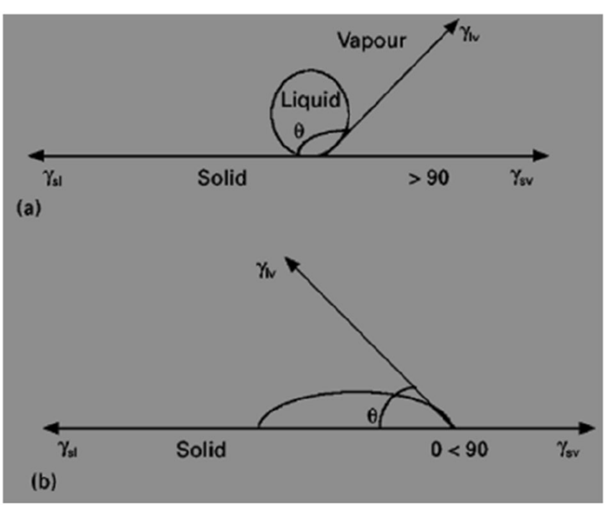

Figure 2. (a) Schematic diagram showing the non-wetting contact angle (θ) in a system. (b) Schematic diagram showing the wetting contact angle (θ) in a system.[5]

MMC.[4] The presence of oxide films on the surface of the molten metal decreases the wetting between aluminum melt and reinforcements. The wettability of the solid reinforcement in the molten matrix is indicated by the contact angle (θ) between the two phases. This relationship is given by Young–Dupre's equation,

$$\gamma_{lv}\cos\theta = \gamma_{sv} - \gamma_{sl}$$

where γ_{sl} is the interfacial energy, γ_{sv} is the surface energy of the solid, and γ_{lv} is the surface tension of the molten metal.

As the contact angle increases (when θ is more than 90°), the molten metal will not wet the solid reinforcement. As the contact angle decreases (when θ is less than 90°), there is said to be good wettability in the MMC. Wettability reaches the maximum when $\theta = 0°$ and wettability becomes minimum when $\theta = 180°$.[5]

Aluminum is the most abundant non-ferrous metallic element extracted from the earth's crust and exhibits excellent physical and mechanical properties. Aluminum alloy is the most widely used matrix in MMC and the most commonly used process to fabricate AMMC is squeeze casting, whereas the squeeze casting process is the combination of both forging and casting. In this process, high pressure is applied to the molten metal to obtain the required shape, as shown in Figure 3, resulting in the minimization of the shrinkage defects and gas defects.[6] As shown in Figure 3, there are two types of the squeeze casting process based on the pressure applied to the cast product: applying direct pressure on the product and applying pressure by the intermediate feeding mechanism, which is called indirect squeeze casting.[6]

Manufacturing AMMC using different techniques such as casting, powder metallurgy, squeeze casting, stir casting, infiltration, and compocasting, often leads to poor bond strength due to weak interaction between the matrix and reinforcement.[7] Manufacturing techniques have a significant impact on the interfacial bond strength, and occasionally, the interface may get damaged or degraded during the fabrication process. Hence to overcome this issue, coating the reinforcement is one of the best techniques. Selection of the coating of reinforcements should be based

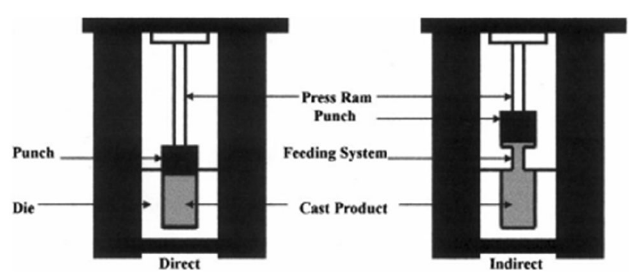

Figure 3. Diagram illustrating the types of squeeze casting process.[6]

on the improvement of bond strength and wettability between the reinforcement and matrix which results in improvement of mechanical and tribological properties of the composite. Coating of reinforcements also avoids the formation of unwanted intermetallic compounds such as Al–Cu compounds and $MgAl_2O_4$ spinels.[5] Coating the reinforcement suitably with a material that exhibits better bonding with both matrix and reinforcement will alter the surface of the reinforcement, hence incorporating coated reinforcement into the matrix results in better wettability and good interfacial bond strength. Metallic or nonmetallic coatings can be deposited on reinforcement surfaces. Ceramic reinforcements need to be coated, as it avoids unwanted chemical reactions and helps to increase the interfacial bond strength between the matrix and the reinforcement. Enhancing the overall surface energy of solid phases can be done by coating ceramic particles.[8] When the metallic coating is done on reinforcements like SiC, Al_2O_3, and TiO_2, their wettability is enhanced and the reinforcements are well bonded within the matrix.[9,10] Hexagonal crystal structure materials like graphite, molybdenum disulfide, titanium dioxide, hexagonal boron nitride,[11–15] etc., are solid lubricants, but their low interfacial bond strength with aluminum restricts their application. Hence, coating nickel on hexagonal boron nitride has excellent interfacial bond strength and wear resistance.[16,17]

This review paper is mainly concerned with the coating of reinforcements for the processing of AMMC, which leads to the modification of many properties of the composite. The current work aims to showcase the merits and demerits of coatings on reinforcements.

Coating Methods

Coating of reinforcements can be carried out using various methods such as electroless deposition, sol–gel process, PVD (physical vapor deposition), thermal spraying, cementation, and CVD (chemical vapor deposition). The following are the most common methods for the coating of reinforcements.

Electroless Deposition

The electroless deposition method of coating is very efficient and the easiest way for coating metallic materials on the reinforcement. Through this technique, uniform coatings can be obtained without any external current supply. The fibers are heated at 450 °C, for about 10 min using a muffle furnace and are cleaned by dipping in acetone for about 1 h, then washed using distilled water. Carbon fibers are treated with $SnCl_2$ and $PdCl_2$, one after the other and are immersed in the bath which contains the solution of the required metal. Through this process, the coating is obtained on the reinforcement and these specimens are dried for a certain amount of time. The apparatus of the electroless process is shown in Figure 4.[18]

Sol–Gel Technique

Sol is a suspension of colloidal solid particles present within a liquid and gel is the porous 3D interconnected network surrounded by a continuous liquid phase. For the sol–gel technique of coating SiO_2 on SiC particles,[19] the sol is prepared in distilled water and absolute ethanol by diluting TEOS (tetraethylorthosilicate), which acts as a precursor. The mixture is subjected to hydrolysis for 2 h by maintaining an acidic condition with a sol concentration of 204g/l later HCl is added suitably to maintain the pH. The SiC particles are immersed and stirred in the sol for about 2 h. The particles are cleaned in ethanol and dried at 120 °C, for 1 h to evaporate ethanol and water; the SiC particles are heat-treated at 500 °C or 725 °C to reduce porosity and improve the coating strength.[20,21] Figure 5 depicts the overall process of sol–gel coating reinforcement.

Chemical Vapor Deposition (CVD)

CVD is a technique in which substances are condensed to generate solid phase material from the vapor phase. Carbon nanotubes (CNT) are synthesized by the chemical vapor deposition (CVD) process and suitable catalysts such as Ni, Co, and so on are added to powder activated carbon (PAC), which acts as a substrate.

By thermal annealing or chemical etching, nucleation of catalysts takes place and the specimen is placed in a tubular reactor, usually, a quartz tube, and is heated at 600–1200 °C. A suitable inert gas or process gas such as hydrogen or nitrogen and hydrocarbon such as methane is allowed to react over the metal catalysts for a given period (15–60 min). Adequate deposition pressure of 4kPa is maintained, the carbon precursor decomposes completely,

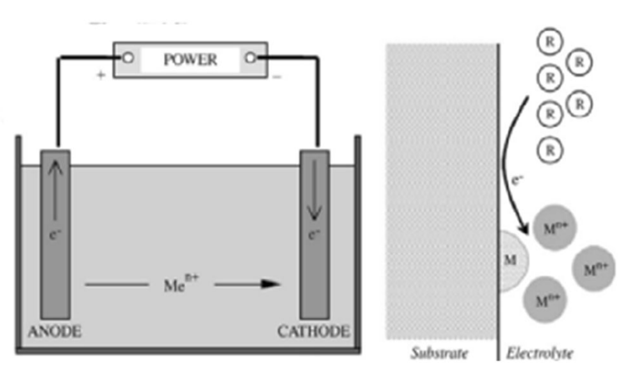

Figure 4. Electroless coating apparatus.[67]

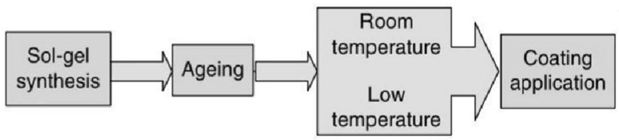

Figure 5. Schematic diagram of a sol–gel process.[68]

and coated CNTs start to grow on the catalyst particle in the reactor.[22] Figure 6 shows the process of CVD coating.

Cementation

Cementation is another technique to apply coating on reinforcement particles and the carbon fibers are heat-treated for about 15 min at 700 °C to remove moisture and any other coupling reagents. These fibers are immersed in glacial acetic acid to treat the surface and improve wettability. An activator bath is prepared by adding known concentration and the required amount of metal salt solutions. The treated fibers are then dipped into the activator bath. Suitable displacing agents like Zn, Al, Mg, or Fe are added into the bath. It displaces the metal in the bath. The completion of the process can be identified by changes in the color of the fiber and the solution. The coated fibers are treated with an acidic stabilizer for about 15 min to reduce tarnishing, and in this way, the cementation process is carried out to coat the reinforcement.[23]

Liquid Phase Coating

In this process, yttrium nitrate powder is taken in a container and dissolved in distilled water. After analyzing the concentration of the solution, Al_2O_3 powder is added to the solution and is ball milled for about 4 h. Then, it forms a thick slurry. This slurry is then dried and the Al_2O_3 powder becomes enriched with yttrium nitrate. This precursor is subjected to calcination at about 850–950 °C and the Y_2O_3-coated Al_2O_3 powders are obtained.[24]

Coating Systems

The following describes some standard coating systems applied to the reinforcing particles.

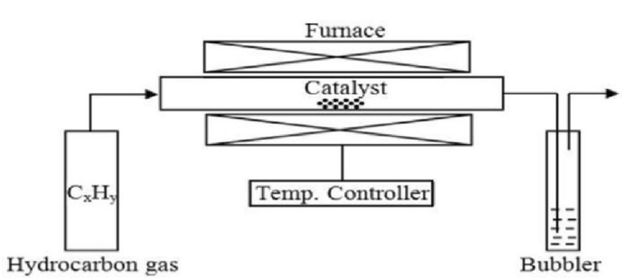

Figure 6. Schematic diagram of the CVD process.[22]

Nickel (Ni)

Electroless coating is the most suitable method for applying a metallic coating on reinforcement particles. Usually, the uncoated reinforcements have low wettability and weak interfacial bond strength; Mandal et al.[25] studied the mechanical and corrosion behavior of aluminum composite when Ni-coated steel fibers are reinforced in AMMC by electroless deposition. Ni dissolves and diffuses into the matrix and forms intermetallics containing Fe and Ni. The study reports that, because of the formation of galvanic coupling between aluminum metal matrix and Ni-coated reinforcement, the electrochemical corrosion of the composite increases. Although a high specific strength in the composite can be achieved, corrosion resistance reduces, limiting its application in marine environments (Figure 7).

AMMC reinforced with Ni-coated carbon fibers has been studied, where Ni is coated on carbon fibers by an electroless method. The wettability between the melts and the reinforcement increases due to the short-time interactions which occur between aluminum and Ni-coated fibers. $NiAl_3$ intermetallics are formed due to the reaction between nickel and molten aluminum. Due to Ni-coating, unwanted interfacial reactions and carbide formation can be reduced. The hardness of the composite made using coated fibers increased due to the formation of Ni intermetallic during processing. Pyrolytic carbon is also used at the interface to enhance the interfacial toughness of the carbon fiber[26–28] reinforced composites. When Ni is coated on carbon fibers through an electroless method and the composite is prepared by a squeeze casting process, porosity in the AMMC is reduced to a greater extent; this leads to an increase in the tensile strength of the composite compared to AMMC prepared using uncoated fibers.[29] When the cementation technique is used for Ni-coating, the interfacial reactions were absent due to the formation of $NiAl_3$ at the interface of AMMC. Hence, it improved the interfacial bonding of the AMMC and the fracture was ductile in nature.[30]

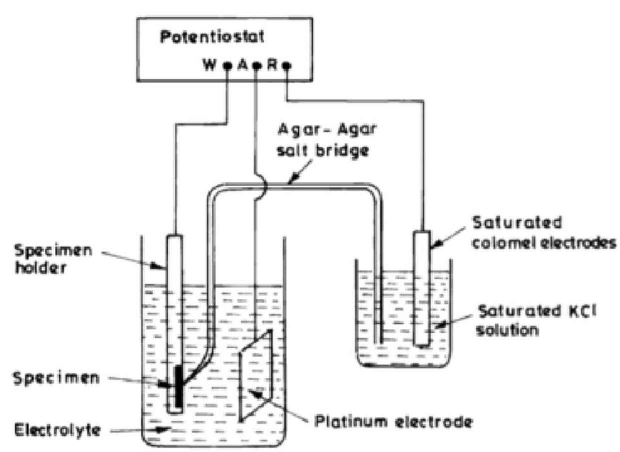

Figure 7. Corrosion testing apparatus.[25]

AMMC reinforced with SiC is prominently used in transportation applications because of its high specific strength ratio.[31] Instead of using AMMC reinforced with SiC, if Ni-coated SiC is used as reinforcement, the mechanical properties will further increase. The AMMC was reinforced with Ni-coated SiC particles, where the coating is done by an electroless deposition method, and the composite is prepared by sintering. The study shows that the binding between the coated reinforcements and matrix increases by forming Ni-Al intermetallic during sintering. The composites made using coated reinforcement have good wear resistance and hardness. In the case of carbon fibers, intermetallic compounds like Al_3Ni were formed and this increases the hardness of the composite. Due to the strong adherence between reinforcement and the matrix, they do not separate from each other.[32,33] Deuis et al.[34] studied the scratch property of the AMMC reinforced with Ni-coated SiC, TiC, and Al_2O_3. The coating was done using plasma transferred arc (PTA) technique. The study showed that the hardness was high for the composite which had fine reinforcement particles. It was found that composite made with TiC coated reinforcement exhibited poor wear resistance compared to SiC. SiC offers the highest interfacial bond strength compared to TiC and Al2O3.

Badia and Rohatgi[35] studied the gall wear property of the AMMC reinforced with nickel-coated graphite particles. The nickel was coated on graphite particles using the carbonyl process. This was one of the first researches on coating reinforcements to improve their wettability. The composite was fabricated by incorporating the nickel-coated graphite particles using an inert gas stream into the molten matrix. The composite melt was poured into permanent molds to form the cast composite. The graphite particles in the AMMC acted as solid lubricants and reduced the gall wear of the composite. A rich layer of graphite was present in the mating regions, which provided a minimal contact surface and increased gall resistance. It is also observed that the addition of nickel and silicon increased the gall resistance of the AMMC.

Copper (Cu)

Copper coating has also been proved as a viable method of coating for fabricating higher performance metal matrix composites and to increase the interfacial bond strength of the composites for ceramic reinforcements. Copper coating on steel wire mesh by the electroless method that is incorporated into aluminum metal matrix to fabricate AMMC by squeeze casting process is studied.[36] In this study, it is shown that when the uncoated steel wire mesh is added, steel wire reacts with aluminum and aluminide, resulting in micropores on the interface and thereby reducing interfacial bond strength. When Cu is coated on steel wire mesh, the reaction between the matrix and reinforcement is prevented. Cu reacts with aluminum to form a solid coherent bond that increases interfacial bond strength and wettability. The fracture does not occur because of the pullout of the steel wire mesh in coated composite, whereas, in an uncoated one, fracture mainly occurs due to the pulling out of the steel wire mesh. In Cu coated AMMC, the galvanic coupling is formed between steel and Al–Cu intermetallic compound which is the main reason for the increase in corrosion rate. Although tensile strength (11%) and hardness (15.8%) are enhanced when Cu is coated, the corrosion resistance decreases.[36]

Aluminum alloy composites reinforced with Cu-coated mica particles by the electroless method were prepared by the stir casting process. The study shows that as the sensitization time increases, the wettability of the reinforcement increases and as a result, the coating is deposited effectively on the reinforcement. The ductile property is higher in Cu-coated mica particle reinforced composite than in uncoated composite. The tensile strength of both composites made out of coated and uncoated reinforcements is almost the same. The wettability of the composite increases due to coating. The copper coating enhances the recovery of ground mica particles to 80%, which is very high compared to uncoated ones.[37]

Ruiz-Navas et al.[38] studied the bonding interface between Al matrix and Ti_5Si_3 particles with copper coating. Copper was coated by mechanical alloying technique and composite was prepared by sintering technique. The ductile nature of copper reduces the deformation of the reinforcement during fabrication. Copper helps in the diffusion of the reinforcements into the matrix. There was an improvement in the composite density with the increase in reinforcement content. The study also showed improved interfacial bond strength because of the chemical bond formed between matrix and Cu-coated reinforcement. A significant increase in hardness and bending strength can be observed mainly due to copper diffusion in the matrix. Because of the robust interface, the fracture did not occur at the interface in coated composite, whereas fracture takes place at the interface in the uncoated composite.

The AMMC reinforced with coated and uncoated SiC particles is studied. Here, the coating is performed through the electroless method and the composite is prepared by the sintering method. There is a reduction in the interfacial free energy because of the coating and thereby the wettability of the composite is increased. There is slight clustering seen in the reinforcements with coating. In this coating, a thin oxide layer (CuO) is formed around the reinforcement because of preheating of reinforcements, which avoids interfacial reactions. This study provides the information that in AMMC made using coated reinforcements, the interfacial bond strength increases as Al–Cu eutectic solution is formed and reduces SiC/Al reactivity which leads to the brittle nature of the composite. The same liquid fills up the pores and reduces porosity. In the tensile test, it was found that the failure strain in the coated composite was more improved compared to the uncoated one. The interfacial bond strength and failure strain of the composite increase as the reinforcement particle size decreases. It was seen that the hardness increases with the increase in SiC wt% and is significantly increased when compared to the uncoated composite. In these specimens, intermetallics were formed, which led to the ductile fracture of the composite. When the coating is done through the sputter coating technique, if the coating is not thick enough, there may be chances of debonding between Cu and SiC particles and this may cause the failure of the composite.[39–41] From Figure 8, it can be observed that the main crack has been formed away from the reinforcement and it depicts the improved interfacial bond strength of the composite.

Pallavi Deshmukh et al.[42] studied the rice husk ash SiO_2 reinforced composites where reinforcement was coated by Cu through the electroless method. This study showed that the coating restricted the formation of intermetallics in the composite. The appearance of interfacial compounds like Al_2CuMg, CuO, and $CuAlO_2$ increased the interfacial bond strength of the composite. As the Mg content in the composite increases, it breaks the Cu-coating, causing the SiO_2 to react with Al–Mg. UTS reaches a maximum value at 1.5 wt% of Mg in the aluminum matrix of the coated composite and above that, the UTS decreases. At the same point, wettability is also high, and strong intermetallic compounds are present. Thus, the composite possesses high strength. Even the yield strength and % elongations show a similar trend and are better than composites made with uncoated reinforcements.

Carbon fibers are one of the most used reinforcements in AMMC. Rather than using uncoated carbon fibers, if Cu-coated carbon fibers are used, the durability and the effectiveness of the component can be increased. However, it is not recommended to use these composites in marine applications because of the high corrosion rate. The properties of aluminum composites reinforced with Cu-coated carbon fibers by electroless and cementation techniques are studied. Cu dissolves in the aluminum matrix to form a solid solution and also exposes the surface of the reinforcement to the molten matrix, thereby providing a larger contact area and hence increasing the wettability of the composite. The exothermic interfacial reaction also produces brittle intermetallics such as Al_4C_3, which improves the interfacial bond strength and hardness of the composite. This study showed that there was no reduction in UTS in the electroless coating method, whereas, in the cementation process, there was a reduction in UTS values. The % elongation of AMMC made using coated reinforcements by electroless method and cementation method is 1.8 and 1.3, respectively. In electroless coated composite, the fracture is initiated by fracture of fibers, whereas in cementation coated composite, the first failure of the coating occurs because of the surface defects. There is no significant chemical reaction between the matrix and reinforcements in both composites. The coating was not efficient and was not uniform in both cases below the coating thickness of 0.2 micrometers.[43,44]

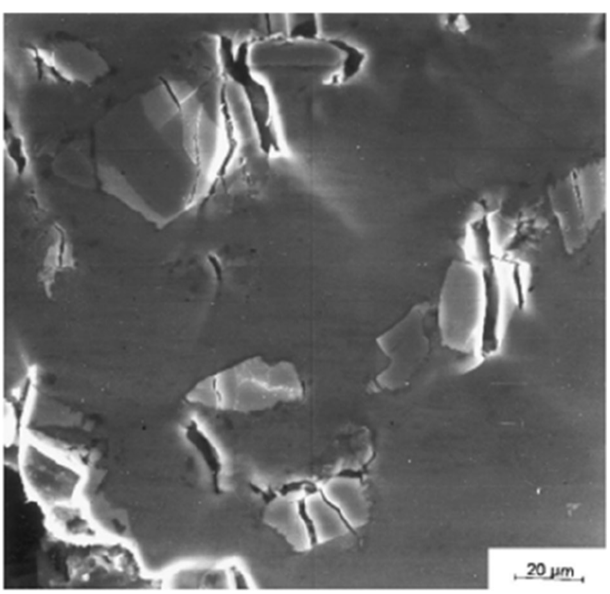

Figure 8. SEM image showing the fractured surface of the composite.[40]

Silica (SiO_2)

Ceramic coatings on reinforcements have been proved very much beneficial in improving the characteristics of the reinforcement and making it suitable for composite fabrication. A study shows that the AMMC is reinforced with SiO_2-coated SiC particles. Through the sol–gel method, Si diffuses into the matrix. Hence, the presence of Si in the matrix of the coated composite makes the composite stronger by restricting the formation of unwanted intermetallics. This experiment also showed that coating of SiO_2 on SiC prevented interfacial reactions and the formation of carbides (Al_4C_3) in the composite. Cracks were observed in the coating when the thickness was less than 0.7 micrometers and increased the chances of debonding. By altering the temperature or by heat-treating the composite properly, the wettability of the reinforcement can be suitably altered. It is an excellent process to improve the surface property like hardness and the coating obtained was dense and uniform. This study shows that when SiO_2 was used as a coating, the oxidation resistance of the metal matrix composite improved because it avoided the reaction between SiC and aluminum matrix. Due to the formation of oxides like Al_2O_3, MgO, and $MgAl_2O_4$ by endothermic reaction, there are chances of degradation of the composite because of their brittle nature. The thickness of the $MgAl_2O_4$ spinels depends on the thickness of the coating. If the $MgAl_2O_4$ spinel layer is thin it helps the composite to withstand high temperatures and if the $MgAl_2O_4$ spinel layer is thick, it makes the composite brittle. Additionally, the study showed that the fracture surface in the coated composite was smooth, whereas, in the uncoated one, it was abrupt. In the thermal spraying technique of composite fabrication, the composite contains defects and porosity. Still, coated composite contains very few pores (almost half or one-third) compared to the uncoated composite.[21,45–47]

Urena et al.[48] studied aluminum composites reinforced with SiC particles where reinforcements were coated with silica film by direct oxidation method and the composite was prepared through the stir casting method. The study demonstrates that the SiO_2 coating on reinforcement controls the interfacial reaction and causes excellent wetting properties. The crystal structure of SiO_2 depends on the oxidation treatment. The SiO_2 coatings contain two layers, one inner layer consisting of Al–Si–O compounds and an outer layer consisting of alumina. The inner layer was a glossy phase. It was also seen that there were secondary reactions in the Al–Si–C interface because of the precipitation of Fe and Cu present in the alloy matrix.

Silicon Carbide (SiC)

The reinforcements tend to react with molten aluminum at high temperatures and degrade the composite. Hence, ceramic coating like SiC is necessary for the reinforcement to maintain the strength of the composite and it acts as a protective coating. The characteristics of the aluminum composite which is reinforced with SiC-coated carbon fiber is analyzed. The coating is applied by a polycarbosilane solution process effectively. The coating acts as a barrier and restricts all the harmful reactions at the interface. This study provided the information that in the SiC coated composite, the reinforcement was fully covered by molten aluminum and the pores were absent, hence wettability improved. The interfacial products which grew perpendicular to the reinforcements strengthened the composite. The SiC coating also changed the bonding state from chemical to mixed type and this increased interfacial bond strength.[49] The interface of the carbon fiber reinforced aluminum composites was studied, where reinforcement was coated by ceramics like SiC using the CVD method. The thermal stresses induced in the interface and the chemical reactions show the nature of bonding present at the interface. The study showed that when SiC is coated on the reinforcement, Si penetrates the matrix and Al reacts with C and forms an ionic compound Al_4C_3 by an exothermic reaction at the interface. By this, the coated SiC reinforced composites show better stability. It was also seen that in ceramic coatings, the strength of the fibers decreases because of the deposition technique and thickness.[50]

The aluminum composites prepared by plasma spray technique were studied.[51] The composite was reinforced with boron and coated with silicon carbide. The study showed that coated reinforcements provided a larger contact area and as a result, interfacial bonding in the coated composite improved to a great extent. During fracture, the failure was not observed at the interface. Boron fibers have smooth surfaces but SiC coating gives serrated surfaces that can easily lock with the matrix and bond strongly. This study reported that the hardness of the composite increases with the increase in vol% of boron fibers. The opposite trend was seen in the density of the composite. The coefficient of friction was also seen enhanced compared to that of a standard alloy. Wear resistance improved in the composite and wear rates were reduced by 80% when compared to the common alloy. The average coefficient of friction for alloy was 0.35, whereas, for composites, it was 0.53.[51,52]

The main feature of the SiC coating is that it improves hardness to a great extent. Thus, wherever hardness should be high, SiC-coated reinforcement can be used as reinforcement in AMMC instead of uncoated reinforcement.

Aluminum (Al)

Ye et al.[53] studied the mechanical characteristics of B_4C reinforced aluminum composite. B_4C particles were coated with nanocrystalline 5083 Al powder by cryo-milling process and the composite was fabricated by cold isostatic pressing. Although the B_4C particles formed agglomerates, the composite became more ductile when compared to the composite made with uncoated reinforcement. Here, the metallic phases in the matrix and the coating tend to weld to each other during fabrication and by this the interfacial bond strength increases by making the interface brittle. The interface was free of voids and free from interfacial reactions. The study also says that the UTS (410 MPa) and stiffness of coated metal matrix composites are greatly improved because of the elongated agglomerates which act as whiskers in the matrix. During the fracture, crack nucleates from the interface because of its brittle nature.

Cobalt (Co)

Baik et al.[54] studied the fracture behavior and interfacial reactions of aluminum composites reinforced with Al_2O_3 fiber coated with Co. The composites were manufactured by squeeze infiltration technique and coating was applied using a sol–gel process. This study provides information that wettability and interfacial bond strength is increased because Co reacts with Al_2O_3 and forms Al_9Co_2 and CoO_3 phases (Figure 8). Due to increased annealing temperature, tensile strength and flexibility are also enhanced in the AMMC. When annealing is performed at lower temperatures, there is debonding between Co-coating and Al_2O_3 fibers, and hence, the failure of the AMMC takes place. Kulkarni et al.[23] studied the aluminum composites reinforced with Co-coated carbon fibers made by the cementation process. In the study, it was observed that the tensile strength of the composite increased, and compared to composites made using uncoated reinforcement. The composites made with coated fibers showed a better distribution of carbon fibers. The voids and cracks in the composites were reduced to a great extent. Taherzadeh Mousavian et al.[55] studied aluminum composites reinforced with SiC particles coated with cobalt by the electroless method. It was observed that cracks were not formed when cobalt-coated reinforcement was used. The average thickness of cobalt coating was 1.83 micrometers. There was an improvement in the hardness, UTS, and yield strength of the composite, when coated reinforcement was used.

In Figure 9, co-coating can be observed with the formation of Al_2Co at the interface.

Nickel–Boron (Ni-B)

Deepa et al.[56] studied aluminum composites reinforced with Ni-B coated B4C particles. Coating of reinforcements is applied by electroless deposition and the composite is prepared by powder metallurgy process. Al–Ni intermetallic layer enhanced the density, close the pores, and inhibit the formation of harmful interfacial compounds. The semi-solid sintering process increases the interfacial bond strength under the influence of argon. The wettability also increased when coated reinforcements were used.

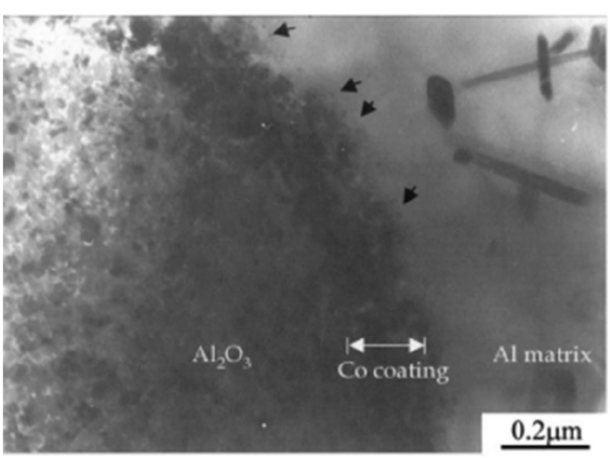

Figure 9. Co-coated Al_2O_3 reinforced composite interface.[54]

Magnesium (Mg)

Gutema et al.[57] studied the aluminum composites reinforced with Mg-coated silicon carbide by stirring method of coating. This coating technique uses the kinetic energy of the relative fluid motion and the fabrication of the composite was performed by the squeeze casting process. The addition of Mg reduces the melting point of the matrix. It was seen that the coating improves wettability by initiating a chemical reaction at the interface, where Mg_2Si is formed. This improves the interfacial bonding strength of the composite. Because of the coating, the tensile strength of the metal matrix composite was significantly enhanced to a maximum value of 135 Mpa, because of the ductile nature of the composite. During Brinell's hardness test, it was seen that the hardness in the composite made using coated fiber increased as compared to the composite made using uncoated fibers with up to 16% SiC content in the composite and the AMMC also showed more ductile fracture.

Molybdenum

Nie et al.[58] studied carbon nanotubes reinforced aluminum composites prepared by sintering, where molybdenum is coated on reinforcements by an organic chemical vapor deposition method. It was seen that the interfacial products were absent and there was a continuous deposition of molybdenum. It was also seen that adding Mo-coated CNT to the matrix decreases the electrical conductivity of the composite. The tensile strength increases as an increase in Mo-CNT content to 0.5 wt% and after that, it decreases as the amount of Mo-CNT increases. At 0.5 wt%, the max tensile strength value is attained and is 29.9% more than that of pure Al. The hardness is 13.2% more than that of pure Al. It was also observed that the addition of MO-CNT reduces plasticity in the composite.

Zinc (Zn)

Samson Jerold Samuel Chelladurai et al.[59] studied aluminum composites prepared by squeeze casting reinforced with Zn-coated steel wire. It was seen that Zn-coating enhances the wettability and interfacial bond strength of the composite to a great extent. It was also noticed that in composite made with zinc-coated fibers, the tensile strength and elongation increased with the increase in the number of steel wires. Tensile strength reached a max value of 183 MPa, which is 24% greater than the standard alloy. Fracture in the composite occurred because of micropores in the interface region. The coating improved its interfacial bond strength and prevented the pull out of steel wires. It was also observed that the wear of the composite decreased with the increase in steel wires in the composite and the friction coefficient also had the same trend. Hardness is also found to be enhanced up to 135 VHN. Also, the tensile strength of the composite is improved and it is maximum (164 MPa) parallel to the steel fibers.[60]

Boron Carbide (B_4C)

R'Mili et al.[61] studied aluminum composites reinforced with B4C-coated carbon fibers made by a chemical vapor deposition process. The composite was prepared by the squeeze casting process. It was seen that by controlling the thickness of the coating, modification of mechanical properties can be achieved. The coating protects the reinforcement from extreme conditions during fabrication and the molten metal during infiltration.

Zinc Aluminate ($ZnAl_2O_4$)

Yue et al.[62] studied aluminum composites reinforced with aluminum borate whiskers which were coated by $ZnAl_2O_4$ by sol–gel process. The composite was prepared by squeeze casting. This study showed interfacial reactions in metal matrix composites made using uncoated reinforcements forming $MgAl_2O_4$. In contrast, interfacial reaction zones were absent and the coating was more continuous in metal matrix composites made using coated fibers. In the metal matrix composites made with coated reinforcements, the wettability increased since there were no voids present at the interface.

At 490 °C, tensile strength decreased in the composite made using uncoated reinforcements, but there was no reduction in tensile strength in the composite made with coated reinforcement. In the metal matrix composite made with coated reinforcements, the thermal stability improved.

Aluminum Oxide (Al_2O_3)

Aluminum composites were reinforced with alumina-coated short carbon fibers (SCF) made by a sol–gel process. This study demonstrated that composite made using coated SCF performs showed better compressive strength than the composite made with uncoated SCF performs. It was also seen that alumina coatings prevented the formation of Al_4C_3 which can degrade the properties. It was seen that after extrusion, the SCF was arranged in the direction of extrusion. After extrusion, thermal conductivity values of the composite made using coated fibers increased compared to the composite made using uncoated fibers.[63]

Yttrium Oxide (Y_2O_3)

The effect of coating of Y_2O_3 on Al_2O_3 particles has been studied. The coating is performed by the liquid-phase coating method, by ball milling Al_2O_3 particles in a Y_2O_3 solution. The squeeze casting process is used to prepare the aluminum composite. It was seen that ductility and interfacial bond strength was increased because of the formation of Y_2Al as an interfacial compound. The wettability increases when a 30% volume fraction of reinforcing particles was used. The yield strength and tensile strength are enhanced to 33% and 27%. At the same time, elongation is improved by 12.2%.[24] No significant interfacial reactions were observed when coated alumina was used (Figure 10 b)

Pyrolytic Carbon (PyC)

The corrosive behavior of carbon reinforced aluminum composites was studied using PyC-coated and uncoated carbon fibers as reinforcement. Here, the coating was done by the electrochemical deposition method. Anodic polarization is seen in the AMMC, which can decrease the corrosion resistance of the AMMC. PyC coating can enhance corrosion rate as there are differences in microstructure between carbon fibers and PyC coating.[27] From Figure 11, it can be seen that there is a formation of Al4C3 needle-like structures at the interface.

From Figure 11, it can be seen that there is a formation of Al_4C_3 needle-like structures at the interface.

Silver (Ag)

The interfacial behavior of aluminum composites reinforced with silver-coated carbon fibers by an electroless process was studied. This coating avoids the formation of interfacial compounds. The high solubility of silver helps

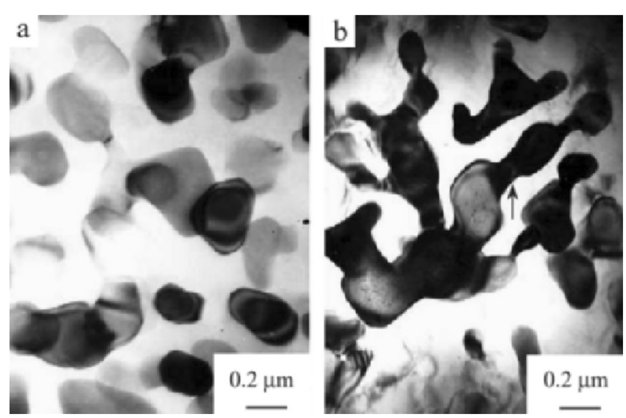

Figure 10. TEM images (a) Al_2O_3 reinforced Al composite (b) coated Al_2O_3 reinforced Al composite.[24]

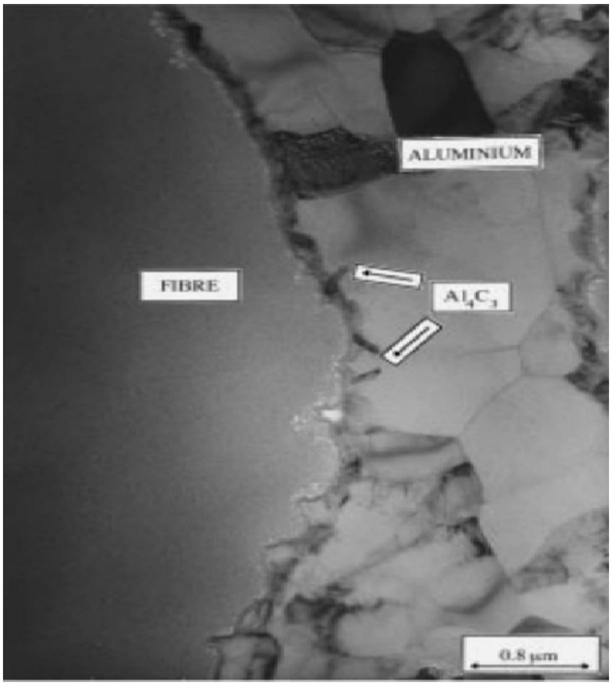

Figure 11. TEM image of coated fibers in the matrix.[27]

the coating to dissolve in the matrix and thereby improving wettability without any interfacial reactions. This study shows that silver coating helps the carbon fibers bond with the aluminum matrix and protect the carbon fibers from damage during fabrication Due to the silver coating, the wettability of the reinforcements with the matrix melts increased. In the composite, the reaction zones mainly consist of Al_4C_3 in platelet form. The tensile strength of the composite decreased when the processing temperature increased.[64]

Nickel–Phosphorus (Ni-P)

The aluminum composites reinforced with Ni-P coated SiC particles were studied, in which coating is applied through electroless technique. The study reported that the composites made with coated fibers show better wear resistance and the wear rates decrease by 25% and 66%.[65]

Carbon (C)

Aluminum MMC reinforced with diamondlike carbon (DLC)-coated carbon fibers has been studied, where the coating was done by a plasma deposition process. It showed that the DLC coating bonded well to both carbon fibers and aluminum and there was no fracture at the interface. As both the matrix and reinforcement are good conductors, there is galvanic coupling between them and hence the composites made using coated reinforcements showed an increase in corrosion rates. The interfacial compound Al_4C_3 is formed at the interface and this is because of the exothermic reaction occurring at the interface between the aluminum matrix and the coated reinforcements.[66]

Table 1 lists the different coatings which have been used on reinforcements while synthesizing aluminum matrix composites, the methods used to deposit these coatings, and the properties of the composites which were enhanced,

Future Research Imperatives

While a variety of coatings including metallic and ceramic have been used on reinforcement to improve the wetting between the reinforcement and the matrix increase their bond strength, and increase the properties of the composites, there have been very little efforts to optimize the composition, thickness, and continuity of coatings to minimize their cost and maximize the properties of composites. Further work is required to understand the interactions between the coatings and the reinforcement, including diffusion and dissolution. The ability of the coating to release alloying elements in the matrix by dissolution needs to be understood and used to improve the properties of the composites. The effect of residual coating left on the reinforcements after processing of the composites, and its influence on the properties of composites need to be quantified as well.

Conclusions

A large array of coatings including metallic and ceramic coatings have been used on reinforcements during the synthesis of aluminum-based composites to improve wetting and bonding with the matrix, resulting in improvements in the properties of composites. However, further research is needed on the optimization of composition, thickness, and continuity of coatings, and understanding of the changes in coatings during processing and their influence on properties.

- Nickel has been the most commonly used coating on reinforcements during the fabrication of aluminum-based composites to promote wetting and bonding with the matrix and to improve the properties of the composites. Nickel has been deposited using the electrochemical and electroless method and carbonyl process. Nickel coating sometimes partly dissolves or diffuses into the matrix to form nickel aluminides to improve the high-temperature properties of the composites. Ni-B coating on reinforcements also increases the wettability and the bond strength and sometimes results in Al–Ni intermetallic compound layer formation.

Table 1. Comparative Table of the Different Matrix, Reinforcement, Reinforcement Size, Coating Material, a Coating Method, and Properties

Matrix	Reinforcement	Reinforcement size (diameter)	Coating material	Coating method	Properties altered	References
Al–2Mg alloy	Steel fibers	80–120 micrometers	Ni	Electroless	Corrosion resistance (decreases)	25
AA6061	Carbon fibers	7.28 micrometers	Ni	Electroless	Interfacial bond strength (increases) Toughness (increases)	26
Pure aluminum	Carbon fibers	T800 H grade	Ni	Electroless	Hardness (increases)	27
AA6061	Carbon	100 micrometers—1mm	Ni	Electroless	Wettability (increases) Hardness (increases)	28
AA2024	Carbon fibers	5.7 micrometers	Ni	Electroless	Wettability (increases)	29
Pure aluminum	Carbon fibers	XA-S grade	Ni	Electroless	UTS (increases)	30
Pure aluminum	SiC	8–70 micrometers	Ni	Electroless	Interfacial bond strength (increases) Hardness (increases) Wear resistance (increases)	32,33
AA5083	SiC	70–140 micrometers	Ni	Plasma transferred arc	Interfacial bond strength (increases)	34
aluminum alloys	Graphite particles	20 to 200 microns	Ni	Carbonyl process	Gall resistance (increases) Friction and wear decreases	35
LM6 aluminum	Steel wire mesh	274 micrometers	Cu	Electroless	Interfacial bond strength (increases) Wettability (increases) Porosity (decreases)	36
AA2024	Mica particles	15–150 micrometer	Cu	Electroless	Wettability (increases)	37
AA2014	Ti_5Si_3 particles	44 micrometers	Cu	Mechanical alloying	Hardness (increases) Interfacial bond strength (increases)	38
Pure aluminum	SiC	142 micrometers	Cu	Sputter coating	Corrosion resistance (decreases)	39
AA6061	SiC	45 micrometers	Cu	Electroless	Interfacial bond strength (increases) Porosity (decreases)	40
Al–Mg alloy	SiO2	50 micrometers	Cu	Electroless	UTS (increases) Wettability (increases)	42
Pure aluminum	Carbon fibers	XA-S grade	Cu	Electroless	Elongation (increases)	43
A-356	SiC	75 micrometers	Cu	Electroless	UTS (increases) Interfacial bond strength (increases)	41
AA6061	Carbon fibers	XA-S grade	Cu	Electroless	UTS (increases) Hardness (increases)	44
AA6061	SiC	26.2 micrometers	SiO_2	Sol–gel	Hardness (increases)	21

Table 1 continued

Matrix	Reinforcement	Reinforcement size (diameter)	Coating material	Coating method	Properties altered	References
AA6061	SiC	26.2 micrometers	SiO_2	Sol–gel	Oxidation resistance (increases)	45
AA6061	SiC	26.2 micrometers	SiO_2	Sol–gel	Hardness (increases)	46
Pure aluminum	SiC	16 micrometers	SiO_2	Direct oxidation	Wettability (increases)	47
Pure aluminum	SiC	125 micrometers	SiO_2	Sol–gel	Wettability (increases)	48
					Porosity (decreases)	
Al–Si alloy	Carbon fiber	6.5 micrometers	SiC	Polycarbosilane solution method	Interfacial bond strength (increases)	49
Pure aluminum	Carbon fibers	XA-S grade	SiC	CVD	Stability (increases)	50
AA6061	Boron fibers	0.143mm	SiC	Plasma spraying	Interfacial bond strength (increases)	52
Al2014	Boron fibers	140 micrometers	SiC	CVD	Hardness (increases)	51
					Wear resistance (increases)	
AA5083	B_4C	2.5 micrometers	Al	Cryo milling	Stiffness (increases)	53
					Interfacial bond strength (increases)	
Al2024	Al_2O_3fibers	RF grade	Co	Sol–gel	Ductility (increases)	54
					Interfacial bond strength (increases)	
					UTS (increases)	
Pure aluminum	Carbon fibers	7 micrometers	Co	Cementation	UTS (increases)	23
					Porosity (decreases)	
Pure aluminum	SiC	80 micrometers	Co	Electroless	Hardness (increases)	55
					UTS (increases)	
					Yield strength (increases)	
Pure aluminum	B_4C	60–80 micrometers	Ni-B	Electroless	Interfacial bond strength (increases)	56
Al6063	SiC	30 micrometers	Mg	Stirring	Hardness (increases)	57
					Melting point (decreases)	
Pure aluminum	Copper nanotubes	20–30 nm	Mo	Organic CVD	Electrical conductivity (decreases)	58
					Tensile strength (increases)	
					Plasticity (decreases)	
LM6 aluminum	Steel wire	304 micrometers	Zn	CVD	Tensile strength (increases)	59
LM6 aluminum	Steel wire mesh	304 micrometers	Zn	CVD	Hardness (increases)	60
A9 aluminum	Carbon fibers	T300 grade	B_4C	CVD	Durability (increases)	61
Al2024	Aluminum Borate whiskers	1 micrometer	$ZnAl_2O_4$	Sol–gel	Wettability (increases)	62
AA6061	Rock dust	20 micrometers	Al_2O_3	Anodizing	Hardness (increases)	69

Table 1 continued

Matrix	Reinforcement	Reinforcement size (diameter)	Coating material	Coating method	Properties altered	References
AC4C aluminum	Short carbon fibers	7 micrometers	Alumina	Sol–gel	Thermal (increases) Conductivity (increases)	63
AA6061	Al_2O_3	0.15–0.3 micrometers	Y_2O_3	Liquid phase method	Elongation (increases) Tensile strength (increases)	24
AA6063	Carbon fibers	10 micrometers	Silver	Electroless	Wettability (increases)	64
Al6061	SiC	5–40 micrometers	Ni-P	Electroless	Wear resistance (increases)	65
Pure aluminum	Carbon fibers	5 micrometers	DLC	Plasma deposition	Interfacial bond strength (increases) Corrosion resistance (Decreases)	66

- Copper has also been used frequently as a coating on reinforcements to promote wetting and bond strength. It also can dissolve in the matrix and improve the strength of the composite by solid solution strengthening the matrix.
- When Co is coated on reinforcements, wettability increases, and interfacial bond strength increases.
- Molybdenum coatings on reinforcements including CNT significantly reduced the formation of interfacial phases at the interfaces
- Magnesium coating improves wettability by initiating a chemical reaction at the interface in which the intermetallic compound Mg_2Si is formed, which enhances the interfacial bond strength.
- Zinc and zinc aluminate coatings on reinforcements enhance the ductility of the composite. This coating helps to increase the tensile strength and % elongation of the AMMC.
- Ceramic coatings including SiO_2, B_4C, and SiC have been used on reinforcements to promote wetting and to protect the reinforcement from the harsh environment during processing. Silica coatings react with the melt to promote reaction-induced wetting and the formation of alumina as a reaction product.
- Further quantitative studies are required to optimize the composition, thickness, and continuity of coatings on reinforcements to minimize the cost of coatings and maximize the properties of the composites.

Abbreviations

AMMC Aluminum metal matrix composites
MMC Metal matrix composites
UTS Ultimate tensile strength

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