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Characteristics of Aluminum Hybrid Composites

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***Abstract*—**Aluminum hybrid reinforcement technology is a response to the dynamic ever increasing service requirements of such industries as transportation, aerospace, automobile, marine, etc. It is unique in that it offers a platform of almost unending combinations of materials to produce various hybrid composites. This article reviews the studies carried out on various combinations of aluminum hybrid composite and the effects on mechanical, physical and chemical properties. It is observed that the extent of enhancement of these properties of hybrid composites is strongly dependent on the nature of the reinforcement, its hardness, particle size, volume fraction, uniformity of dispersion within the matrix and the method of hybrid production.

***Keywords*—**Aluminum alloy, hybrid composites, properties, reinforcements.

I. Introduction

METAL matrix composites have potential advantages over monolithic alloys and this has activated considerable attention in the past years. These composites have provided solution to the problem of increasing service requirements for various structural applications through the reinforcement of metal matrix by metallic or non metallic materials [1]. Metal matrix composites (MMCs) are commonly reinforced with high strength and high modulus ceramic phases, which may be in the form of fibre, whiskers, or particulates. The addition of ceramic reinforcement to metal matrix improves strength and stiffness while ductility is compromised [2]. Commonly used metals as matrix in producing structural materials include titanium, aluminum, and exotic metals such as silver, magnesium, beryllium, copper, cobalt, and nickel [3].

One of the most widely used composites is the aluminum based composites (Aluminum Matrix Composites). Aluminum matrix composites (AMCs) refer to the class of light weight high performance – aluminum centric materials. The reinforcement in AMCs could be in the form of continuous or discontinuous fibres, whiskers or particulates with volume fractions ranging from a few percent to 70% [4]. Reinforcements commonly used in aluminum matrix composites have been extended to include organic wastes such as rice husk ash, coconut shell ash, palm oil fuel ash, fly ash and sugar cane bagasse [5], [6]. Ceramic materials being used as reinforcement include carbides, borides, nitrides and alumina. These have been reported to produce desired physical and mechanical properties in aluminum based composites [7]–[9].

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The use of Aluminum Matrix Composites (AMCs) has attracted interest in aerospace, defense and automotive applications owing to its high strength to weight ratio, improved stiffness, moderately high temperature properties, controlled thermal expansion coefficient, enhanced and tailored electrical performance, improved abrasion and wear resistance as compared to the monolithic alloys [4], [9]–[11].

Over the years, the quest for knowledge brought about by the need for complex combination of properties not obtainable in ordinary composite led to the production of hybrid composite. This is made possible by the dynamism of technology. Generally, different processing technique has been employed to produce metal matrix composites namely; Solid State technique, Liquid State technique, Powder Metallurgy technique, Physical Vapor Processing (PVD) technique and Direct Processing/Spray Deposition technique [8]. Although previous works on the improvement of hybrid composites properties such as; mechanical (hardness, tensile strength, fatigue resistance), physical (wear resistance, thermal stability) and chemical (corrosion resistance) over conventional composites have been carried out and reported in literature [12]–[15]. However, the methods used and results obtained differ from one another. The overall conclusion points in the direction of improvement on the basic properties. This work presents a careful and methodological review of current works on the effects of hybrid reinforcement on aluminum alloy's mechanical, physical and chemical properties.

II. Mechanical Properties

The mechanical properties of aluminum hybrid composites namely, tensile strength, yield strength, elongation and hardness have been determined through studies by some researchers. Table I shows the mechanical behaviours of some Aluminum Hybrid Composite.

Reference [16] shows that the addition of silicon carbide and fly ash (5%-SiC + 10%-fly ash) to Al 2024, produces a lighter composite with increase in hardness. Increase in tensile strength and decrease in elongation of the hybrid metal matrix composite occur in comparison with unreinforced aluminum. These results are attributed to increase in area fraction of reinforcement in matrix which results in improved tensile strength, yield strength and hardness.

TABLE I
MECHANICAL BEHAVIOURS OF ALUMINUM HYBRID COMPOSITE [15]-[18]

Aluminum Matrix Used	Reinforcement used	Mechanical Behaviour of Hybrid Composite
Al 2024	Silicon Carbide and Fly Ash	Lighter composite with increases, in hardness, in tensile strength and decrease in elongation of the hybrid metal matrix composite in comparison with unreinforced aluminum
	Silicon Carbide and Graphite	Tensile strength and the elastic modulus decrease with increase in volume fraction and particle size of graphite
Al‐Mg‐Si alloy	Silicon Carbide and bamboo leaf ash (an agro waste ash)	The hardness, ultimate tensile strength, and percentage elongation of the hybrid composites decreases with increase in bamboo leaf ash (BLA) content
A356.2 alloy	Rice husk ash (RHA) and Silicon Carbide (SiC)	Increase in hardness occurs as reinforcement volume fraction increases. Also, the ultimate tensile (UTS) and yield strength increases but with a decline in elongation

It has also been observed that texture of reinforcement can influence the mechanical behavior of the hybrid composites. The tensile strength and the elastic modulus of Al/SiC/Gr hybrid composites fabricated by squeeze casting are found to decrease with increase in volume fraction and particle size of graphite [17]. Reference [15] shows the viability of developing low cost – high performance Al matrix hybrid composites with the use of bamboo leaf ash (an agro waste ash) and silicon carbide as complementing reinforcement. The results shows that the hardness, ultimate tensile strength, and percentage elongation of the hybrid composites decreases with increase in bamboo leaf ash (BLA) content. But with 2 wt% BLA the hybrid composite demonstrates specific strength comparable to that of the single reinforced composite. However, the fracture toughness of the hybrid composite are superior to that of the single reinforced Al - 10 wt% SiC composite. Reference [18] studies the mechanical properties of aluminum hybrid composites containing various volume fractions of rice husk ash (RHA) and Silicon Carbide (SiC) particulates in equal proportion. It is observed that increase in hardness and porosity of the hybrid composites occurs as reinforcement volume fraction increases while the density decreases. Also, the ultimate tensile strength (UTS) and yield strengths increase but with a decline in elongation. The increase in strength of the hybrid composites are generally attributed to the increase in dislocation density and the attendant impediment to deformation.

Heat treating aluminum hybrid composites has also been found to generally affect its mechanical behavior. Reference [19] shows increment in hardness occurs as volume fraction of hard reinforcement in soft matrix increases. The heat treatment of the hybrid composites produces marked effect on its micro hardness over those not heat treated. The micro hardness of Al6061 hybrid composites is observed to be higher when compared with the matrix alloy. Heat treatment is reported to promote uniform grain structure which reduces the porosity and increases the hardness. Reference [20] studies the effect of heat treatment parameters on the wear behavior of aluminum hybrid composites. The volume loss of heat treated composite is found to diminish initially with increasing ageing duration and this revealed a minimum and then a reversal in the trend at longer ageing times.

III. TRIBOLOGICAL PROPERTIES

Wear rate of aluminum hybrid composites has been reported to be lower than that of binary composites. Different aluminum matrix and processing methods has also been employed by various researchers to determine tribological behaviours in aluminum hybrid composites. Table II shows aluminum matrix, reinforcement and tribological behaviours observed in some aluminum hybrid composites.

TABLE II
TRIBOLOGICAL BEHAVIOURS OF ALUMINUM HYBRID COMPOSITE [21]–[30], [33], [35]–[37]

Aluminum Matrix Used	Reinforcement used	Tribological Behaviour of Hybrid Composite
AA6061 alloy	Saffil and Silicon Carbide particles (SiCp)	Low wear rate.
	Silicon Carbide particles and graphite/antimony trisulphide	Wear rate decreases with increase in load and increases with increased speed and low friction coefficient, low temperature rise and low noise level
	Saffil and SiC	Better wear resistance under dry sliding at elevated temperature and high load compared to monolithic composite
Al-12Si alloy	Al_2O_3 and Carbon fibres	The wear rate decreases with increase in volume fraction of carbon fibre.
AA6061	Silicon Carbide and Graphite	Wear decreases with SiC content up to 20 vol. %, but increases above this content
	Silicon Carbide and Graphite	The wear resistance of the hybrid composites increases with increase of graphite particle size.
Al 6061 alloy	Silicon Carbide and Nickel coated Graphite (Gr – Ni)	The friction coefficient decreases as the percentage of Gr–Ni addition increases. The wear rates of all the composites with Gr–Ni additions are higher than the wear rate of base Al/SiC material with no Gr–Ni addition
A356 alloy	Silicon Carbide and Graphite	Addition of graphite leads to decrease of counter body wear.
AlMg10 alloy	Silicon Carbide and Graphite	Higher wear resistance of hybrid composites is achieved when compared to AlMg10 basic material Also, there is higher wear resistance for the same wt% of SiC in composites at higher graphite content
	Silicon Carbide and Graphite	Increased in resistance to wear and reduced coefficient of friction.
pure Zn-Al alloy	Silicon Carbide and Graphite	The hybrid composites possess values of coefficient of friction in between that of Zn-Al-SiC and Zn-Al-graphite composites and also possess excellent wear resistance as compared to the monolithic composites.
Al 2219 alloy	Silicon Carbide particles (SiCp) and Graphite	Increased in dry sliding wear resistance of Al/SiCp composite due to addition of graphite particles.
Al-Si10Mg alloy	Alumina and Graphite	sliding distance has the highest influence on wear rate followed by load and sliding speed
Al 6061 alloy		the wear resistance of hybrid composite increases with increase in the ageing durations.

Reference [21] investigates the dry sliding wear behavior of aluminum alloy reinforced with silicon carbide particles and graphite/antimony trisulphide (Sb_2S_3). Two composites are produced; the first a binary composite of Al. with 20% Silicon Carbide particles (SiCp) and the other an hybrid of Al with SiCp and solid lubricant (Graphite + Sb_2S_3) in solid state. Generally, the wear rate decreases with increase in load, increases with increased speed and low friction coefficient, low temperature rise and low noise level. The hybrid composites have acceptable level of tribological characteristics with blacky and smooth worn surface. Reference [22] examines the wear behavior of AA6061 alloy and its composites (AA6061 + 20 vol.% Saffil, AA6061 + 20 vol.% SiC, AA6061 + 11 vol.% Saffil + 20% SiC, AA6061 + 60 vol.% SiC). Hybrid composites of AA6061/11% Saffil/20% SiCp and 60% SiCp/AA6061 are found to show the best wear resistance against P400 SiC grit adhesive bonded paper. When tested against BS817M40 (EN24) steel, small improvements are observed for AA6061/11% Saffil and AA6061/20% SiC. However, hybrid of AA6061/11% Saffil/20% SiCp and the 60% SiCp/AA6061 composites still records low wear rates.

Hybrid composites of aluminum containing Saffil/SiC have been demonstrated to have better wear resistance under dry sliding at elevated temperature and high load compared to Al/Saffil and Al/Saffil/Al_2O_3 [23]. The dominant wear mechanism is abrasive under mild load and room temperature, and the dominant wear changes to adhesive as load or temperature increases. However, under lubricated condition, Al/Saffil display best wear resistance among them. The dominant wear mechanism of the composites is micro-ploughing with micro-cracking occuring to a large extent. In Reference [24] the composites of Al-12Si alloy reinforced with 12 vol. % Al_2O_3 shows a critical transition during loading from mild to severe wear between 196 and 245. However, for the monolithic Al-12Si alloy it is from 147 to 196 N. Moreover, the addition of short fibre of 4 vol. % Carbon in the 12 vol. % Al_2O_3/Al-12Si composites enhances further the critical transition load between 245 and 294 N. In essence, Carbon fibre has proven to be more efficient in improving wear resistance of the hybrid composites at higher applied load. Analysis of worn surfaces and subsurface regions indicates that the fibres show no significant effect on wear mechanisms of Al-12Si alloy. When applied load is below the critical load, dominant wear mechanisms are ploughing grooves and delamination. The unpeeling delamination layer is damaged and the dominant wear mechanisms shifts to severe wear when applied load exceeds the critical load. The hybrid composites of 12 vol. % Al_2O_3/Al-12Si containing carbon fibres has superior wear resistance over entire range of test temperatures carried out [25]. The critical transition temperature from mild to severe wear of the composites reinforced with only 12 vol. % Al_2O_3 fibre improves between 250 - 300^{o}C and 150-200^{o}C for the monolithic aluminum alloy. However, the critical transition temperature of the hybrid composites reinforced with Al_2O_3 and carbon fibres improves further in the range 350 - 400^{o}C. The wear rate of the hybrid composites of 12 vol. % (Al_2O_3/Al – 12Si) decreases with increase of volume fraction of carbon fibre up to 6 vol. %. Analysis of worn surfaces and subsurface regions indicates that reinforcing fibres have no significant effect on wear mechanisms of Al-12Si alloy. The dominant wear mechanisms shift to severe adhesion at test temperatures above the critical transition temperature.

Reference [26] shows the effect of SiC content on the tribological behavior of Al/SiC/Gr hybrid composites obtained by in-situ powder metallurgy (IPM) with AA6061 alloy as the base. The composites contain 9 vol. % of graphite with 0 – 40 vol. % content of SiC. Sliding distances used are 250, 500, 750 and 1000 m. It is observed that wear decreases with SiC content up to 20 vol. %, but increases above this content. The friction coefficient value decreases with increase in SiC content with minimum value at 30 vol. % SiC and beyond this, it increases. Reference [27] shows that the addition of graphite decreases the friction coefficient and the wear resistance of SiC/Al composites significantly by 170-340 times. Moreover, the wear loss of counter face steel is observed to decrease by a factor of about 2/3. The wear resistance of SiC/Grp/Al composites increases with increase of graphite particle size. The improvement of wear resistance is mainly attributed to the enhancement of lubrication tribo-layer which is composed of a complex mixture of iron oxides, graphite, fractured SiC particles and some fine particles containing aluminum.

Reference [28] studies the tribological behavior of Al/SiC/Ni-coated graphite (Gr–Ni) hybrid composites with various amounts of Gr–Ni addition synthesized by the semi-solid powder densification method. The SiC and nickel-coated graphite (Gr–Ni) particles is reported to be distributed quite uniformly in the aluminum matrix. There was reduction in graphite agglomeration in composites with coated Gr–Ni particles than in composites with non-coated Gr particles. Both the coefficient of thermal expansion (significantly) and fracture energy (monotonously) decrease with the amount of Gr–Ni addition. Wear debris becomes smaller, which causes smaller electric contact resistance, as the amount of Gr–Ni addition increases. Seizure (the inability of a material to resist physical joining or friction welding when it is in contact with surface of another material) occurs for monolithic aluminum alloy, but no seizure in Al/SiC and Al/SiC/Gr–Ni composites. The friction coefficient and its fluctuations decrease as the percentage of Gr–Ni addition increases. The graphite particles released from the composites adhered to the wear surfaces of the composites and its counterparts. Due to the "composite effects", wear rates of both the composite and its counterpart increases as the amount of Gr–Ni addition increases up to 5 vol. % Gr–Ni addition. It then decline for 8 vol. % Gr–Ni addition. The wear rates of all the composites with Gr–Ni additions are higher than the wear rate of base Al/SiC material with no Gr–Ni addition. Thus, composite incorporating graphite is not suitable for wear reduction, as the loss in mechanical properties is higher than the very small benefit in friction reduction.

Metal matrix composites based on zinc/aluminum alloy (ZA) matrix are increasingly applied as light-weight and wear resistant materials. In [29] the tribological behavior of hybrid composite with A356 base reinforced by 20 vol. % of SiC and 3 vol. % of graphite (Al/20SiC/3Gr) is studied. Wear resistance of Al/20SiC/3Gr hybrid composite is approximately equal to wear resistance of Al/20SiC composite at low and medium loads. Tribological tests are performed on a block-on-ring contact pair without lubrication at load size from 1- 441 N. For loads lower than 20N, wear of Al/20SiC/3Gr hybrid composite and Al/20SiC composite is 10 times lower than wear of a basic material without reinforcement (A356). Due to hardness of SiC particles, Al/20SiC/3Gr hybrid composite has 0.5 times higher wear resistance than Al/20SiC/10Gr at higher loads. However, the graphite leads to decrease of counter body wear. Hybrid composites with the following reinforcement content: AlMg10/5SiC/2Gr, AlMg10/5SiC/5Gr, AlMg10/15SiC/2Gr and AlMg10/15SiC/5Gr are tested for influence of combined reinforcement by silicon-carbide and graphite on a hybrid composite with AlMg10 matrix [30]. Tribological tests are performed on tribometer block-on-disc with load of 50 N and sliding distance of 3000 m. The results show that wear resistance of hybrid composites is higher than wear resistance of AlMg10 basic material. Also, there is higher wear resistance for the same value of SiC with composites at higher graphite content [31], [32]. Thus, higher wear resistance is found for hybrid composites with 15% SiC and 5% Gr. Newly formed Al/SiC/Gr hybrid composites are combination of two different hybrid materials.

In the reviews of the tribological characteristics of aluminum hybrid composites reinforced with silicon carbide and graphite, the hard particles of silicon carbide increases the hardness and resistance to wear, while soft particles of graphite improve lubrication and reduce friction coefficient and wear [33]. Percentage of silicon – carbide (SiC) ranges from 0-40% and that of graphite within 0-13%. The particle sizes of SiC and graphite used depends on the manufacturer and procedure for obtaining hybrid composites. Tribological tests show that load, sliding speed, sliding distance, content and size of reinforcement particles influence the magnitude and type of wear and friction coefficient of Al/SiC/Gr hybrid composites with aluminum matrix. Thus, while tribological characteristics of Al/SiC/Gr hybrid composites depend on a number of factors, their characteristics are much better in comparison to Al-SiC and Al-Gr composites. Reference [34] examines the melting of pure Zn-Al using coke fired furnace. Preheated silicon carbide and graphite powders in the weight ratios of 3:1, 5:1, 10:1 are added to the vortex of the molten metal. A 10 min. stirring time is used, while degassing is done using commercially available degassing tablets. The composite melts are poured into preheated cast iron cylindrical moulds. Cast hybrid composites are machined and subjected to metallographic studies, hardness, friction, and wear tests. Friction and wear tests are conducted using a 10 mm diameter specimen on a pin-on-disc machine. Counter disc used is made of high carbon high chromium steel of hardness RC 60. Sliding speed is between 100 and 500 rpm with a sliding velocity of 0.3 - 1.5 ms^{-1} while load is between 10 and 50 N. Frictional force is recorded using a force transducer while the wear loss is measured in terms of height loss of the specimens using an LVDT (Linear Variable Differential Transformer). It is observed that there is a fairly uniform distribution of reinforcements in the matrix metal. The addition of SiC to Zn-Al, promote enhancement of hardness of Zn-Al composites. Use of graphite as an additional reinforcement to Zn – Al – SiC composites is responsible for the loss in hardness although it is not drastic. The hardness of the hybrid composites is lower than Zn-Al-SiC but superior to both Zn-Al and Zn-Al-graphite composites. The increased wear resistance of the hybrid composites when compared with pure Zn-Al is attributed to increase content of SiC, a hard ceramic which results in hardness enhancement of the composites. Increase in hardness leads to lowering of wear loss and seizing. Thus, the hybrid composites possess values of hardness and coefficient of friction in between that of Zn-Al-SiC and Zn-Al-graphite composites but possess excellent wear resistance to the monolithic composites.

The hybrid composite of Al 2219 alloy containing 15% SiCp and 3% graphite shows less degree of subsurface deformation in comparison to Al 2219/15SiCp non-graphitic composite [35]. The subsurface deformation increases with increased sliding speeds in the mild wear region. The statistical evaluation using analysis of variance (ANOVA) to study the role of graphite during dry sliding wear of hybrid composite Al/SiCp/Gr found that graphite particles are effective agents in increasing dry sliding wear resistance of Al/SiCp composite. Reference [36] shows the tribological behaviour of aluminum alloy (Al-Si10Mg) reinforced with alumina (9%) and graphite (3%) fabricated by stir casting process. The influences of applied load, sliding speed and sliding distance on wear rate, as well as the coefficient of friction during wearing process are carried out using ANOVA while regression equations for each response are developed. The results show that sliding distance has superior influence followed by load and sliding speed.

Reference [37] shows that the wear resistance of hybrid Al 6061 composite increases with increase in the ageing durations. However, in as-cast and heat-treated hybrid composites, the wear rate increases when the sliding distance increases.

IV. Thermal Properties

The evaluation of thermal properties of aluminum hybrid composites is important in order to be able to determine their suitability for high temperature applications. Table III shows the thermal behaviour of some aluminum hybrid composites.

TABLE III
THERMAL BEHAVIOURS OF ALUMINUM HYBRID COMPOSITE [14], [38]

Aluminum Matrix Used	Reinforcement used	Thermal Behaviour of Hybrid Composite
Aluminum-Silicon alloy	Silicon Carbide and graphite	The thermal conductivity of hybrid composites is reduced due to the enrichment of the graphite component
A242 aluminum alloy	SiC and Ni	The development of Ni_xAl_y intermetallic reinforcement, in addition to SiC particulate as reinforcement to an aluminum alloy is important for improved high temperature property. The hybrid composite is found to provide improved elevated temperature property over the test temperature even up to 400°C.

Reference [14] shows the thermal property of aluminum-silicon alloy based hybrid composites reinforced with silicon carbide and graphite particles and produced by liquid phase particle mixing (melt stirring) and squeeze casting. The hybrid composites with 5, 7.5 and 10 vol. % graphite contents with a consistent reinforcement fraction of ~20 vol. % of silicon carbide are investigated. Results indicate that increasing the graphite content improves dimensional stability, and there is no significant variation between the thermal expansion behaviors of 45 µm and the 53 µm silicon carbide reinforced composites. The thermal conductivity of hybrid composites is reduced due to the enrichment of the graphite component. In Reference [38] the elevated temperature property of aluminum hybrid composites produced through squeeze cast technique is examined. This technique involves the preparation of a preform and subsequent infiltration of the preform with an aluminum alloy. The hybrid composite is derived from SiC, Ni particulates and A242 aluminum alloy with SiO_2 used as the ceramic binder. The preform is made with 40 vol % SiC and 2.8 vol % Ni powder. During the second stage of composite fabrication, molten aluminum is infiltrated into the SiC and Ni particulate preform and the molten aluminum reacts with the Ni particulates to form Ni_xAl_y intermetallics. The development of Ni_xAl_y intermetallic reinforcement, in addition to SiC particulate as reinforcement to an aluminum alloy is important for improved high temperature property. The hybrid composite is found to provide improved elevated temperature property over the test temperature even up to 400°C.

V. CHEMICAL PROPERTIES

Studies have been carried out to determine the behavior of aluminum hybrid composites in environment where materials are susceptible to corrosion. Table IV shows the Corrosion Resistance behavior of some Aluminum Hybrid Composite.

TABLE IV
CORROSION RESISTANCE BEHAVIOURS OF ALUMINUM HYBRID COMPOSITE [39], [15]

Aluminum Matrix Used	Reinforcement used	Corrosion Behaviour of Hybrid Composite
Al–Si–Mg alloys	Silicon Carbide and fly ash	By using calcined fly ash the chemical degradation of the composites is fairly avoided
AlMgSi	Bamboo leaf ash (an agro waste ash) and silicon carbide	In salt solution, hybrid composites shows higher corrosion resistance in comparison to the single reinforced Al - 10 wt% SiC composite

Reference [39] shows the corrosion behavior of hybrid $Al/SiCp/MgAl_2O_4$ composites processed at different temperatures and exposed to indoor laboratory atmosphere. The aluminum-based composites have two different Si/(Si+Mg) molar ratios processed by the pressure-less infiltration technique, starting from SiCp/fly ash preforms and two purpose-designed Al–Si–Mg alloys (prepared from recycling aluminum and extra additions of Mg and Si). Type A composite contains an alloy with a typical Si/(Si+Mg) molar ratio of 0.32 and fly ash in the as-received condition. The type B composite is an alloy with a Si/(Si+Mg) molar ratio of 0.148 and with calcined fly ash. The preforms (reinforcement) are infiltrated with the corresponding aluminum alloy at 1050, 1100 and 1150°C for 60, 50, and 70 min respectively, using ultra high purity argon at a pressure slightly above that of the atmospheric pressure (total pressure ≈ 1.2 atm). After physical property evaluation and microstructural characterization, the composites are exposed to indoor ambient atmosphere. The average relative humidity, minimum ambient temperature and maximum temperature are 54%, 15±4°C and 26±5°C respectively. Type A composite exhibit signs of deterioration after 1 month of exposure with the appearance of a light-gray powder on its surface. On the other hand, the surface of type B composite remains free of corrosion products even after 11 months of exposure. Powdery corrosion products are collected from type A and Type B composites which remain un-corroded and are both characterized. The apparent densities of both types of composites are found similar (~2.7 g cm^{-3}) independent of the processing temperature. Likewise, the residual porosity in type A and type B composites are comparable, with an average of 2.8±1%. For type A composite prepared with an alloy Al–8Si–15Mg (wt. %), corresponding to a Si/(Si+Mg) molar ratio of 0.32, the intermetallic Mg_2Si is precipitated during solidification. In the presence of condensed humidity it acts as a micro anode coupled to the matrix, leading to a catastrophic localized corrosion. Although the potential attack of SiC by liquid aluminum is successfully avoided by the presence of SiO_2 in the fly ash (FA) added to the SiCp performs. However, Al_4C_3 is still formed due to the reaction of carbon in the fly ash with aluminum and thus, chemical degradation occurs. For type B composite processed with the alloy Al–3Si–15Mg (wt. %), the silicon content is low enough to avoid the formation of Mg_2Si. The absence of such intermetallic compound explains the physical integrity of the composite even after 11 months of exposure to the humid environment. Moreover, chemical degradation did not occur either, because formation of the Al_4C_3 phase is successfully avoided by the presence of SiO_2 (in the FA added to the SiCp preforms) or by the absence of carbon in calcinated fly ash. By using calcined fly ash the chemical degradation of the composites is fairly avoided. Thus, the control of Mg_2Si formation during processing becomes a critical parameter to avoid aggressive localized corrosion.

Reference [15] shows the viability of developing low cost – high performance Al matrix hybrid composites with the use of bamboo leaf ash (an agro waste ash) and silicon carbide as reinforcements. The addition of 0-3 wt % of silicon carbide (SiC) particulates and 4 wt % bamboo leaf ash (BLA) are utilized to prepare 10 wt % of the reinforcing phase with AlMgSi (6000 series) alloy as matrix using two-step stir casting method. In evaluating the corrosion behavior of the hybrid composite using 5wt% NaCl solution, it is observed that the 2 and 3 wt % BLA hybrid composites shows higher corrosion resistance in comparison to the single reinforced Al - 10 wt % SiC composite. But in 0.3 M H_2SO_4 solution reverse trend is observed where the single reinforced composite has superior corrosion resistance.

VI. Machinability

References [40] and [41] show the machinability of hybrid Al/SiC/Gr composite material. The results show that the hybrid composites can easily be machined by Electric Discharge Machining EDM and a good surface quality obtained by controlling the machining parameters. The machining difficulty is the reason for the limited use of aluminum hybrid composite. The identified problems encountered during machining of hybrid MMCs are; rapid tool electrode wear rate, irregular material removal rate (MRR), requirement of large pulse current values, difficulty to cut very complex and complicated shape or geometrical profile. Others include; very poor surface finish and low machining rate, frequent stoppages of metal removal during machining as SiC particles in the particulate reinforced behaves like a cutting edge during machining of Al/SiC/Grp-MMC. Aluminum matrix composites are harder than Tungsten carbide (WC) which is basically one of the cutting tools materials used in machining [41].

Reference [42] shows the surface roughness characteristics of hybrid aluminum metal matrix (Al6061-SiC-Al_2O_3) composites. The experimental studies are carried out on a lathe while the composites are prepared using the liquid metallurgy technique, with 3, 6 and 9 wt % of particulates of SiC and Al_2O_3 dispersed in the base matrix. The surface roughness increases with increase of feed rate and reduces with increase of cutting speed.

The machining properties and mathematical modeling of aluminum alloy hybrid (Al-alloy/SiC/flyash) fabricated by stir casting and powder metallurgy methods are examined [43]. Different volume fractions of SiC particles (10, 15 and 20 vol. %) with fixed volume of 10 vol. % fly ash are used for the synthesis. Results indicate that wear resistance and hardness improved with increase vol.% SiC. The tensile strength is high at 10 vol. % SiC and decreases beyond this content. Microstructure shows a fairly uniform distribution of the dispersoids. Electric discharge machining is done on the composite specimens and mathematical models are developed for predicting the material removal rate and tool wear rate using design of experimentation with current, pulse duration and vol. % of SiC as the process variables. Curves describing the direct and interaction effect of the process variables are drawn. It is found that the material removal rate and tool wear rate increases with increase in current and decreases with increase in pulse duration and vol. % of SiC. The behaviour of the composites is similar both for powder metallurgy and stir casting processes, except that stir cast specimens exhibit higher hardness, wear resistance and tensile strength. This increase is attributed to the close interfacial bonding existing in stir cast specimens.

VII. Hybrid Processing

Aluminum hybrids can be produced through various processes consisting of conventional methods, modifications or entirely new methods. These methods includes; stir casting/Compocasting [44], powder metallurgy [45] spray atomization and co-deposition [46], plasma spraying [47] and squeeze-casting [48], in-situ powder metallurgy – IPM [26]. Liquid metallurgy has been observed to be most explored by researchers. However, the stir casting/vortex technique is the simplest and most commercially used in Liquid Mettalurgy because it offers better matrix-particle bonding due to stirring action of particles into the melts [49]. It has also been observed that the selection of appropriate processing parameters like stirring speed, time, and temperature of molten metal, preheating temperature of mould and uniform feed rate of particles provides for homogeneous mixing and good wetting [50]. Reference [51] shows the effect of processing technique on Al6061-SiC- Al_2O_3 Hybrid composites produced by stir casting. It is observed that, the vortex technique is one of the best known approaches used to create good distribution of reinforcement material in the matrix. Good quality composites can be produced by this method through proper selection of the process parameters such as pouring temperature, stirring speed, preheating temperature of reinforcement e.t.c,. The coating of alumina on the blades of the stirrer is also essential to prevent the migration of ferrous ions from the stirrer into the molten metal.

VIII. Summary

The review of physical, mechanical, tribological and chemical properties of aluminum hybrid composites have shown possibility of enhancement with the right combination of reinforcement materials, its percentage volume, particle size among others. The deductions from previous works on aluminum hybrid composite are that:

- Hybrid composites generally have better mechanical, physical and chemical properties than the conventional composites.
- The use of Ceramic materials as hybrid reinforcement generally increase hardness, tensile strength, toughness, wear resistance and corrosion resistance of the composites over the base aluminum alloy.
- The degree of improvement of physical, mechanical and chemical properties of hybrid composite is strongly dependent on the nature of the reinforcement's hardness, particle size, and uniformity of dispersion within the matrix, volume fraction and the method of production of the hybrid.
- The use of soft reinforcement with the hard reinforcement

in hybrid composite such as graphite reduces friction coefficient and increases machinability of the hybrid composite unlike having all hard (ceramic) reinforcement.

- Heat treatment of hybrid composites promotes uniform grain structure which reduces porosities thereby enhancing the hardness.
- Corrosion resistance of composite is a function of the reinforcing material and the corrosive medium.
- Different methods of production of hybrid composites have been identified with the vortex principle (stir – cast procedure) being the most widely used. Good quality composites can be produced by this method through proper selection of the process parameters such as pouring temperature, stirring speed, preheating temperature of reinforcement etc.

IX. Conclusion

Improvement in the physical, tribological, mechanical and chemical properties of hybrid composites over conventional composites have been shown by studies. Factors such as nature and volume fractions of reinforcement, particle size, degree of uniform distribution of reinforcing particles in the matrix, production method and heat treatment have been identified as the determinants for hybrid composite properties improvement. Hybrid technology provides the opportunity to use various materials ranging from organic to inorganic. Therefore, the use of cheaper, easily accessible and non long chain reinforcements for the production of aluminum hybrid composite with satisfactory properties should be explored.

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