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Silicon Carbide Reinforced Aluminium Metal Matrix Composites for Aerospace Applications: A Literature Review

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Abstract: This paper considers the potential of use Al-SiC metal matrix composite (MMC) with particular reference to the aerospace industry. Initially, the required properties are identified, after which, the work explores pure aluminium and its importance in the industry along with its limitations. Using these limitations, MMC's were recommended as a possible replacement for aluminium and it is seen that the exact set of properties depend on certain factors. Therefore these factors such as reactivity at the interface, volume fraction of the reinforcing material, type of the reinforcing material and distribution of the reinforcing material are reviewed using the existing literature. Using the information available, the paper advocates the use of Al-SiC MMC in the fuselage skins of high performance aircrafts. However, it must be noted that the recommendations are purely based on the data available and the author's interpretation of it although every effort has been made to be as logical as possible.

Keywords: Aluminium, silicon carbide, metal matrix composite, aerospace

I. INTRODUCTION

Ever since the Wright brothers flew their 'heavier-than-air' machine, the aviation industry has grown in great leaps and bounds. Because aircrafts were getting faster and/or bigger, the need to develop newer materials took centre stage- the use of wood and fabric gave way to stronger metallic structures (built predominantly using aluminium and its alloys). However, ceramics and composite materials are slowly replacing these too [1]. Since the need to develop more efficient aircraft hasn't subsided, the requirementfor better materials is stillin great demand. This paper explores the possibilities of one such material; aluminium- silicon carbide composite (Al-SiC).

Initially, the work will look to identify the necessary properties of a material that is to be used in the aerospace industry. The reasons for aluminium's extensive application in the aircraft industry will then be identified and the use of metal matrix composites (MMC) to counter the pure element's (aluminium) shortcomings will be advocated. Once a case for Al-SiC MMC has been made, the work will look to explore and understand the different factors that could have an effect on the fabrication and the final properties of the composite.

II. REQUIRED PROPERTIES

Since this work concentrates on the aviation industry, it is advisable to initially consider the properties of the materials used in such applications. According to Corke [2], the most commonly used criterion whilst deciding on a material is the weight. A lighter aircraft requires less energy and, hence, less fuel to operate.It is said that a large aircraft (turbojet) could reduce its fuel usage by 1.1-1.5 per cent when the weight is decreased by 1,000 kgs [3].Apart from this, properties such as high strength, corrosion resistance, creep characteristics, fatigue behaviour/performance, machining and fabrication ability, fracture toughness and high modulus, ductility and distortion after machining [2, 4, 5] also play an important part in the selection. It is also seen that materials with high thermal strength and stability produces a great saving on fuel consumption – forexample, an increase in the turbine inlet temperature from 1,200°C to 1,500°C would produce 6-8 per cent increase in fuel burn efficiency) [3].

However, the exact set of properties and their importance is heavily dependant on the specific component/part [5]. Starke Jr. & Staley [1]have shown that whilst considering a material for the fuselage of an aircraft, properties like fracture toughness, strength, Young's modulus, corrosion, fatigue initiation and fatigue crack growth are all important. Similarly, materials in the wing spar are chosen based on shear yield strength and compressive modulus (for the spar web), compressive yield strength and modulus (for the web stiffeners), fatigue, damage tolerance and corrosion resistance [1]. Therefore, sometimes up to 20 different alloys are used in an aircraft [3].

III. ALUMINIUM

Although aircrafts utilise numerous elements in their construction (as discussed in the previous section), perhaps the most important of these is Aluminium.To illustrate, although the Airbus A380 is considered to have the lowest percentage (by weight) of aluminium, it still contains 61 per cent of the element [3]. The main reason for this extensive use is its low weight; density being about one-third of copper or steel alloys [6] and its specific gravity being 2.72 [7].According to Prabu et al., [8] aluminium has high strength, ductility, thermal and electrical conductivity. Although the material's electrical conductivity of 34 X 10^4 ohm^{-1} cm^{-1}[7] may only be around 62 per cent of that of copper's, it is preferred in many industrial situations because of its low weight [6]. In addition, aluminium also has very good machinability and workability, it can be cast (by any known method), rolled, stamped, spun, drawn, forged, hammered and extruded to almost any shape [6] which makes it easier for manufacturers to produce intricate shapes and patterns required in the aircraft industry. Its ability to resist corrosion through the formation of dense and strong layer of Al_2O_3 (Aluminium oxide) on its surface when exposed to the atmosphere [7] is also seen as factor in its extended use.

Aluminium's usage is constrained by its limited strength and hardness (hence, being used only in lightly loaded structures) as well as its low melting point- 658°C [7]. Additionally, Prabu et al. [8] and MahendraBoopathi et al. [9] also comment about the material's poor stiffness and tribological properties respectively.Thus, the material is combined with various other elements to improve the above-mentioned (and other) properties depending upon its application.An example of such a combination includesa family of materials known as aluminium metal matrix composites.

IV. METAL MATRIX COMPOSITES

Metal matrix composites constitute a metallic matrix that is reinforced with another material, usually in the form of fibres, particulates, whiskers etc.According to Pai et al., [10] the reinforcing material usually carries most of the load and the matrix material, by holding them together, enables load transfer. The advantages of using these materials (with metals as matrices) include high tensile and shear moduli, good fatigue and fracture properties, small thermal expansion coefficient, high melting point, high toughness, high ductility, high thermal and electrical conductivities, good erosion (and/or corrosion) resistance, dimensional stability and good moisture resistance [11, 12].In addition, MMCs with aluminium as the matrix benefit from good wear resistance, high specific modulus and specific strength [13].

A. Silicon Carbide-Aluminium MMC

One such example of MMC is an aluminium matrix composite reinforced with silicon carbide (Al-SiC). The most important property of aluminium-silicon carbide with reference to the aerospace industry is its strength to weight ratio, which is three times more than mild steel[14]. In addition,composites containing SiC (reinforcing material) and Al (matrix) have high modulus, strength values, wear resistance, high thermal stability, less weight and a more effective load carrying capacity compared to many other materials [15, 16]. It is also expected that this composite will exhibit good corrosion/ oxidation properties since silicon carbide forms a protective coating of silicon oxide at 1,200°C [9] and, as discussed earlier, aluminium also displays a similar reaction. Therefore, it can be seen that this material offers considerable advantages to the aerospace industry especially in applications that require good thermal and tensile properties.

V. FACTORS AFFECTING THE PROPERTIES OF AL-SIC

Although the previous section briefly discussed some of the properties of Al-SiC, the composites exact set of properties depend on a number of factors.Apart from the changes in microstructure of matrix and reinforcements that could result from various work hardening or heat treatment processes, this work has identified four factors from the existing literature that could affect the properties of Al-SiC:

- Reactivity of the matrix and the reinforcing material
- Type of the reinforcing material
- Volume fraction of the reinforcing material
- Distribution of the reinforcing material

Before we explore how each aspect affects the properties of the material, we briefly discuss certain fabrication methods of Al-SiC, since theyultimately decidethe aforementioned factors.

A. Fabrication of Al-SiC

Chou et al. [11] broadly classify fabrication of MMC's into two categories i.e., Solid Phase and Liquid Phase. Solid Phase methods include Diffusion bonding (such as Cold Isostatic Pressing), Rolling, Extrusion, Hot Isostatic Pressing (HIP) etc., Liquid Phase techniques involve molten metals and examples are Squeeze Casting, Stir Casting, Rheo Casting and various types of infiltration processes. The authors [11]also advocate the use of multiple methods to fabricate the composite including a combination of certain infiltration techniques, rolling and hot pressing or vacuum infiltration and HIP.

This work recommends the use of Liquid Fabrication techniques for producing Al-SiC, since this melts the aluminium and aids in the formation of an interface layer, which improves certain properties (this discussion will be taken up in more detail later on). Processes such as Stir Casting [9] and Disintegrated Melt Deposition (DMD) [17] have been used in fabricating Al-SiC Composites.

VI. PROPERTY DEPENDANCE OF AL-SIC COMPOSITES

This part of the paper primarily involves the study of various factors that could contribute to a change in the properties of an Al-SiC composite. The study will look to explore how the changes ultimately affect the physical properties and the chemical composition of the material.

A. Reactivity of the Matrix and the Reinforcing Material

The properties at the interface contribute largely to the overall working and behaviour of the composite. It is seen that the load transfer across the interface is responsible for thestrength and stiffness; ductility is influenced by relaxation of peak stress near the interface and toughness is dependant on the crack deflection in the interface [11, 17, 18, 19, 20].Therefore, it is essential to study the reactions at theinterface whilst considering any MMC.

In the case of Al-SiC the primary reaction at the interface is [21, 22, 23, 24]:

$$\mathbf{4Al + 3SiC \rightarrow Al_4C_3 + 3Si}$$

According to Tham et al., [17] Al_4C_3 (brittle in nature) is insoluble and therefore forms either as a detached precipitate or a continuous layer around the SiC particles. However, silicon enters the aluminium matrix to form an Al-Si binary alloy.

The Al_4C_3 layer at the interfaceimproves the average offset yield strength (0.2%), ultimate tensile strength, work-to-fracture and work hardening ratewith only a slight reduction in the ductility of the material [17]. However, before exploring the reasons for this change in the properties, it is essential to briefly consider the fracture characteristics of both types i.e., with and without the Al_4C_3 layer. When Al_4C_3 is not present, fracture i.e., crack propagation primarily happens through decohesion at the interface. This is because many particles are only partially bonded to the matrix [17]. Howeverwhen the Al_4C_3 layer is present, fracture propagates mainly through particle breakage, suggesting a strong interfacial bond [17]. This 'well bonded' interface ensures a more efficient load transfer across the interface [25] and ispredominantly responsible for the increase in mechanical properties [17]. The reason for this increased bond strength is because of the Al_4C_3 layer's ability to form orientation relationships and semi-coherent interfaces with both the matrix and the particle and also because it is 'keyed' in to both the surfaces [17]. Ductility, however, was reduced because of the stress levels in matrix exceeding the matrix failure stress, which happens as a consequence of the greater levels of plastic constraint introduced by the more rigidly bonded interfaces and the greater work hardening [26, 27].

Althoughthis layer produces benefits in terms of mechanical properties, it must be ensured that the layer doesn't become very thick as thicker layers are more prone to fracture since, they have more chances of containing a flaw that is larger than a critical size and will reduce the mechanical properties [17]. It should also be understood thatthis critical length is system specific [20]. A further reason to limit the reaction is because increasing theamount of silicon in the system will lowerthe melting point of the alloy [28].

Another method used to improve the mechanical properties is to increase the wettability of the particle and the matrix. Lloyd et al. [28]show that the reaction to form Al_4C_3 requires time, saturating only after an hour. Hence, it may be more viable to increase the wettability since holding the material at high temperatures consumes time and energy. The fact that this route may complicate the process because of the additional elements and techniques involved must also be considered prior to fabrication.

TABLE I
VALUES OF PROPERTIES WITH AND WITHOUT THE AL_4C_3 AYER

Property	Without Al4C3 layer	With Al4C3 layer	Reference
0.2% yield strength (MPa)	97	103	Tham et al. [17]
Ultimate tensile strength (MPa)	113	139	
Work-to-fracture ($x10^{-3}$ J/mm^3)	17	18	
Work hardening rate	0.0704	0.1122	
Ductility (%)	16	14	

Note: Although the original study gives the possible variation of the values (tolerance), it is omitted here.

1) *Wettability:*According to Oh et al., [29] good wetting between the solid and liquid is essential for the formation of satisfactory bonds between them during casting. This section will briefly discuss this phenomenon in terms of Al-SiC fabrication. Wettability is defined as the ability of the liquid to spread on a solid surface and represents the magnitude of intimate contact between them [30].Pai et al. [31] and Hashim et al. [30] remark that the principles to improve wettability are mainly based on – decreasing the surface tension of the liquid, decreasing the solid-liquid interfacial energy at the interface or increasing the surface energy of the solid. Using this, Young [32],Himbeaultet al. [33], Tafto et al. [34] and Chou et al. [11] suggest techniques such as the addition of an alloying element, coating and/or treating the particles to increase the wettability in MMCs.

It has been found that the addition of magnesium improves the wetting characteristics of aluminium-based composites because of its lower surface tension [30]. In accordance, Sukumaran et al. [35] found the optimum percentage (of magnesium) for obtaining the best distribution and mechanical properties to be around 1 and MahendraBoopathi et al. [9] added 1.5 per cent of magnesium to increase the wettability of the Al-SiC composite. Magnesium also acts as a scavenger of oxygen, thereby increasing the surface energy of the particles [30]. However, care must be taken not to add excess magnesium, as this will form low melting compounds, which will degrade the mechanical properties of the composite [30].
The second method to increase the wettability is to heat treat the reinforcing materials. It has been found that heating SiC particles above 900°C has improved wettability. In their work, Warren & Anderson [21] show that the contact angle at 900°C is 150 but when the temperature was increased to 1,100°C (at a constant pressure of $2.7 \text{ x } 10^{-4}$torr), the study conducted by Kohler [36] shows that it had decreased to 42, thereby increasing the wettability. One of the causes for this increase is the formation of an oxide layer by the meltat temperatures lower than 900°C [30, 37]. Other reasons include the removal of impurities in the surface, desorption of gases and the formation of an oxide layer on the surface [38].Hashim et al. [30] state that the function of this oxide layer is different to that of the melt oxide layer (which reduces the wettability of the compound).

Another process used to increase the wettability of a MMC is to coat the reinforcing agent with another material. Generally non-metallic metals are coated with metals because liquid metals find it harder to wet non-metallic substances compared to solid metals [30]. Methods of coating include chemical vapour deposition (CVD), physical vapour deposition (such as evaporation, direct ion beam deposition and sputtering), plasma spraying, electrochemical plating and cementation [11]. Although Nickel is the most commonly used coating metal for aluminium composites [39, 40, 41, 42], chromium carbide has also been suggested because it forms a more stable layer from the formation energy's viewpoint than an Al_4C_3 compound in Al-SiC composites [11]. However, the authors also add that a duplex coating is more time consuming.

In addition to the above-mentioned process, Hashim et al. [30] also discuss ultrasonic vibrations and application of mechanical forces (such as stirring) as possible methods to increase the wettability of a composite. It can be seen that the wettability of the matrix and the particle plays a major role in determining the properties of the composite material as good wetting results in a stronger bond at the interface [30].

B. Volume Fraction of the Reinforcing Material

Since the reinforcing material bears a major portion of stress in the MMC (because it's stiffer) [9], its use in the composite (such as volume fraction, distribution and type) goes a long way in determining the final properties of the material.

The study carried out by MahendraBoopathi et al. [9], considers tensile strength, density, yield strength, elongation and hardness of the MMC with respect to the percentage of the reinforcing material i.e., SiC.

Whilst consideringdensity,MahendraBoopathi et al. [9], show that it decreases with the increase in SiCcontent; the reason being the lower density of the SiC particles. It is also seen that properties, such as tensile strength [9], yield strength [9], hardness [9, 43, 44], impactstrength [43] and wear resistance [44],all of which increase/improve with an increase in SiC. It is felt that the reasons for this increase in these properties is attributed to the number of SiC particles that are directly proportional to the stress needed to initiate and propagate the cracks in the composite.However, the elongation percentage reduces as the SiC content grows [9].Nevertheless, the work of Singla et al. [43] shows that when SiC increases to above 25%, properties such as hardness and impact strength reduce. The authors say this happens because the increasing quantities of SiC particles react with each other (clustering) and settle down,thereby contributing to a local reduction in density (of SiC particles) and lower hardness (refer Singla et al. [43] for more details).

In another study, NeelimaDevi et al. [14] also compare the percentage of SiC content with tensile strength and elongation wherein they found that the tensile strength increases with the SiC content up to 15% after which it drops. The percentage of elongation, unlikeMahendraBoopathi et al. [9],was proportional to the SiC percentage.

It is believed that the cause of the drop in tensile strength when the SiC content crosses 15% is probably because ofthe increased(total) area of the interface i.e., number of interfaceswhich, could result in void nucleation (through interfacial decohesion) and coalescenceleading to failure at lower stresses (void nucleation and coalescence are discussed in more detail byTham et al. [17]). With respect to elongation, both the considered studiesi.e., MahendraBoopathi et al. [9] and NeelimaDevi et al. [14] show contradicting results. It may be argued that there are some anomalies in the latter study's data since there is always a trade off between strength and ductility and, both cannot rise/fall simultaneously as described in the study (where both tensile strength and elongation percentage are proportional to each other till 15% SiC content).

TABLE II
VALUES OF PROPERTIES WITH DIFFERING SIC CONTENT

Property	SiC- 5%	SiC- 10%	SiC-15%	SiC-20%	Reference
Density (g/cm^3)	2.4660	2.3125	N/A	N/A	MahendraBoopathi et al. [9]
Yield strength (N/mm^2)	236	257	N/A	N/A	
Hardness (BHN)	85.3	87.2	N/A	N/A	
Tensile strength (N/mm^2)	248	265	N/A	N/A	
Elongation (%)	19.0	18.2	N/A	N/A	
Tensile strength (N/mm^2)	80.84	88.11	94.21	83.00	NeelimaDevi et al. [14]
Elongation (%)	5.42	5.92	5.57	6.87	
Hardness (BHN)	40.2	41.1	43.7	44.4	Singla et al.[a] [43]
Impact strength (N-m)	22	24	N/C	30	

N/A- value not available in the study

N/C- value not clear/ legible

a- The values of hardness (BHN) for 25% and 30% SiC content are 45.5 and 41.9 respectively and the values of impact strength (N-m) are 36 and the value of Impact strength (25%) is 36, but the value for 30% is not clear

Note: The different values of the same property in different studies can be explained by different fabrication techniques, environment and other similar factors used/available.

C. Type of the Reinforcing Material

This work uses the study of Arsenault [15] in this section and considers two types of SiC reinforcements – fibresand platelets (although the study uses a 6061 alloy, it is argued that these results could be extrapolated to pure aluminium matrix as well since both types of reinforcements in the study have been considered under similar environments).Considering fibre and platelets without any heat treatment from Arsenault's [15] work, it is seen that even though both the composites demonstrate similar proportional limits (121 MPa), the material with the SiC fibre shows greater yield stress and ultimate tensile strength. However because the fibre's strength was higher, its ductility compared to the platelets were lower. The increase in the properties of the fibre-reinforced composites is a result of the void density percentage, which according to Arsenault [15]is 2% (±1%) for the fibres and 5% (± 2%) for the platelets.Hence, it is seen that the type (shape) of the reinforcement affects the overall properties of the material.

TABLE III
VALUES OF PROPERTIES CONTAINING DIFFERENT TYPES OF REINFORCEMENTS

Property	Platelets	Fibres	Reference
Proportional Limit (MPa)	121	121	Arsenault [15]
Yield Stress (MPa)	162.2	258.8	
Ultimate Tensile Strength (MPa)	249.1	452	
Plastic Strain (Elongation) (%)	8.1	3.5	

Note: Although the original study gives the possible variation of the values (tolerance), it is omitted here.

D. Distribution of the Reinforcement Material

When fabricating MMCs through casting or similar liquid phase techniques, the distribution of the reinforcement material is an important factor to consider as it affects the properties and the quality of the material [44].Hashim et al. [45] say that the particle distribution is affected at three stages of the fabrication process i.e., (1) during mixing, (2) after mixing but before solidification (holding) and (3) during solidification.The authors suggest the use of stir casting as it not only helps in the transfer of the particles to the melt but also retains them in a state of suspension.

It is also seen thatthe solidification/cooling rate (of the composite) is important because it influences the distribution of the SiC in the final ingot [28, 45]. According to Lloyd et al. [28] when the material is cooled, the SiC particles are rejected at the meniscus and pushed ahead of the solidification front; they are then trapped by converging dendrite arms in the intercellular regions. When the material is cooled rapidly, there is a more homogenous distribution of SiC particles compared to a more slower rate which results in a more clustered distribution (because of more particle pushing) [28, 45]. According to Singla et al. [43], the distribution of the particles also depends on the wetting (discussed previously). This paper believes that a more homogenous distribution of SiC particles results in less localised damaged (since both the particles and interfaces are more spread out) and also that the clustered particles can result in the formation of stress concentration regions because the load bearing particles are drawn together.

VII. RECOMMENDATIONS

From the literature considered above, this work makes a few recommendations regarding the use of Al-SiC MMC's. Firstly, although Miracle [12] discusses several aeronautical and space applications for different MMCs, the paper doesn't explore the potential uses of Al-SiC individually. However, it is felt that Al-SiC MMCslook promising as materials for fuselage skinsin high performance aircrafts. The main reason for its consideration was its high strength to weight ratio [14] and good tensile properties; according to Avner [6] tensile strength of pure aluminium is 13,000 psi (89.6 N/mm^2), which is lower than the value of Al-SiC from most of the studies – toillustrate, for 10% SiC, MahendraBoopathi et al. [9]calculated the value at 265 N/mm^2. Even if we consider the lowest value – 88.11 N/mm^2, [14] it is seen that it's similar to that of pure aluminium (however, Al-SIC's better strength weight ratio makes it a more efficient choice). In addition, these MMCs also offer good corrosion/wear resistance and thermal stability (which becomes important in supersonic applications). Nevertheless, it must be noted that data for other critical properties such as fatigue and fracture toughness [1] were not available. Therefore, before any concrete predictions regarding its applications are made, effort must be taken to determine these as well.

Next, although a number of fabrications methods have been discussed (by Chou et al. [11]), stir casting is recommended as the most viable process because of its simplicity and its ability to produce large quantity. Another advantage of this method is that, in principle, it allows conventional metal processing route to be used, hence reducing the final cost of the product [43, 45]. Skibo et al. [46] state that the cost of a casting method is about one-third of similar methods. Finally, stir casting also allows a homogenous distribution of the reinforcing material in the metal matrix.

If we consider fuselage skins as an application for Al-SiC MMCs, it is argued that using fibres as a reinforcing material is a better option (compared to platelets) since, according to Arsenault [15] they offer a higher yield stress and ultimate tensile strength, which are critical parameters for the discussed applications.With respect to the amount of SiC fibres in the matrix, this paper feels that if the volume fraction is maintained between 10% - 15%, it will yield the optimum set of properties because, as discussed earlier, if the value is higher than 15% there is a drop in the tensile strength (which is an important property for fuselage skins) and if it is lower, the benefits gained from the SiC addition is not as high.

This paper also strongly advocates the growth of the Al_4C_3 interface layer. Apart from advantages gained through better properties [17], the interface layer also contributes to better thermal fatigue properties. Mizumoto et al. [47] state that the coefficient of thermal expansion of an Al-SiC MMC with Al_4C_3 layer does not vary even after repeated thermal (cyclic) loading unlike its counterpart without the interface layer. Therefore, the Al_4C_3 layer becomes an important prerequisite while using this material in applications that are subjected to cyclic loading such as the fuselage skin, which may heat up during flight and cool down whilst on the ground.

The final suggestion is to considerchromium carbide coatings on the SiC particles. Chromium carbide coatings increase the bonding at the interface of the composite and provide a more stable interface layer (as discussed in the previous sections). However, further research must be undertaken to determine its advantages (in terms of properties) with respect to the Al_4C_3 layer.

VIII. CONCLUSION

It is seen that for any material to be used in aerospace applications, certain criteria must be met. Although the exact set of required properties depend on the specific application, certain properties such as low density, good fatigue performance, and high wear and corrosion resistance are seen as universal requirementsfor effective functioning in the industry. Therefore, this paper makes a case for Al-SiC MMC and its application in the aerospace industry by exploring its properties. One of the main reasons for its consideration was the material's low density and its good wear (and corrosion) resistance.

From the literature, it is seen that these materials can be manufactured by either solid phase or liquid phase methods. This work, however, recommends the latter as they seem to show better results while being tested (if certain issues such as wettability are overcome). But for the most effective results, factors such as interface reactions, volume fraction of SiC, type (shape) of the reinforcing material andits distribution in the matrix must be taken into consideration during design, material selection and fabrication processes because when these factors are considered and the right selections made, it is genuinely believed that Al-SiC has tremendous potential for application (such as the fuselage skin) in the aerospace industry.

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