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Review Article

Conventional and Advanced Composites in Aerospace Industry: Technologies Revisited

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Abstract: Composites as a separate class of engineering material have found many applications in aerospace industries where high performance and safety are a prime concern. A review has been done in order to provide a comprehensive analysis on various types of composites used in the aerospace industry, emphasizing on the features, properties, advantages, limitations, and emerging trends in the field.

Keywords: Aerospace, Composite Materials, Polymer Matrix Composites (PMCs), Metal Matrix Composites (MMCs), Ceramic Matrix Composites (CMCs)

1. Introduction

Generally, composite materials are a combination of at least two distinct constituents differing in form or material composition, where they do not dissolve or melt in each other, resulting in a new material with superior properties than the sum of their constituents. It typically consists of a reinforcing dispersed phase and a matrix which transfers the stress to the dispersed phase and allows for the easy manufacture of the composite material. Every single component in a composite plays a role in obtaining the final properties of the composite [1-5]. Composites are commonly classified at two distinct levels; matrix and reinforcements. An important classification of composites is according to the matrix of the composite [5].

1. Polymer-matrix composites (PMCs) use a polymer-based resin matrix which is usually reinforced with a wide variety of reinforcements such as carbon and glasses.
2. Metal matrix composites (MMCs) use a metallic-based matrix which is mainly reinforced with metallic and ceramic particles.
3. Ceramic matrix composites (CMCs) use a ceramic-based and the reinforcements are mainly short fibers.

Theoretically, carbon-carbon composite (CCCs) and intermetallic matrix composites (IMCs) can be considered a subcategory. Polymer matrix composites are the common type of composites, cause of its room-temperature properties, low cost and ease of fabrication. MMCs allow higher operating temperatures than PMCs, whereas CMCs provide higher toughness [5, 6].

Conventional metal and alloys such as aluminum alloys are substituted by composite materials in different industrial applications due to the demand for lightweight, high performance, cost and energy saving, as well as environment-friendly materials. There has been an ever-increasing demand for composite materials in the aerospace industry. Combination of high specific strength, stiffness, fracture toughness, good resistance to oxidation and corrosion are some of the reasons for the high demand of composites in the industry. However, the driving force for composites to be used as a substitute for metal alloys in aerospace is the reduction in weight that in turn reduces the cost through reduction in fuel. Properties of composites that make them ideal candidates for structural applications and component manufacturing are the ability to withstand the extreme conditions, which are unattainable by conventional materials [4].

In this paper, a critical review is done on various features, properties, advantages, limitations and recent trends of the various types of composites used in the aerospace industry. The composites discussed are under the categories PMC, MMC and CMC.

2. Information Analysis

2.1. Polymer Matrix Composites (PMCs)

Polymer matrix composites (PMCs) are generally comprised of a continuous polymer-based matrix phase and a discontinuous reinforcement phase. PMCs are known because of their specific characteristics including high strength and stiffness coupled with lightweight. Superior corrosion, fatigue resistance and good damping characteristics compared to metals are other characteristics of PMCs. However, application of PMCs is limited to service temperatures below about 316°C (600 ºF) due to decomposition of the matrix at elevated temperatures [7, 8].

The properties of the PMCs are associated with the matrix, reinforcement, and the interphase. In PMCs, the interphase is defined as the transition region between fibers and matrix, which governs the effective load transfer between the relatively weak matrix and reinforcements [9]. Therefore, various variables must be taken into account when designing a PMC system including type and content of matrix, characteristic and geometry of reinforcements and the nature of interphase [7-9].

PMCs use organic polymer as the matrix, which is primarily responsible for shape, rigidity, transference of load uniformity through the bonding of reinforcement and matrix, and protects both composites and reinforcements from chemical and corrosion attacks [7, 10]. In commercial PMCs, the matrix phase can be classified as either thermoset or thermoplastic. Thermoset plastics cannot be heat-softened, melted and reshaped again once molded. Some examples of thermosetting plastic are polyesters, vinyl esters, epoxies, bismaleimides, and polyamides. 3D crosslinked structure originating from the curing possesses provides high dimensional and chemical stability, high-temperature strength, good resistance to cracking and durability compared to thermoplastics [7]. Thermosetting polyesters and vinyl esters are primarily used in fiber-reinforced plastics due to their low cost. Epoxies are the most important resins in the market, particularly in structural and aerospace applications, as it can perform under various temperatures and conditions, depending on the curing agents and monomer chemistry [11]. Thermosetting polyimides, bismaleimide (BMI), and cyanate esters resins are favoured for high-temperature applications (above 200◦C) because of their higher glass transition temperatures [11]. Meanwhile, thermoplastic resins include some polyesters, polyetherimide (PEI), polyphenylene sulphide (PPS), polyamide imide and polyetheretherketone (PEEK), which are candidate resin systems for some aerospace applications [7, 11]. Unlike thermosets, thermoplastics can be heat-softened, melted and re-shaped over and over again. From a manufacturing point of view, the processing of thermoplastics is easier and faster compared to thermosets. As the processing of thermoplastics is reversible, they can be reshaped and reformed by reheating to the process temperature [7, 11-13].

Reinforcements are used primarily to improve strength and stiffness of relatively weak polymer-based resin matrix. The continuous reinforcing phase is responsible for high strength and stiffness of PMCs which can be in the form of fabrics, particles, or nanoparticles and mainly fibers [14]. In fact, the magnitude of strength and stiffness can be decided by the volume, fraction of reinforcements and intrinsic properties of reinforcements [8]. Fiber reinforcements of short or long fibers including glass fiber, carbon fiber, and polyaramid fibers are the main reinforcements for PMCs [7, 11]. Fiber reinforcements have higher strength and modulus than matrix material, thus, acts as a load-bearing component [8].

The technology of PMCs is largely extended to the aerospace industries applications where high safety and weight is of concern. PMCs have been used from small to large size aircrafts, including commercial, civil and military aircrafts. The extended application of PMCs compared with metals in aerospace sector is related to their high specific strength and stiffness, coupled with low density which results in weight savings. Benefits of weight reduction includes reduction of fuel consumption and emissions as well as an increase in the speed, range and maneuverability of aircraft [7, 15].

For aerospace applications, the most commonly used PMCs are fiber or filament reinforced polymers or plastics (FRP) wherein embedded fibers yield superior properties. Typically, they consist of an epoxy-based system and a large percentage of high-performance continuous fibers. However, high-temperature thermoplastics such as PEEK has been recently used as a matrix for many aerospace applications [7, 12, 13]. One of the important characteristics of FRPs is anisotropy, which is related to the designing of performance. In fact, properties of FRPs can be further controlled by a designated fiber arrangement. For example, by aligning fibers along the primary loading direction within the composite the maximum level of properties can be obtained [8].

In FRPs, reinforcements can be either natural fibers or synthetic fibers. Synthetic fibers such as high-stiffness glass (S-glass), graphite/carbon, aramid (e.g., Du Pont's Kevlar) have been widely used in aerospace industries. Synthetic fibers have lower density and higher specific strength than natural fibers [10]. However, natural fiber reinforced composites have also found some application in aerospace industries [10, 16]. Being lightweight is one of the main advantages of synthetic fiber reinforced polymer (SRP) composites. It has been reported that SRPs reduce up to 50% in weight and consequently up to 20% of cost as compared to metals [10]. Glass fiber reinforced plastics (GFRPs) were first introduced to aerospace as the structural composite aircraft components during 1950-60s. Up to now, GFRPs are still the most commonly used FRP due to relatively high specific strength and low cost. Carbon fiber reinforced composite (CFRPs) were later developed to meet the requirements of high-tech performance of aircrafts including high specific strength and modulus. Since then, different FRP composites like boron fiber reinforced plastics (BFRP), aramid fiber reinforced plastics (AFRP) and have been introduced to the field as a substitute for aluminum in high-performance aircraft structures. GFRPs and AFRPs have been used for lightly loaded structural components as a standard material. In fact, usage of AFRPs is restricted to lightly loaded structural components due to low compressive strength [8, 10, 11, 15].

Nowadays, PMC materials have been extensively used for both structural and non-structural applications in a large number of aircraft components depending on the in-service loading, environmental conditions etc. Some of the structural applications of FRPs can be found in various components of wings, vertical and horizontal stabilizers, fuselages, propulsion systems, rotor blades for helicopters etc. [12, 17]. The most common aerospace structural composites are laminates and sandwich structures. The sandwich structure consists of two laminated composite sheets, known as skins attached to a core using adhesive. The most common type of core is the honeycomb, which can be either metallic or non-metallic depending on the design parameters. Compared to other structural composites, sandwich panels possess the highest strength and stiffness-to-weight ratios which allow superior resistance to bending and buckling [18]. Honeycomb-cored sandwich panels provide higher stiffness at a lower weight than monolithic composite materials. Most of the sandwich structures PMCs are generally comprised of a honeycomb core and sheets of carbon fiber or combined carbon fiber-aramid or carbon fiber-glass. Non-structural applications, fiber reinforced epoxy or phenolic resin are used for interior aircraft applications to meet the requirement of impact resistance and surface smoothness. However, glass fibers are the most common fiber used for interior aircraft application [12, 18-20].

In order to improve the performance, there are several trends that have emerged in the field of polymer matrix composites with emphasizing the weight reduction as a key factor. One of the interesting trends in the field is using nanoscale reinforcement rather than micro-scale reinforcements [21]. The reduction of the reinforcement size from micrometer scale to nanoscale constituents, with critical dimensions on the order of 100 nm and below, offers new opportunities in the tailoring of mechanical and physical properties of the polymers [22]. One of the advantages of nanocomposites is improved surface area to volume ratio by decreasing reinforcement scale, which provides larger interphase regions and potential for reaction with the surrounding matrix material. The two most common nano-reinforcements are Nano clays, such as organically modified montmorillonite (MMT), and carbon nanotubes (CNTs) or a combination of these materials [11]. In particular, CNT reinforced nanocomposites have been used as a new and advanced materials system with multifunctional applications in aircraft and spacecraft. Carbon fibers provide a way to reduce the weight of structural components and to reduce carbon footprint in high-performance composites. Carbon nanotubes have at least the tensile strength of carbon fiber, but they are quite flexible. However, the relatively high cost of carbon fibers and stability are the main challenges when using these nanomaterials [23]. The fiber-like structure of the carbon nanotube can have extremely large aspect ratios (length/diameter) which are particularly desirable for mechanical reinforcement [24]. Liu and Kumar [23] reviewed recent developments of fabrication, structure, and properties of carbon fiber, especially in high-performance PMCs. According to Liu and Kumar [23], CNT fibers provides higher strength properties compared to carbon fibers. However, further developments will be required in CNT synthesis, purification, and fiber processing. Pandey and Thostenson [24] have studied CNT reinforced polymers and recent developments in multifunctional applications. They have also provided detailed information on the structure-property relationships in polymer nanocomposites. It can be concluded that CNT reinforced composites offer simultaneous enhancements in a wide range of material properties including mechanical, electrical, and thermal.

Another trend in aerospace is further emphasis on environmentally friendly and sustainable materials processing. In this sense, green composites, also called biocomposites, have been developed using biomaterials to produce the fibers and resin. Bio-renewable feedstock usage instead of petrochemical feedstock for both the polymer matrix (for example bio-based resins from vegetable oils) and the reinforcement (bio-based natural fibers) is under study worldwide. Fuqua et al. [25] have provided detailed information about natural fibers or bio-based fibers and also their developments. Varieties of those fibers are introduced and the characteristics of those fibers including fiber type, length, architecture, surface characteristics, resultant effect of their constituents and hierarchal structures on properties of various polymer-based composites are discussed. The main advantage of bio composites is the biodegradability; hence, it is innocuous to the environment [26, 27]. In addition, recycling of composite materials will reduce or eliminate volatile organic compounds (VOCs) during manufacturing [11].

Development of hybrid composite materials is another significant direction in the aerospace industry. Hybrid composites technology is of great importance, due to a higher level of properties, excellent performances and lower costs than single fiber composites. Addition of two or more reinforcements into a single polymer matrix result in the development of dual reinforced or hybrid composites, which leads to improvement of properties compared to a single reinforced polymer composite. Hybrid composites are designed as functional and functional-structural composite materials. Recently, the functional structural hybrid composites have been developed successfully, such as absorption/structural composite materials. In the case of FRPs, carbon fiber-aramid fiber composites are the most commonly used materials wherein carbon fiber provides compressive strength aramid improves the toughness of the material. Another popular hybrid is a mixture of the glass fiber and carbon fiber where carbon fiber provides high specific strength and specific modulus, and glass fiber provides better toughness and lower material cost [8]. Gupta and Srivastava [10] have reviewed mechanical properties of various hybrid fibers reinforced polymer composites. They investigated the effect of both natural and synthetic fibers on the final mechanical properties of hybrid composites. They concluded that hybridization of single reinforced PMC improves the mechanical properties. They also found that incorporation of different forms of natural fibers and synthetic fibers into natural fiber reinforced thermosets composite improves the mechanical properties. However, they didn't report significant improvement of properties with the addition of synthetic fibers into synthetic fiber reinforced composites.

2.2. Metal Matrix Composites (MMCs)

The aerospace industry is in need of materials with specific characteristics such as high mechanical and thermal properties while having low weight and cost. Metal matrix composites (MMC) have found their application not only in aerospace industries but also in space industries [28] It has been reported that the world demand for MMCs is increasing continuously as illustrated in Figure 1 where information is extracted from [29]. They benefit from high strength to weight ratio which is a very important factor for space and aerospace applications [30].

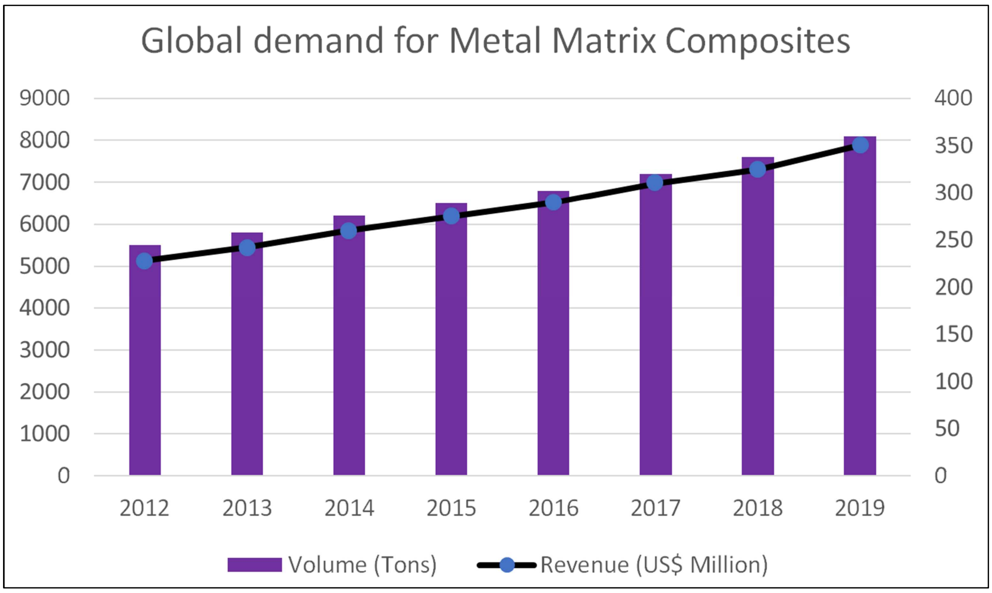

Figure 1. *Global demand for Metal Matrix Composites. (Data extracted from [25]).*

MMCs consist of a metallic-based matrix and reinforcement which can be in the form of particles, short fibers or whiskers [31]. Aluminum, magnesium and titanium are the most common matrices used in aerospace industries as an MMC matrix or as an alloy. Mechanical properties of MMCs such as elasticity, tensile strength and strain can be adjusted to the requirement of the design for any specific design by varying the ratio of the metal to the ceramic components of the composite [32]. However, due to various operational and maintenance requirements of the industry, many other properties such as thermal, electrical acoustic etc. are also demanded by the today's aviation system designers (Table 1).

Table 1. *Factors affecting material cost. (Some information extracted from [33]).*

Costs incurred	Properties	Processing
Raw material	Corrosion resistance	Exploration & Exploitation
Improvisation of material	Mechanical and Flexural Strength	Production & operation
Testing and property validation	Density	Batch testing
Transportation and labour	Stiffness and hardness	Disposal
Overheads and administration	Malleability and ductility	
Wastage and processing losses	Electrical resistance	
Environmental protection	Thermal properties	
Other direct and indirect costs	Acoustic properties	
	UV resistance	
	Durability	

Material selection highly depends on the finishing costs, besides other property requirements. There are several factors that are illustrated in Table 1. MMCs are produced mostly by two methods; powder metallurgy technique and stir casting methods [34]. Friction stir welding (FSW) is also another method for aluminium matrix composites (AMC) [29, 30].

Metal matrix composites of aluminium, magnesium, titanium and the intermetallic titanium aluminide are highly in demand because of their low density while having significantly high mechanical and thermal properties such as hardness, formability, fatigue life, thermal shock and high-temperature tolerance [35]. Researchers are interested in aluminium or magnesium based MMCs due to their lightweight properties and high stiffness [34-36]. Titanium matrix composites (TMC) reinforced with silicon carbide fibers has also found a great application in aerospace industries, mostly in turbine engines. TMCs demonstrate a high performance to weight ratio [37]. Aluminum matrix composites (AMCs) are the most widely used type of MMCs in aerospace, and has extensively studied. However, aluminum shows the drawbacks of corrosion and fatigue cracks [38]. Among aluminium alloys, Al6061 is one of the aluminium alloys used for aerospace industry. It has been reported that CNTs is a proper reinforcement of AMCs especially for Al6061 [34] while for Al6082, it is shown that adding graphite particles is not beneficial because it does not show a uniform microstructure and also the hardness reduces [39]. Metal composites of Al2080 Al alloy were studied by Koli et al. [35] to determine that decrease in SiC particles size increases the fatigue life of the alloy. Besides it is shown that for AA6061-Al_2O_3 and AA6063-SiC, hardness increases with increasing particles of Al_2O_3 and SiC particles [35]. Typically, magnesium is used in the gearbox of the aircraft because of its low density [31].

2.3. Ceramic Matrix Composites (CMCs)

Ceramic is an inorganic non-metallic solid; which is composed of metal, non-metal or metalloid atoms and it is mainly formed by the combination of ionic and covalent bonds [40]. Ceramic materials have the characteristics of being brittle, hard, strong in compression and also weak in shearing and tension due to the combination of ionic and covalent bonds. Several studies have reported that usually, ceramics materials can withstand very high temperatures between 1000 ºC to 1600 ºC [40-42]. Besides that, ceramics also can withstand the chemical erosion in an acidic or caustic environment without affecting their structure [40, 42].

Advanced ceramics, such as alumina, silicon nitride and aluminium nitride have several advantageous physical properties which results in them being used in manufacturing critical components in aerospace [43]. However, according to Ashby and Cebon [44], ceramic materials are brittle and have a low-value toughness. Therefore, to overcome the brittleness, ceramic matrix composites (CMCs) have been developed [45-47].

According to Gohardani and Gohardani [48], the problems of using conventional materials for engines, such as limitation of operating at high temperatures, combustion efficiency and the increasing of fuel consumption or hazardous emissions, can be eliminated or minimized by using the ceramic-based material for engine production. By using CMCs, the good behaviour of the product such as resistance against high temperatures, light weight and cost-effectiveness can be achieved [47]. Chawla [31] stated the main properties of the CMCs are high strength and modulus, low density, high temperature resistant and greater toughness compare to monolithic ceramics. The example of CMCs is carbon/carbon composites (C/C), silicon carbide whisker/alumina composites (Al_2O_3/SiC whisker) and continuous carbon fiber or silicon carbide fiber reinforced ceramic matrix composites (SiC or Si_3N_4).

Fiber-reinforced CMCs are used in the production of engines rocket. Schmidt et al. [49] claimed that fiber-reinforced CMCs have low specific weight, high specific strength over a large temperature range, and the capability of high resistance towards damage compared to monolithic ceramics (for example silicon nitride and silicon carbide). These great advantages increased interest in fiber-reinforced CMCs as an aerospace construction material. Carbon fiber-reinforced silicon carbide (C/SiC) is used in thrust-chamber components for a rocket engine and in the nozzle extensions for the upper-stage engine AESTUS. Its advantages include being lightweight, high resistance to thermal shocks and having the stability or resistance towards chemical attack [49]. Boron bearing species in the interphase or matrix of non-oxide CMCs is used in aerospace engine application as to improve the oxidation resistance under load at high temperatures [50].

Products of high performance with low cost are always welcome in the aerospace industry. Since there is a high demand for the industry, continuous research and development will take place especially for new material; i.e.: advanced ceramic materials that deliver with powerful physical and good thermal and electrical properties.

3. Conclusions

The aerospace industry is in need of materials with specific characteristics such as high mechanical and thermal properties while having low weight and cost. Composite materials as a separate class of engineering materials have found much application in aerospace industries. This work has reviewed the available commercial composites materials used in aerospace industries namely, PMCs, MMCs and CMCs. A brief introduction to various types composites used in the aerospace with emphasizing the features, properties, advantages, limitations, and emerging trends in the field is provided. It was found that reducing weight and cost as well as high performance are the key factors for material selection in aerospace industries. However, further improvement of performance of those composites by focusing on using hybrid composites, nanocomposites and bio composites particularly in the case of.

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