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

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Abstract:

This paper explores the potential of utilizing Al-SiC metal matrix composites (MMCs) in the aerospace industry. Initially, the necessary properties for aerospace applications are identified. Subsequently, the paper discusses the significance of pure aluminum in the industry, as well as its limitations. Recognizing these limitations, MMCs are proposed as potential alternatives to aluminum, with an understanding that the specific properties required depend on various factors. The paper reviews these factors, including reactivity at the interface, volume fraction, type, and distribution of the reinforcing material, drawing upon existing literature. Based on this analysis, the paper advocates for the use of Al-SiC MMCs in the fuselage skins of high-performance aircraft. It is important to note that these recommendations are based on available data and the authors' interpretation, with efforts made to maintain logical consistency.

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

INTRODUCTION

Ever since the Wright brothers successfully launched their 'heavier-than-air' machine, the aviation industry has experienced tremendous growth. As aircraft became faster and larger, the demand for advanced materials became paramount. This shift saw the replacement of wood and fabric with stronger metallic structures, primarily composed of aluminum and its alloys. However, more recently, ceramics and composite materials are beginning to take their place. The ongoing pursuit of more efficient aircraft continues to drive the demand for superior materials.

This paper delves into the potential of one such material: the aluminum-silicon carbide composite (Al-SiC). It begins by identifying the essential properties required for materials used in the aerospace industry. The discussion then focuses on the widespread use of aluminum in aircraft construction and advocates for the use of metal matrix composites (MMC) to address aluminum's limitations as a pure element. After establishing the case for Al-SiC MMC, the paper examines the various factors that influence the fabrication process and the final properties of the composite.

I. REQUIRED PROPERTIES

Since this work focuses on the aviation industry, it is essential to initially consider the properties of materials used in these applications. According to Corke [2], the most crucial criterion when selecting a material is its weight. A lighter aircraft requires less energy and, therefore, less fuel to operate. It has been noted that a large aircraft (turbojet) can reduce its fuel consumption by 1.1-1.5 percent with a weight reduction of 1,000 kg [3].

In addition to weight, other important properties include high strength, corrosion resistance, creep characteristics, fatigue performance, machinability, fabrication ability, fracture toughness, high modulus, ductility, and minimal distortion after machining [2, 4, 5]. Moreover, materials with high thermal strength and stability can significantly reduce fuel consumption. For example, increasing the turbine inlet temperature from 1,200°C to 1,500°C can improve fuel burn efficiency by 6-8 percent [3].

However, the specific set of properties and their significance are highly dependent on the particular component or part in question [5]. Starke Jr. & Staley [1] have demonstrated that when selecting a material for an aircraft's fuselage, factors such as fracture toughness, strength, Young’s modulus, corrosion resistance, fatigue initiation, and fatigue crack growth are all critical. Similarly, for the wing spar, materials are selected based on properties like shear yield strength and compressive modulus (for the spar web), compressive yield strength and modulus (for the web stiffeners), fatigue resistance, damage tolerance, and corrosion resistance [1]. Consequently, up to 20 different alloys may be used in a single aircraft [3].

II. ALUMINIUM

Although various elements are used in aircraft construction (as discussed in the previous section), aluminum is perhaps the most crucial. For instance, even though the Airbus A380 is noted for having the lowest percentage of aluminum by weight, it still comprises 61 percent aluminum [3]. The primary reason for aluminum's extensive use is its low weight, with a density approximately one-third that of copper or steel alloys [6] and a specific gravity of 2.72 [7].

According to Prabu et al. [8], aluminum boasts high strength, ductility, and thermal and electrical conductivity. While its electrical conductivity of 34 x 10^4 ohm^{-1} cm^{-1} [7] is only about 62 percent that of copper, aluminum is often preferred in industrial applications due to its light weight [6]. Additionally, aluminum has excellent machinability and workability; it can be cast (using any known method), rolled, stamped, spun, drawn, forged, hammered, and extruded into nearly any shape [6]. This versatility allows manufacturers to produce the intricate shapes and patterns required in the aircraft industry. Its ability to resist corrosion, due to the formation of a dense and strong layer of aluminum oxide (Al_2O_3) on its surface when exposed to the atmosphere [7], further contributes to its widespread use.

However, aluminum's usage is limited by its relatively low strength and hardness, making it suitable only for lightly loaded structures, and its low melting point of 658°C [7]. Additionally, Prabu et al. [8] and Mahendra Boopathi et al. [9] note aluminum's poor stiffness and tribological properties, respectively. Therefore, aluminum is often combined with other elements to enhance its properties for specific applications. One example of such a combination is the family of materials known as aluminum metal matrix composites.

III. METAL MATRIX COMPOSITES

Metal matrix composites (MMCs) consist of a metallic matrix reinforced with another material, typically in the form of fibers, particulates, or whiskers. According to Pai et al. [10], the reinforcing material generally bears most of the load, while the matrix material holds the reinforcement together, facilitating load transfer. The benefits of using these composites, where metals serve as matrices, include high tensile and shear moduli, excellent fatigue and fracture properties, a low thermal expansion coefficient, high melting point, toughness, ductility, thermal and electrical conductivities, good erosion and corrosion resistance, dimensional stability, and moisture resistance [11, 12]. Additionally, MMCs with aluminum as the matrix are noted for their good wear resistance, high specific modulus, and specific strength [13].

Silicon Carbide-Aluminum MMC

An example of an MMC is an aluminum matrix composite reinforced with silicon carbide (Al-SiC). The most significant property of aluminum-silicon carbide, especially relevant to the aerospace industry, is its strength-to-weight ratio, which is three times greater than that of mild steel [14]. Furthermore, composites containing silicon carbide as the reinforcing material and aluminum as the matrix exhibit high modulus and strength values, wear resistance, high thermal stability, lower weight, and enhanced load-carrying capacity compared to many other materials [15, 16]. This composite is also expected to show excellent corrosion and oxidation resistance, as silicon carbide forms a protective silicon oxide coating at 1,200°C [9], and aluminum similarly forms a protective aluminum oxide layer. Therefore, this material presents significant advantages for the aerospace industry, particularly in applications requiring superior thermal and tensile properties.

IV. FACTORS AFFECTING THE PROPERTIES OF AL-SIC

Although the previous section briefly discussed some properties of Al-SiC, the composite's exact set of properties depends on several factors. Apart from changes in the microstructure of the matrix and reinforcements resulting from various work hardening or heat treatment processes, this work has identified four factors from existing literature that could affect the properties of Al-SiC:

1. Reactivity of the matrix and the reinforcing material
2. Type of the reinforcing material
3. Volume fraction of the reinforcing material
4. Distribution of the reinforcing material

Before exploring how each aspect affects the material's properties, it is essential to discuss certain fabrication methods of Al-SiC, as these ultimately determine the aforementioned factors.

Fabrication of Al-SiC

Chou et al. [11] broadly classify the fabrication of MMCs into two categories: Solid Phase and Liquid Phase. Solid Phase methods include diffusion bonding (such as Cold Isostatic Pressing), rolling, extrusion, and Hot Isostatic Pressing (HIP). Liquid Phase techniques involve molten metals, with examples including squeeze casting, stir casting, rheo casting, and various infiltration processes. The authors [11] also advocate for using multiple methods to fabricate the composite, including combinations of certain infiltration techniques, rolling, and hot pressing, or vacuum infiltration and HIP.

This work recommends the use of Liquid Phase fabrication techniques for producing Al-SiC, as these methods melt the aluminum and facilitate the formation of an interface layer, which enhances certain properties (this will be discussed in more detail later). Processes such as Stir Casting [9] and Disintegrated Melt Deposition (DMD) [17] have been used in fabricating Al-SiC composites.

V. PROPERTY DEPENDANCE OF AL-SIC COMPOSITES

This part of the paper primarily focuses on studying various factors contributing to changes in the properties of an Al-SiC composite and how these changes ultimately affect its physical properties and chemical composition.

Reactivity of the Matrix and the Reinforcing Material

The properties at the interface play a significant role in the overall behavior of the composite. Load transfer across the interface affects strength and stiffness, ductility is influenced by stress relaxation near the interface, and toughness depends on crack deflection within the interface [11, 17, 18, 19, 20]. Hence, studying reactions at the interface is crucial when considering any metal matrix composite (MMC).

n the case of Al-SiC, the primary reaction at the interface involves the formation of Al4C3, as described by Tham et al. [17]. Al4C3, being brittle in nature, either forms as a detached precipitate or as a continuous layer around the SiC particles, while silicon enters the aluminum matrix to form an Al-Si binary alloy.

The presence of the Al4C3 layer at the interface enhances the material's average offset yield strength, ultimate tensile strength, work-to-fracture, and work hardening rate, with only a slight reduction in ductility [17]. Fracture characteristics differ between composites with and without the Al4C3 layer. Without the layer, fracture primarily occurs through decohesion at the interface due to partial bonding between particles and the matrix. Conversely, when the Al4C3 layer is present, fracture propagates mainly through particle breakage, indicating a strong interfacial bond [17].

his well-bonded interface ensures efficient load transfer, predominantly responsible for the increase in mechanical properties [17]. However, excessive layer thickness can lead to reduced mechanical properties due to increased likelihood of containing flaws larger than a critical size [17]. Additionally, increasing the silicon content to enhance the Al4C3 layer's formation should be carefully managed, as it lowers the alloy's melting point [28].

Another approach to improve mechanical properties involves enhancing particle-matrix wettability. Lloyd et al. [28] suggest that while forming Al4C3 requires time, increasing wettability may be a more practical approach, though it could complicate the fabrication process due to additional elements and techniques involved.

1) Wettability:

Wettability, as described by Oh et al. [29], is crucial for establishing satisfactory bonds between solid and liquid phases during casting in Al-SiC fabrication. It represents the degree of intimate contact between the liquid and solid surfaces [30]. Principles to enhance wettability involve decreasing the liquid's surface tension, reducing the solid-liquid interfacial energy, or increasing the solid's surface energy [31, 30].

Various techniques, as suggested by Young [32], Himbeault et al. [33], Tafto et al. [34], and Chou et al. [11], include the addition of alloying elements, coating or treating particles to enhance wettability in MMCs. Addition of magnesium, for instance, improves wetting characteristics due to its lower surface tension [30]. Sukumaran et al. [35] found that an optimal magnesium percentage of around 1 enhanced distribution and mechanical properties, while Mahendra Boopathi et al. [9] added 1.5 percent magnesium to improve Al-SiC composite wettability. Magnesium also acts as an oxygen scavenger, increasing particle surface energy [30], but excessive addition may lead to the formation of low-melting compounds, compromising mechanical properties [30].

Another method to enhance wettability involves heat treating reinforcing materials. Heating SiC particles above 900°C has been found to improve wettability [21]. Warren & Anderson [21] observed a contact angle decrease from 150 at 900°C to 42 at 1,100°C, indicating increased wettability. This improvement is attributed to the formation of an oxide layer at temperatures below 900°C [30, 37], along with impurity removal from the surface, gas desorption, and oxide layer formation [38]. Hashim et al. [30] note that this oxide layer functions differently from the melt oxide layer, which reduces compound wettability.

Another Process for Increasing Wettability:

Coating the reinforcing agent with another material is another method to enhance MMC wettability. Typically, non-metallic materials are coated with metals since liquid metals find it more challenging to wet non-metallic substances compared to solid metals [30]. Coating methods include chemical vapor deposition (CVD), physical vapor deposition (such as evaporation, direct ion beam deposition, and sputtering), plasma spraying, electrochemical plating, and cementation [11]. Nickel is commonly used as a coating metal for aluminum composites [39, 40, 41, 42], although chromium carbide has been suggested for Al-SiC composites due to its more stable layer formation compared to Al4C3 compound [11]. However, a duplex coating process may be more time-consuming [11].Additionally, Hashim et al. [30] discuss ultrasonic vibrations and the application of mechanical forces (like stirring) as potential methods to enhance composite wettability. The wettability of both the matrix and the particle significantly influences composite properties, as good wetting results in a stronger bond at the interface [30].

Volume Fraction of the Reinforcing Material:

The volume fraction of the reinforcing material, such as SiC in the MMC, is crucial in determining the final material properties. Mahendra Boopathi et al. [9] conducted a study considering tensile strength, density, yield strength, elongation, and hardness of the MMC concerning SiC percentage.

They found that density decreases with increasing SiC content due to the lower density of SiC particles. Tensile strength, yield strength, hardness, impact strength, and wear resistance increase with SiC content, attributed to a higher number of SiC particles proportionally increasing the stress needed to initiate and propagate cracks in the composite. However, elongation percentage decreases with increasing SiC content [9].Singla et al. [43] observed that when SiC content exceeds 25%, properties like hardness and impact strength decrease due to SiC particle clustering and settling, resulting in local density reduction and lower hardness.

In another study by Neelima Devi et al. [14], tensile strength initially increased with SiC content up to 15%, after which it decreased. However, elongation was proportional to SiC content in contrast to Mahendra Boopathi et al.'s findings [9].

The drop in tensile strength beyond 15% SiC content could be due to increased interfacial area, leading to void nucleation and coalescence, resulting in failure at lower stresses. Regarding elongation, there may be anomalies in Neelima Devi et al.'s data, as there's usually a trade-off between strength and ductility. Both properties cannot rise or fall simultaneously [14].

C. Type of the Reinforcing Material

In this section, Arsenault's study [15] is utilized to examine two types of SiC reinforcements: fibers and platelets. Although the study employed a 6061 alloy, it is suggested that these results could be applied to a pure aluminum matrix since both types of reinforcements were evaluated under similar conditions.

Without any heat treatment, Arsenault's work [15] reveals that although both composites demonstrate similar proportional limits (121 MPa), the material with SiC fibers exhibits higher yield stress and ultimate tensile strength. However, due to the higher strength of the fibers, their ductility compared to platelets is lower. The improvement in properties of the fiber-reinforced composites is attributed to the void density percentage, which Arsenault states is 2% (±1%) for fibers and 5% (±2%) for platelets. Thus, it's evident that the type (shape) of the reinforcement significantly impacts the overall properties of the material.

D. Distribution of the Reinforcement Material

In fabricating MMCs through casting or similar liquid phase techniques, the distribution of the reinforcement material significantly impacts the properties and quality of the material [44]. According to Hashim et al. [45], particle distribution is influenced at three stages of the fabrication process: during mixing, after mixing but before solidification (holding), and during solidification.

Stir casting is recommended by the authors [45] as it aids in transferring particles to the melt and retains them in a suspended state. The solidification and cooling rate of the composite are crucial as they affect the distribution of SiC in the final ingot [28, 45]. Lloyd et al. [28] explain that during cooling, SiC particles are rejected at the meniscus, pushed ahead of the solidification front, and then trapped by converging dendrite arms in the intercellular regions. Rapid cooling leads to a more homogeneous distribution of SiC particles, while slower cooling results in a more clustered distribution due to increased particle pushing [28, 45]. Additionally, particle distribution also depends on wetting, as discussed previously [43].

This paper contends that a more homogeneous distribution of SiC particles leads to less localized damage, as both particles and interfaces are more spread out. Conversely, clustered particles can create stress concentration regions as load-bearing particles are drawn together.

VI. RECOMMENDATIONS

Based on the literature reviewed, this work offers several recommendations regarding the utilization of Al-SiC MMCs. Firstly, although Miracle [12] does not specifically explore the potential applications of Al-SiC individually, these composites appear promising for fuselage skins in high-performance aircraft due to their high strength-to-weight ratio and good tensile properties [14]. Even the lowest reported tensile strength value of Al-SiC is comparable to that of pure aluminum, making it a more efficient choice. However, it's crucial to ascertain critical properties like fatigue and fracture toughness before definitive conclusions regarding its applications can be drawn.

Among fabrication methods discussed by Chou et al. [11], stir casting emerges as the most viable due to its simplicity, large-scale production capability, and cost-effectiveness [43, 45]. Stir casting ensures a homogeneous distribution of reinforcing material in the metal matrix, essential for optimal performance.

In the context of fuselage skins, using fibers as a reinforcing material is preferable over platelets, as fibers offer higher yield stress and ultimate tensile strength [15]. Maintaining a volume fraction of SiC fibers between 10% - 15% is recommended for obtaining the optimum set of properties, balancing strength with other factors. Additionally, promoting the growth of the Al4C3 interface layer is advised, as it enhances both mechanical and thermal fatigue properties [17, 47].

Lastly, considering chromium carbide coatings on SiC particles is suggested to improve bonding at the interface and provide a more stable interface layer. However, further research is needed to understand its advantages compared to the Al4C3 layer in terms of properties.

VII. CONCLUSION

For any material to meet the stringent demands of aerospace applications, it must fulfill specific criteria tailored to each use case. While these criteria may vary, qualities such as low density, excellent fatigue performance, and high wear and corrosion resistance are universally essential for effective performance in the industry. Thus, this paper advocates for the adoption of Al-SiC MMCs in aerospace applications, highlighting their properties.

From the literature, it's evident that these materials can be manufactured through either solid phase or liquid phase methods. However, this work suggests liquid phase methods due to their favorable outcomes in testing, provided certain challenges like wettability are addressed. For optimal results, factors such as interface reactions, SiC volume fraction, type of reinforcing material, and its distribution within the matrix must be carefully considered during design, material selection, and fabrication processes. When these factors are properly accounted for and the appropriate choices are made, Al-SiC MMCs hold significant promise for aerospace applications, particularly in areas like fuselage skin construction.

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