REVIEW PAPER

NANOCOMPOSITES FOR AIRCRAFT APPLICATIONS

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Abstract

The steady increase in jet fuel prices in recent years has accelerated the quest for greater economy in airline operations. While improvements in aerodynamic efficiency, engine fuel efficiency, etc., have been sought, lighter and stronger materials for aircraft structural components remain a very important goal. The percentage of advanced composites, utilizing carbon fibers, in modern aircraft has reached 50 percent. The trend now is to use nano reinforcements such as graphene and carbon nanotubes to further reduce the structural weight. Due to the difficulties in fabricating nanocomposites with a high enough volume fraction of nano reinforcement, the nano reinforcements are either added to the polymer matrix or grown on the carbon fibers. The nano reinforcements are multi-functional; thus, in addition to contributing strength, they contribute to other properties such as electrical conductivity which in turn enhances the lightning strike protection, electrostatic discharge, electromagnetic shielding, etc. This paper summarizes these aspects and also describes the applications of nanocomposites in aircraft interiors, brake components, aircraft repair, etc.

Introduction

The first civilian commercial flight took place in 1914 in a Benoist XIV (Ref.1). The plane was able to transport one passenger and flew 1205 commercial flights, with a range of 35 km, across the Tampa Bay in USA before discontinuing the service for lack of profitability. The Airbus A380, which made its first commercial flight in October 2007, has a capacity of 525 people in a typical three-class configuration or up to 853 people in an all-economy class configuration. The design range of A380 is 15,700 km; a Boeing 777-200LR has flown 17,500 km.

The price of jet fuel has been increasing in recent years (Ref.2). In 2011, American airline companies are reported to have spent $48 billion on jet fuel for domestic and international travel. Fuel costs have increased from 10 percent of operating costs in 2001 to 35 percent now. At least a dozen airlines globally have filed for bankruptcy; many others have opted for mergers to cope with the rising costs.

The fuel economy of an aircraft depends on a number of factors, including aerodynamic efficiency, engine fuel efficiency, number of passengers carried and the weight efficiency. As the oil prices have increased over the years, airlines have attempted to increase the fuel economy by a number of steps. These include underfueling aircraft to reduce the weight carried, and thus reduce fuel consumption, and grounding older and less fuel efficient aircraft, and acquiring modern fuel efficient aircraft. The steady decrease in the fuel consumption of aircraft due to increase in fuel efficiency is shown in Fig.1 (Ref.3). The correlation between high fuel costs and high demand for more efficient replacement aircraft is shown in Fig.2 (Ref.3). Another trend in recent years is the airlines quest for cleaner, greener and cheaper fuels (Ref.2). This has resulted in the attempts to use and develop biofuels.

Aircraft structural materials, over the years, have evolved from wood to aluminum alloys and from metals to conventional composites, using micro scale reinforcements such as carbon fibers. The trend towards new materials has been based on property improvements; the driving force for the steady increase in the use of composites has been the reduction in structural weight necessitated by rising fuel costs. Nano composites incorporating nano reinforcements such as carbon nanotubes (CNTs),

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nanoclay particles, etc., represent the next frontier in order to increase the specific mechanical properties such as strength, stiffness, fracture resistance, etc., as well as nonflammability and multi functionality. While the use of micro composites, with carbon fibers in a polymeric matrix, has increased to 50 per cent of the aircraft structural weight, the poor electrical conductivity has necessitated the use of metallic meshes on the outer surface for lightning strike protection. The resulting weight penalty can be removed if CNTs can be used in the outer layers of the composites.

The use of nanocomposites in primary aircraft structures will take more time. The aerospace use of new materials requires "rigorous building block approach and quality control system" (Ref.4), because of safety and environmental considerations. The US Federal Aviation Administration (FAA) Advisory Circular (Ref.5) on Composite Aircraft Structure provides guidelines for composite structures that are essential in maintaining the overall safety of the aircraft and are considered acceptable for showing compliance with the certification requirements of civil composite aircraft.

Significant improvements in nano composites and their fabrication methods need to be realized to offset the development and certification costs (Ref.4). Certification of a new material for aircraft structures requires significant risk mitigation; the nano composites need to demonstrate safety and they should meet regulatory compliance throughout the life cycle (Ref.4). Therefore the use of nano reinforcements and nano composites is likely to be incremental. Nano composites will be used in non-load bearing applications first and nano reinforcements will be incorporated in conventional micro composites. For instance, CNTs can be grown on carbon fibers and CNTs and nanoclays can be added to polymeric matrices.

Conventional Composites in Aircraft Structures

Starting from the first flight attributed to the Wright brothers in 1903, the aircraft structural material was wood until 1932 when aluminum replaced wood. Aluminum, alloyed mainly with copper, offered several advantages such as low density, high conductivity and good bonding characteristics. Aluminum-lithium alloys have even lower density and their initial disadvantages, such as reduced ductility and fracture toughness were overcome, resulting in their increasing use; for instance, their use in the nose section of Airbus A350 XWB has resulted in a 600kg reduction. The use of polymer matrix fiber reinforced composites has been increasing steadily over the years. Glass fibers were used (2%) in Boeing 707 in the 1950s. Later carbon fiber reinforced composites (CFRP) were used by Airbus as well as Boeing for several aircraft external components such as ailerons, belly fairing, rear pressure bulkhead, floor beams, nose cone, wing box, wing beams, wing skins, horizontal stabilizer, vertical tailplane, nacelles, reversers, fan blades, etc. (Ref.6). The percentage of composites increased from 25% by weight on the Airbus A380 to 53% in the A350. Parallel increases in the composites usage led to 50% composites by weight in Boeing 787 Dreamliner.

The laminate thicknesses in composite applications in aircraft vary from several mm up to 40 mm on the heavily stressed parts of the A380 (Ref.7); thicker laminates, more than 70 mm thick, have been used in the A330/A340 vertical tailplane's attachment fittings. Thicker monolithic structures such as the horizontal and vertical tailplanes have been found to be better compared to sandwich structures which have developed problems due to water diffusion (Ref.7). On the A380 plane, monolithic CFRP laminates have been used in the entire rear fuselage, center wing box and select wing ribs while the complete fuselage on A350 consists of large CFRP panels (Ref.7). The thicker laminates pose challenges in detecting and repairing damage.

The evolution of composites usage in several aircraft models over the years is shown in Fig.3 (Ref.8). Metals such as aluminum, steel and titanium are still used in aircraft structures. The makeup of a Boeing 787 plane in terms of structural materials is shown in Fig.4(a) (Ref.9) and a similar distribution of materials for an Airbus 380 plane is shown in Fig.4(b) (Ref.10).

Some concerns have arisen regarding the expanded use of composites in aircraft structures (Ref.11), due to the lack of prior experience with these materials in such applications. For instance, the Government Accountability Office (GAO) in USA has raised four safety-related concerns (Ref. 8): lack of information regarding the ageing of composite materials in service, the difficulties in detecting damage in composite materials, dearth of standardization of composites and their repair techniques and concerns regarding the training and awareness of workers handling composites.

The combination of metals and fiber reinforced polymers results in an interesting class of materials denoted as 'hybrid materials'. Such materials are also known as 'Fiber metal laminates' (FML). These materials, developed at the Delft University, combine the advantages of metals and composites, while compensating for the weaknesses of each. The first generation FML was developed in early 1980s. It was based on aramid fibers in a polymer matrix and aluminum sheets and was called ARALL. In 1987 the second generation FML was made with the name GLARE. It was based on high strength S-glass fibers in an epoxy matrix and aluminum sheets. Then CARALL, based on carbon fibers in an epoxy matrix and aluminum sheets, was developed (Ref.12). Later TiGr, a laminate of Carbon/Polyimide and Titanium sheets, was developed (Ref.13). These FML materials have excellent fatigue properties and offer unique advantages due to the laminated structure: better impact strength, residual and blunt notch strength, flame resistance and corrosion resistance.

Unlike an aluminum sheet, the FML has greater resistance to fatigue crack propagation. Due to the 'fiber crack bridging mechanism', the stress intensity factor at the crack tip in the aluminum sheets is significantly reduced by crack closure by the fibers, as shown in Fig.5 (Ref.12). The material benefits, lower production costs, lower operating costs and increased level of safety in case of fires have led to the use of FML in the entire top half of the A3XXX fuselage around the passenger cabin, cargo floors, bulkheads, flap skins, etc. (Ref.12).

As mentioned in the 'Introduction', the spiraling costs of aircraft operation require significant gains in fuel economy. While the use of conventional micro composites incorporating carbon fibers in polymeric matrices is increasing steadily, reaching 50 per cent by weight at present, their serious limitations need to be overcome. Improvements in their damage tolerance and damage detection are needed. Their poor electrical conductivity requires the use of metallic meshes in the outer skin, imposing a weight penalty. The use of multifunctional CNTs has the potential to reduce the weight of aircraft structures, while enhancing the mechanical properties, lightning strike protection, etc. However, due to the stringent requirements for certification, the use of nanocomposites in load-bearing aircraft structures can be expected to occur gradually and over a period of time.

Conventional Composites in Aircraft Interiors

The application of composites to the aircraft exteriors-namely structural components- is far more visible and publicized than the application to aircraft interiors. The performance demands for the aircraft interiors are very similar to those for the aircraft primary structures; parts must have mechanical strength, stiffness, dimensional stability and in addition, low heat and smoke release in the event of a fire. With the rising jet fuel prices, there is a serious effort by designers and manufacturers of aircraft interiors to reduce the weight by using composite materials (Ref.14). A variety of composite materials have been used over several decades for making the aircraft interior components and fixtures, including floor boards, bulkheads and cabin dividers, lavatories, galleys, wall and ceiling panels and stowage bins (Ref.14). Glass fiber reinforced composites amount to 65 percent of the composites used in the cabin interior, with carbon fiber reinforced composites accounting for most of the remainder; aramid fiber reinforced composites are used to a limited extent, such as in cargo compartments. The market for interior composite parts is large and can amount to (Ref.15) 5,100 kg for a single Boeing 777. The interior market is two-fold: 'new-build' or built by Original Equipment Manufacturer (OEM) and 'aftermarket'. The interior components are estimated to have a service life between three and seven years and complete interior refurbishment is done within eight years. The estimated number of new aircraft to be delivered by manufacturers between 2012 and 2022 is 17,000 (Ref.14), with 60 percent of these representing replacement of ageing aircraft. The actual and projected increase in the use of composites in aircraft structures as well as the OEM and aftermarket usage in aircraft interiors is shown in Fig.6 (Ref.14).

Reducing the weight of seats by using composites leads to slimmer seats and substantial savings. By one estimate (Ref.15), in A319 aircraft the weight saving of 415 kg per aircraft due to lighter seats results in 4.3 percent reduction in fuel consumption. In addition, making the seats slimmer allows the airlines to increase the number of seats. By another estimate, "for Lufthansa, fitting 168 aircraft with BL3520 seats generated a capacity of 12 additional A320s" (Ref.16).

Another application under consideration is the aluminum parts such as seat rails/pedestals and the overhead stow bin brackets. Replacing these metal parts with composites will make them more compatible with composite aircraft such as Boeing 787 and make isolation plies for preventing galvanic corrosion unnecessary (Ref.15).

While the use of conventional micro composites with glass and carbon fibers in a polymeric matrix reduces the weight of aircraft interior components, further improvements are possible if nano reinforcements such as CNTs are incorporated in these interior components. Nano reinforcements have significantly higher specific mechanical properties compared to carbon fibers. The fabrication of aircraft interior components exclusively out of nano composites will have to wait for compliance with certification requirements but nano reinforcements such as CNTs and nanoclays can be incorporated in conventional composites for some weight saving; the addition of nanoclays can enhance the flammability resistance.

Nanocomposites for Aircraft Applications

Nanocomposites incorporate nano reinforcements in a suitable matrix- at present mostly polymer matrices. The nano reinforcements, having at least one dimension of the order of 100 nm or smaller, are increasing in variety; at present the commonly used nano reinforcements are:

- Graphene
- Fullerene
- Carbon and boron nitride nanotubes
- Nano fibers
- Nano clays
- Polyhedral Oligomeric Silsesquioxane (POSS)
- Ceramic nano particles (in a metallic matrix)

Graphene, Fullerene, Nanotubes, Nano fibers, Nano Clays and POSS

A very brief description of the first six of the above-mentioned nano reinforcements is given here.

Graphene, discovered in 2004, is a single layer of carbon atoms tightly arranged in a honeycomb pattern (Ref.17). It can be considered as a CNT unrolled. Graphene and its boron counterpart, hexagonal boron nitride (also called ‘white graphene’) have exceptional mechanical and thermal properties.

Fullerene, discovered in 1985, is a carbon allotrope with carbon atoms arranged in closed shells having the structure of a truncated icosahedron (Ref.18). Fullerenes have a high strength and are stable up to 1000°C. This type of structure occurs in other materials like WS_2, giving unique properties.

Multiwalled CNTs (MWCNTs) were experimentally identified in 1991 and single walled CNTs (SWCNTs) were discovered in 1993. Nanotubes of other materials have also been made. Among these, boron nitride nanotubes (BNTs) are important. CNTs and BNTs have very high strength and stiffness (Ref.19).

Carbon nanofibers (CNFs) consist of graphite platelets arranged in various orientations (Ref.20). Due to the much larger surface area, their properties are inferior to those of CNTs.

Nano clays are naturally occurring minerals and consist of 1 nanometer (nm) thick layers made up of two sheets of silica fused to a sheet of alumina (Ref.21). In composites they impart high temperature resistance and impermeability.

POSS is a nanostructure and can be considered as the smallest silica particle, with a diameter in the range 1 to 3 nm (Ref.22). It consists of a silica cage core and other organic functional groups attached to the corners of the cage. Dispersing POSS in a polymer can increase the strength and stiffness, while reducing flammability.

Ceramic Nano Particles in a Metallic Matrix

Metal matrix composites with ceramic reinforcements in the form of micron sized particles or fibers belong to a very important class of composites. They can withstand much higher temperatures compared to polymer matrix composites. Ceramic nano particles added to metal matrices represent a further improvement. SiC, TiC, WC, TaC, TiB_2, AlN and Al_2O_3 are common types of nano particles added to Al, Mg, Ni and Cu matrices, as shown in Table-1 (Ref.23). The nano reinforcements improve strength, modulus, fracture toughness, creep resistance, thermal shock resistance, wear resistance and dimensional stability at elevated temperatures (Ref.24). It is interesting and important to note that the volume percentage of nano particles needed to achieve a property enhancement (such as wear resistance, tensile strength, etc.) is considerably smaller than the volume percentage of micro particles. For instance, the tensile strength of an aluminum alloy reinforced with 1 volume percent of 10 nm size Si_3N_4 has found to be comparable to the tensile strength of the same aluminum alloy reinforced with 15 volume percent of 3.5μm size silicon nitride particles (Ref.24). This is due to the significant increase in the surface area of the nano particles.

The major challenge in using the nanocomposites with metallic matrices (as in all nanocomposites) is fabrication-

Table-1 : Nano Ceramic Reinforced Metal Matrix Composites (PSZ : Partially Stabilized Zirconia; YSZ : Yttria Stabilized Zirconia)

Matrix/Nano-sized Reinforcement	Properties
Al/SiC Mg/SiC Al/Al_2O_3 Mg/Al_2/O_3	Improved ultimate strength, hardness and elastic modulus
Al/AlN	Higher compression resistance and low strain rate
Ni/PSZ/and Ni/YSZ	Improved hardness and strength
Cu/Al_2/O_3	Improved microhardness

dispersing the nano particles, overcoming their tendency to agglomerate. Several methods are being developed: *ex-situ* methods such as powder metallurgy, and *in-situ* methods such as combustion synthesis, exothermic dispersion (XD) and direct metal oxidation (DIMOX).

Methods of Using Nanoreinforcements

Nano reinforcements have exceptional mechanical properties. But in order for these properties to be translated into composite properties, the volume fraction of the nano reinforcements has to be high and the nano reinforcements need to be uniformly dispersed in the matrix. Due to the strong tendency for some of the nano reinforcements, such as the carbon nanotubes, to agglomerate, only 1 or 2 per cent concentration of these nanotubes in a polymer matrix can be achieved. As mentioned in the Introduction, significant improvements in the fabrication of nanocomposites need to be made to meet the certification requirements before nanocomposites can be used in aircraft primary structures. To overcome these difficulties, the nano reinforcements are either added to complement the conventional fiber reinforced composites or used as a thin coating to derive special benefits in properties. The former procedure results in 'hierarchical-reinforced nanocomposites' or 'fiber-reinforced nanocomposites'. These methods of incorporating nano reinforcements in conventional composites are briefly described here.

Growing Carbon Nanotubes on Fibers

Carbon nanotubes have been grown on carbon and other fibers, as shown in Fig.7 (Ref.25). It has been found that this process sometimes significantly weakens the substrate fibers. The reason has been attributed to the absence of large tension forces during the growth of the carbon nanotubes- in contrast to the high tensile forces applied during the fabrication of the carbon fiber itself (Ref.26). The metal catalysts used to grow the nanotubes also contribute to the strength degradation. Coating the carbon fibers with alumina and a special polymer (called K-PSMA) coupled with applying tension has been observed to preserve the carbon fiber strength. Another strategy has been using K-PSMA along with lower temperatures (Ref.27).

Adding Carbon Nanotubes to the Matrix

At present, carbon nanotubes cannot be added to polymeric matrices in concentrations greater than a few per cent due to the tendency of the nanotubes to agglomerate. The composite matrix can be used in conjunction with carbon fibers to give better materials for aircraft structural materials. This concept is shown in Fig.8 (Ref.28). The carbon nanotube- polymer matrix composite can also be used as a conductive adhesive to join carbon fiber reinforced polymer matrix parts to each other or carbon fiber reinforced polymer matrix parts to metals.

Nano Stitching of Composites

In a conventional polymer matrix composite, the interfaces between the plies are weak as they consist of only the polymer matrix. To overcome this deficiency, plies have been stitched together with the same type of fibers present in the plies. While enhancing the strength in the thickness direction, this technique has been found to weaken the composite in the plane of the plies. This problem has been solved by using carbon nanotubes for stitching the plies together, as shown in Fig.9 (Ref.29, 30). The carbon nanotubes can be introduced between the plies either by growing the carbon nanotubes on the carbon fibers themselves, as described earlier, or by first lowering the viscosity of the polymer layer between the plies, by heating, and then sucking up the nanotubes into the polymer.

Adding Carbon Nanotubes to Aircraft Paint

When carbon nanotubes are dispersed in a polymer, even at only a few percent, the resulting composite can have a variety of characteristics and applications, as described later. The composite can be applied as a coating or paint on an aircraft to accomplish one or more tasks.

Nanocomposite Applications in Aircraft

An aircraft is a machine that is able to fly by gaining support from the air or atmosphere by using the dynamic lift of an airfoil or the downward thrust from jet engines. While fixed wing aircraft and rotorcraft are commonly used, the former is used mostly in the commercial transportation of passengers and is considered here.

Nanoclay and Carbon Nanotubes for Aircraft Interiors

Polyurethanes (PUs) have a wide range of properties that can be tailored to meet the requirements of several applications such as coatings, adhesives, elastomers and foams (Ref.31). Polyurethane foam consists of closed cellular structures embedded in a continuous matrix. This closed cell geometry is good for mechanical and insulating properties. Polyurethane foam is widely used as a core material for sandwich structures as well as thermal insulation, cushioning, buoyancy, energy absorbing packaging, etc. Its low density has led to its use in light, stiff components such as aircraft interior panels. However, PUs have some drawbacks also, such as low thermal stability, low mechanical strength, etc.

Nanoclay (silicate) particles provide many benefits when they are incorporated in PUs. Such composites possess high dimensional stability, high heat distortion temperature, reduced gas permeability, improved flame retardance as well as higher mechanical properties. All these property enhancements are attractive for aircraft interiors, which play an increasing role in the reduction of aircraft weight as mentioned earlier.

Carbon nanotubes- filled PUs are not only lighter in weight, but also highly absorptive of acoustic and vibration energy for passive noise control- another attractive feature for aircraft interior applications.

The aircraft interior components that can benefit from weight reduction include floorboards, ceiling, panels and seats. Nanocomposites incorporating nanoclays and CNTs can play a significant role in replacing, at least in part, the metal and plastics in current use. Reducing the weight of seats can result in major aircraft weight reduction. Slimmer seat designs can lead to increases in the number of seats per aircraft. For example, Deutsche Lufthansa recently adopted RECARO BL3520 seats for its entire fleet of A319 aircraft; at less than 11 kg per seat, it has resulted in 30 per cent weight reduction compared to the previous seats. For its fleet of 330 planes of A319 model, this single change alone saves 137,000 kg or about415 kg per aircraft (Ref.15). Lufthansa reports that the resulting fuel consumption reduction is approximately 4.3 percent. When more interior parts incorporate nano reinforcements, further benefits can be expected.

Nanocomposites for Aircraft Brakes

From a safety point of view, aircraft brakes are very critical components. The material employed in the brake must have stable and reliable frictional and wear properties under varying conditions of load, speed, environment and temperature conditions (Ref.32). The brake disc should be capable of absorbing the generated heat without suffering distortion or cracking and the thermal stresses must be manageable until the heat is dissipated

Carbon-carbon composites, which incorporate carbon fibers in a carbon matrix, were initially used in military aircraft brakes. Later, cost considerations resulted in the use of steel brakes on smaller, short-haul airplanes and carbon-carbon brakes on larger, long-haul commercial aircraft. The higher cost of the composite brakes in larger aircraft was justifiable due to the cost savings associated with reduced weight and longer service life. Recent improvements in brake manufacturing have made carbon-carbon brakes cost competitive with steel brakes.

Carbon-carbon brakes meet the high-performance demands of modern aircraft and are now basic equipment. They have high temperature stability, high thermal conductivity, high specific heat and low density. The use of carbon-carbon brakes results in savings of 249 kg in Boeing 757 and 363 kg in Boeing 767 (Ref.33) compared to steel brakes. Nano reinforcements such as CNTs can further enhance the mechanical and thermal properties of carbon-carbon brakes.

One of the candidate materials being considered is carbon nanotube reinforced aluminum alloy. The aluminum matrix provides ease of fabrication of the composite by powder metallurgy technique while the carbon nanotubes provide the enhanced thermal and electrical conductivity, resistance to wear and damage as well as improvements in mechanical properties (Ref.32). The combined benefits of the metal matrix and the nano reinforcements make these composites viable candidates for landing gears also (Ref.34).

Graphene and nano graphene platelets (NGP) have electrical conductivity similar to CNTs but higher thermal conductivity and higher specific area. In addition, unlike the CNTs, the NGPs are less expensive and can be incorporated in a matrix at much higher concentrations.

Nanocomposites for Aircraft Repair

It is estimated (Ref.35) that approximately 30 percent of the global commercial aircraft fleet is more than 15 years old. Corrosion and fatigue exact a constant toll on the ageing aircraft. In general, the replacement costs are 10 times greater than the repair costs. With the emergence of composite materials as the primary (50 percent or more) structural material in Airbus A380 and Boeing B787, new repair materials compatible with both metals and composites are needed. The European IAPETUS 7th Framework Programme project, led by TECNALIA is developing a new technology for the repair of aircraft made of aluminum as well as composites; multifunctional composite materials using carbon nanotubes, both in the matrix of the composite material as well as in the adhesive are being developed (Ref.36).

New nanofilled polymer resins, such as bisphenol E cyanate ester (BECy), are being developed to reduce toxicity and volatile organic compounds while reducing waste due to spoilage (Ref.37) compared to traditional thermosets. A repair material with BECy, reinforced with alumina nanoparticles, has also been suggested (Ref.38).

Nanocomposites for Aircraft Engines

Multi-layered composite and graded coatings based on stabilized zirconia are used as thermal barrier coatings (TBC) on gas turbine blades of aero engines (39). These protective coatings are deposited by plasma spraying or electron beam evaporation (EB-PVD) techniques. In the conventional approach, a two-layer coating is used: an oxidation resistant metallic layer (bond coat, typically NiCr alloys) and a ceramic top coat consisting of partially stabilized zirconia which functions as a thermal barrier (Ref.39). An example of such a dual layer TBC coating is a NiCoCrAlY alloy bond coat with a $ZrO_2Y_2O_3$ top coat. Many improvements are being made, for example, depositing multilayers of ZrO_2-Al_2O_3 in which the layer spacing is scaled to have nanosized zirconia crystallites (Ref.39).

Solid particle erosion is a problem for turbine blades of advanced aircraft engines (Ref.40). Instead of fabricating the whole blade out of a hard material, it is more economical to apply hard protective coatings of nanocomposites on conventional materials (such as a super alloy). It has been reported (Ref.40) that super-hard, very tough and erosion-resistant nanocomposite coatings have been developed for deposition on aircraft turbine blades. The coatings are reported to consist of thick layers of Ti-Si-C-N with a structure composed of titanium carbonitride (TiCN) nanocrystals 4-7 nm thick in a matrix of amorphous silicon carbonitride. These coatings exhibit superior toughness and erosion resistance and are deposited by plasma-enhanced magnetron sputtering (PEMS) technology to produce very thick coatings.

In addition to employing ceramic coatings on super alloy components, strengthening ceramics with micro and nano reinforcements can enhance the toughness and crack growth resistance and provide an alternate solution to increase the operating temperature and reliability. Aluminum oxide nano fiber, called NAFEN (Ref.41) is reported to improve the ductility, stiffness and creep- resistance of ceramic matrix composites (CMCs). Silicon Carbide fibers and nanofibers enable ceramic matrix composites to withstand temperatures in excess of 1300°C, while weighing only one-third as much as nickel super alloys that dominate gas turbines and jet engines.

Replacing super alloys with CMCs with micro and nano reinforcements has the potential to reduce the engine mass by hundreds of kilograms while improving thrust by 10 per cent (Ref.41). The CMC shroud weighs approximately 1 kg, which is one-third the weight of an equivalent nickel super alloy shroud. General Electric (GE) is currently studying the use of such CMCs for turbine blade upgrades on the F414 engine, which powers the Boeing Super Hornet and the Hindustan Aeronautics Ltd Tejas light combat aircraft.

Nanocomposites for Aircraft Coatings

Ancient fresco paintings, using nano composite paint pigments, have been preserved in harsh environments for several centuries (Ref.42). Modern aircraft paints are required (Ref.43) to possess diverse properties to meet diverse needs: mechanical properties (high modulus, strength, toughness), barrier properties (low moisture absorption, increased chemical resistance), fire retardant properties (reduced burn-through, enhanced fire, smoke and toxicity), thermal properties (increased heat distortion temperature, stability), tribological properties (scratch resistance, reduced wear), and electrical properties (EMI shielding, ESD protection). Some of the interesting applications of nanocomposites in aircraft paints are briefly mentioned here.

Drag Reduction : The energy consumption by aircraft can be reduced by using nanocomposite coatings for drag reduction. It is estimated (Ref.44) that around 50 percent of fuel burn for a commercial airliner in cruise conditions is used just to overcome skin friction.

A new nanocoating, which has already been used on military aircraft, is expected to be tested on commercial aircraft (Ref.45). The coating on an entire plane is estimated to add only 113 grams to the weight of the plane, compared to the 80 kg for the regular paint, and has the potential to reduce fuel consumption by 2 percent. The nanocoating prevents the buildup of dirt and debris in the microscopic pits and crevices within the regular paint.

De-Icing Aircraft : Buildup of ice on aircraft wings during severe winters results in either cancellation of flights or expensive procedures to remove the ice. Conventional de-icing procedures include the use of a de-icing liquid, the use of bleed-air systems to heat the leading edge of the wings, mechanical boots that can be inflated to break off the ice and the use of weeping-wing devices that release antifreeze onto the wings (Ref.46).

A modern method relies on nanocomposites. In this method, a thin coating of carbon nanotubes in a polymer matrix is applied to aircraft wings and is heated by an electric current to melt the ice (Ref.47).

Promoting Stealth : Carbon nanotube based paint, applied to an aircraft, can absorb a broad spectrum of light (Ref.48). Such aircraft can provide invisibility in the visual range as well as to radar, if the nanotubes are grown with some space among them so that their refractive index matches that of the surrounding air (Ref.49).

Other Applications : Applications of new materials in load-bearing aircraft structures requires stringent and time-consuming certification requirements. Lockheed Martin has announced (Ref.50) plans to integrate nanocomposites in non-load bearing airframe components, such as wing-tip fairings, in the Joint Strike Fighter F-35. A nanocomposite with carbon nanotubes in an epoxy thermoset matrix is expected to replace carbon fiber reinforce polymer composite in the wingtip fairings.

Carbon nanotubes, due to their electrical conductivity, are being used to develop smart or multi-functional adhesives for joining aircraft parts while providing early warning of high stresses and possible failure (Ref.51). The strain or damage in an aircraft part, coated with paint containing carbon nanotubes, can be read by an infrared spectrometer (Ref.52). The near-infrared fluorescence from carbon nanotubes can also be used in the detection of underlying damage (Ref.53).

Another application of nanocomposites is in lightning strike protection of composite aircraft. With the increasing use of polymer matrix composites for the fuselage and wings, the electrical conductivity of the aircraft surface has decreased. The current method of enhancing the electrical conductivity of aircraft exterior is to incorporate expanded aluminum or copper meshes. These meshes are relatively heavy and in addition, galvanic corrosion is a potential problem. Conductive nano reinforcements, such as carbon nanotubes and nickel nano wires, are expected to be used in the surface layers of structural composites (Ref.54, 55).

Concluding Remarks

The use of carbon fiber reinforced polymeric composites in commercial aircraft has been increasing over the years and has reached 50 percent recently due to the steep rise in jet fuel prices and the consequent demand for lighter structural materials. To overcome the shortcomings of the carbon fiber-polymer composites- such as insufficient electrical conductivity, lack of interlaminar strength, initiation and growth of invisible damage, etc. - several methods to introduce nano reinforcements in these composites are being explored. Such hierarchical composites can combine the advantages of nano reinforcements and micro reinforcements.

Nano reinforcements such as CNTs have very high mechanical properties such as strength and stiffness. Their significantly larger surface area (per unit volume or mass) leads to better interfacial characteristics in matrices, leading to enhanced mechanical, electrical and other properties. The benefits of nano reinforcements occur even at relatively lower concentrations compared to the micro reinforcements. Nanoclay particles, even at low concentrations, increase the mechanical properties while enhancing thermal and fire resistance; they also reduce the permeability due to the significantly larger path that the gases have to diffuse through such composites. Conductive nano particles, such as CNTs, increase the electrical conductivity of polymer matrix nanocomposites, providing lightning strike protection when such nanocomposites are used in the outer layers of macro composites in aircraft fuselage and wings; the weight saving, compared to the use of expanded metal meshes in the outer layers of conventional composites, is substantial and contributes to fuel economy.

While CNTs exhibit much higher strength and stiffness compared to carbon fibers, at present it is difficult to fabricate nanocomposites with large concentrations of CNTs with uniform dispersion. Due to the stringent certification requirements for aircraft structural materials mentioned in the Introduction, it will be some time before nanocomposites are used in aircraft primary structures. However, nanocomposites can be used in non-load bearing applications and nano reinforcements can be added to carbon fibers and polymeric matrices in conventional micro composites, as described in this paper.

Several specific materials and applications in the aircraft exterior and interior have been described in this paper. Success in such applications can eventually lead to the development and certification of structural nanocomposites with larger concentrations of nano reinforcements.

Boeing, one of the world's leading manufacturers of commercial aircraft, has recognized the importance of nanocomposites. The company has listed twelve priorities regarding nanocomposites (Ref.56), such as enhancements in electrical conduction, thermal resistance, acoustics, structural performance, adhesives and bonded repair, ice-phobic characteristics, nano sensors, etc.

Airbus, another leading aircraft manufacturer, is also preparing for the integration of nanocomposites in airframes. The three approaches for the future are named (Ref.57) nano-augmented, nano-engineered and nano-enabled materials. Nanostitching to increase the interlaminar strength, increasing electrical conductivity by adding CNTs to the matrix, etc. are some of the anticipated applications of nanotechnology.

A precursor to the use of nanocomposites in structural parts of commercial aircraft is their application in other types of aircraft where the certification requirements are not stringent. One such application is in aerobatic aircraft. In 2008, Avalon Aviation's Giles G-200 aircraft flew with carbon nanotubes integrated into its carbon fiber composite engine cowling (Ref.58). The Giles G-200 is a high-performance, single-engine aerobatic carbon composite aircraft.

In the next decade or two, the use of nanocomposites in aircraft structural and non-structural parts to supplement traditional (fiber reinforced) composites or by themselves, can be expected to increase significantly.

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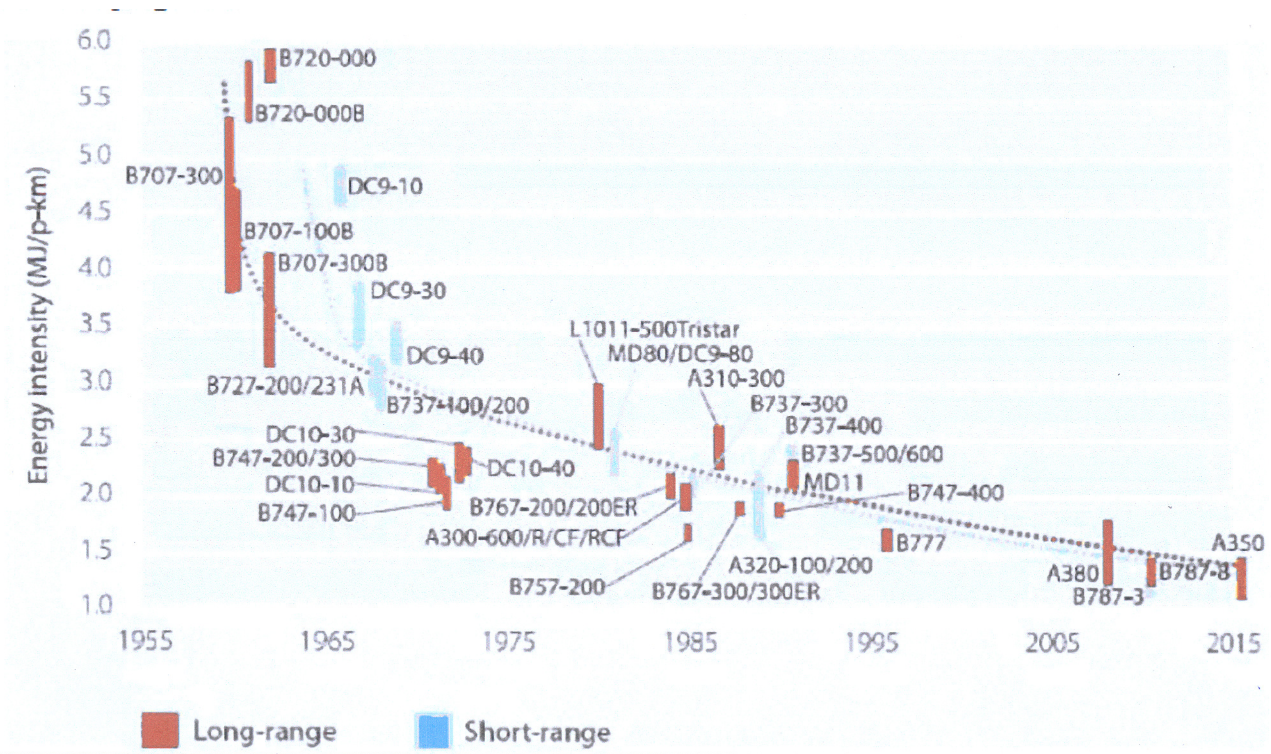
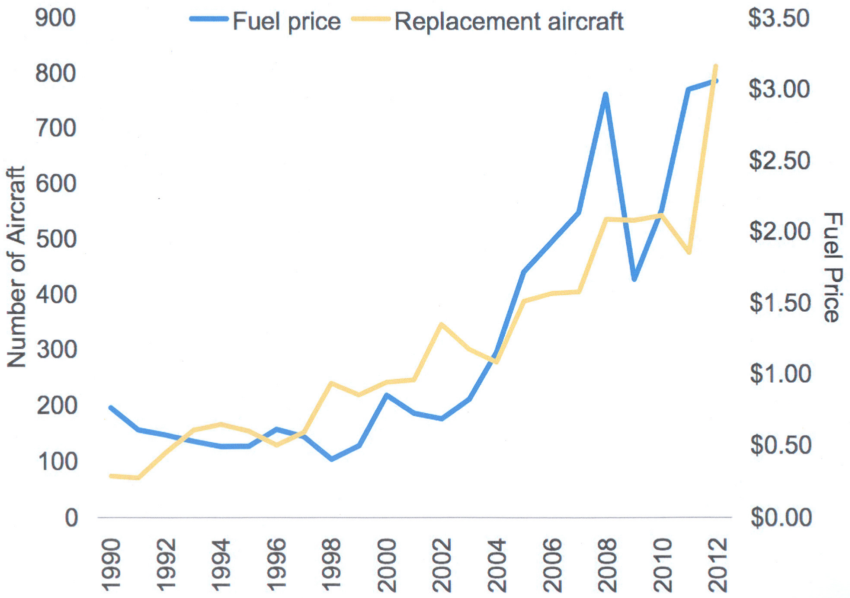


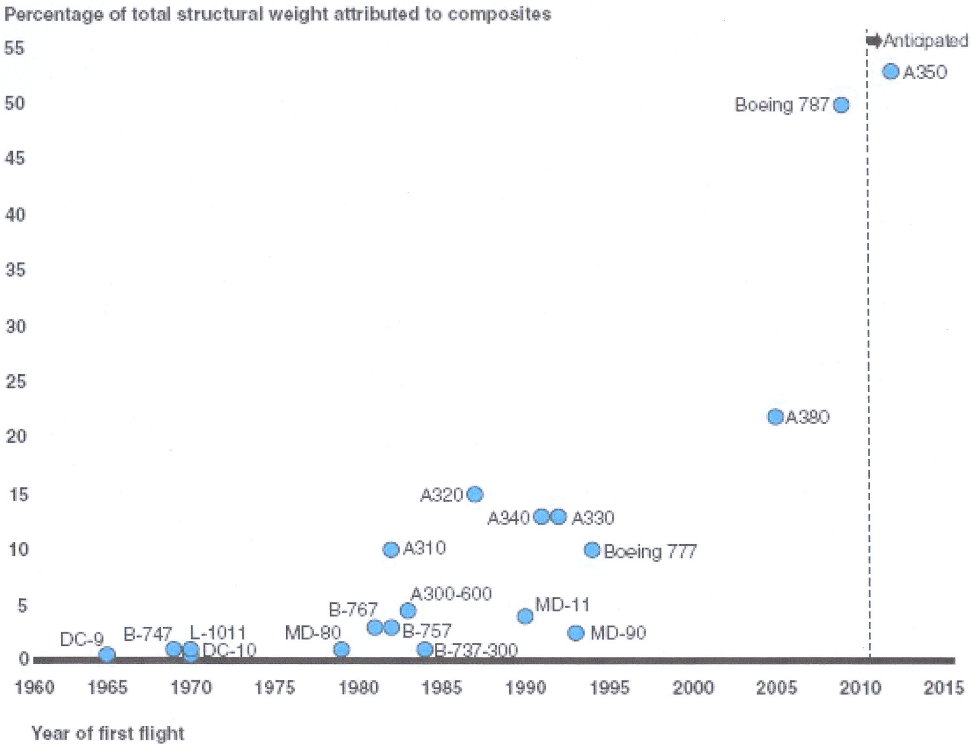
Source: Lee, IATA

Fig.1 Improvement of Fuel Efficiency of New Aircraft Over the Years [Ref.3]



Source : US A4A Cost Index, Ascend : Western Jets as of 31/12/12, Morgan Stanley Research

Fig.2 Correlation Between Rising Fuel Costs and Demand for New Aircraft [Ref.3]



Sources : GAO analysis of information from FAA, NASA, Boeing Company, Jane's All the World's Aircraft, and Jane's Aircraft Upgrades

Fig.3 Commercial airplane Models Over Time by Percentage of Composites [Ref.8]

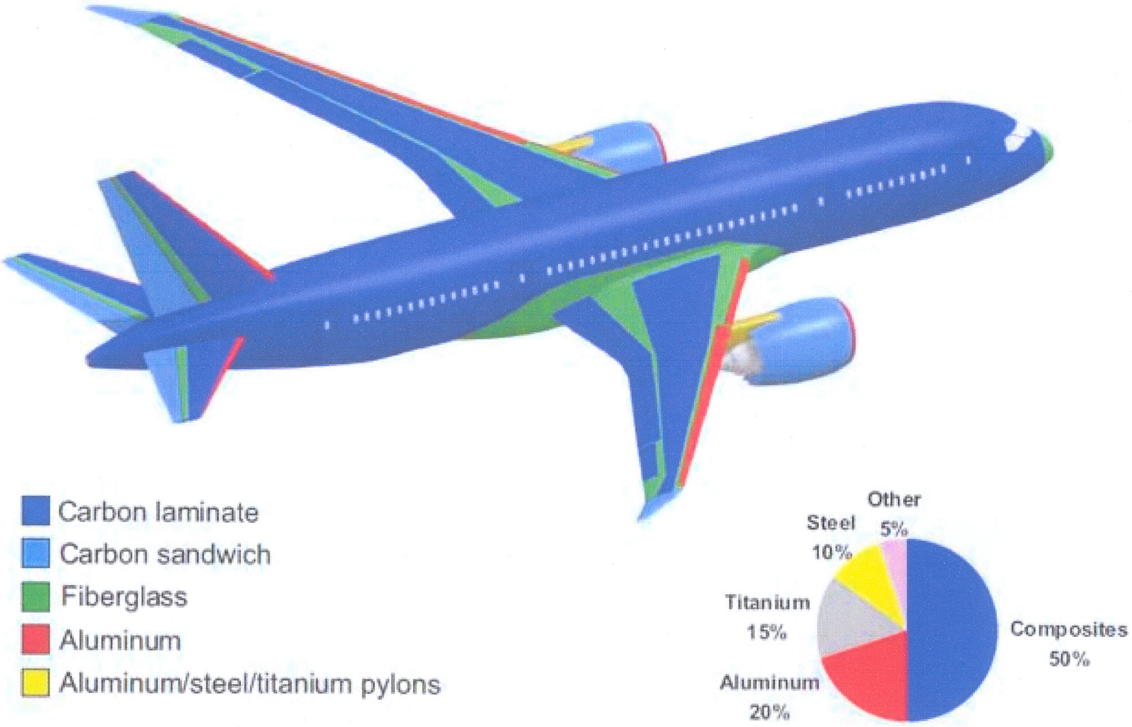


Fig.4a Materials Used in the Boeing 787 [Ref.9]

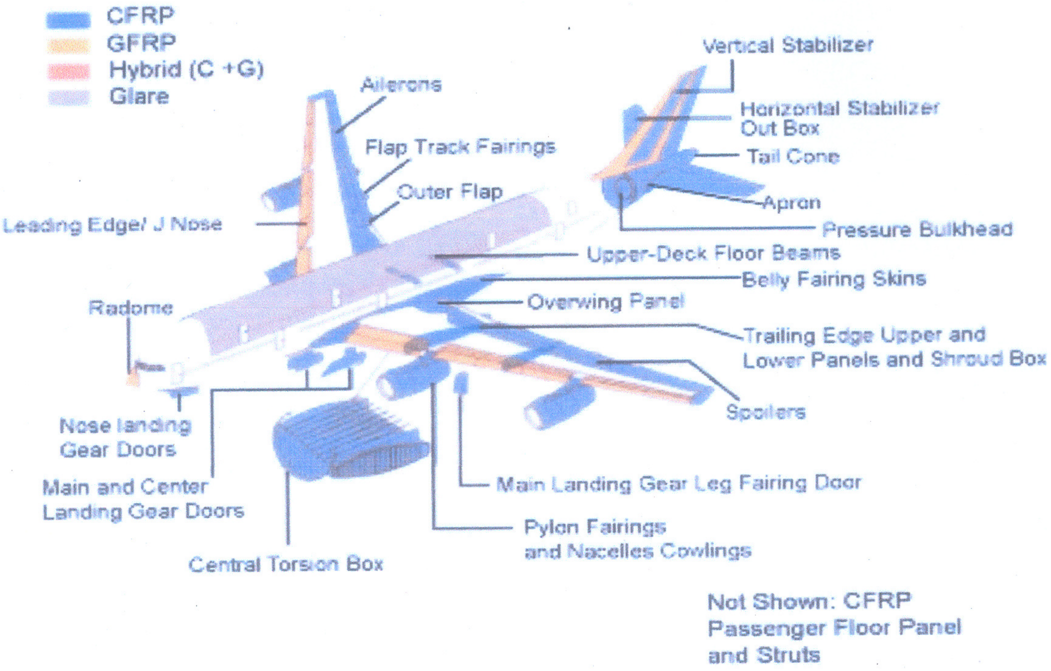


Fig.4b Materials Used in the Airbus 380 [Ref.10]

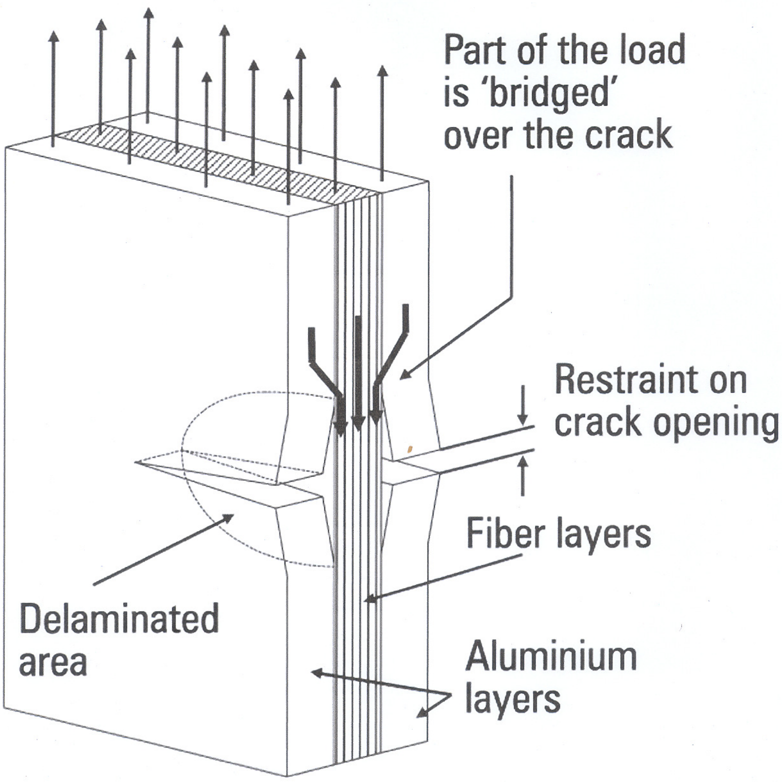


Fig.5 Crack Bridgging in Fiber Metal Laminates [Ref.12]

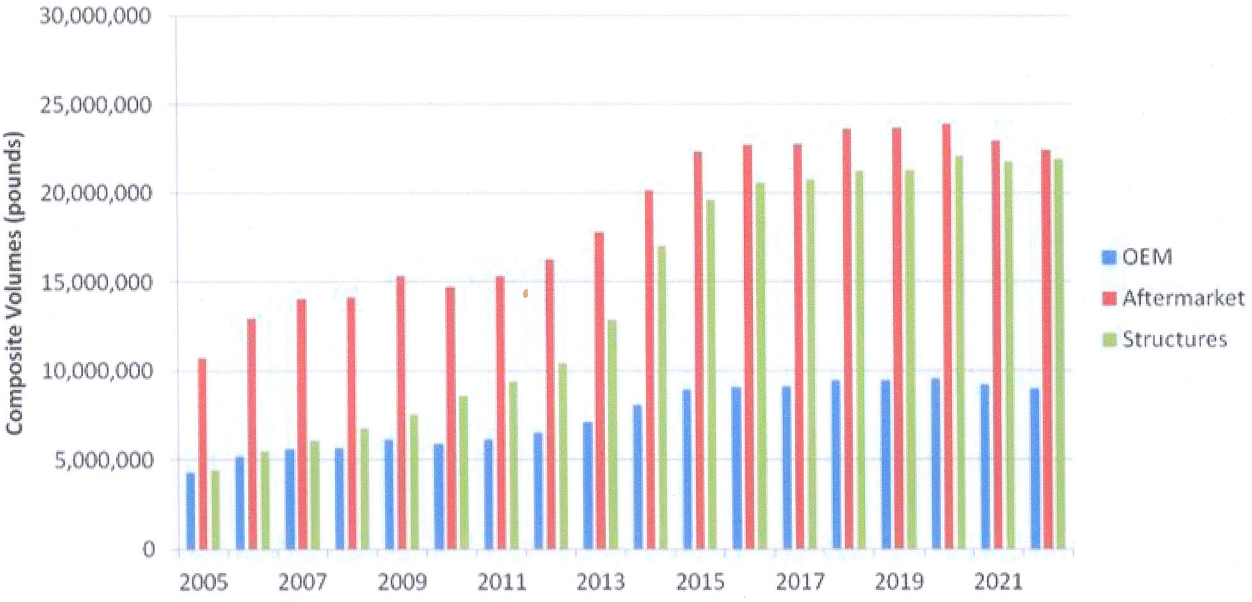


Fig.6 Composites Usage in Aircraft Structures Vs. Aircraft Interiors (OEM and Aftermarket) [Ref.14]

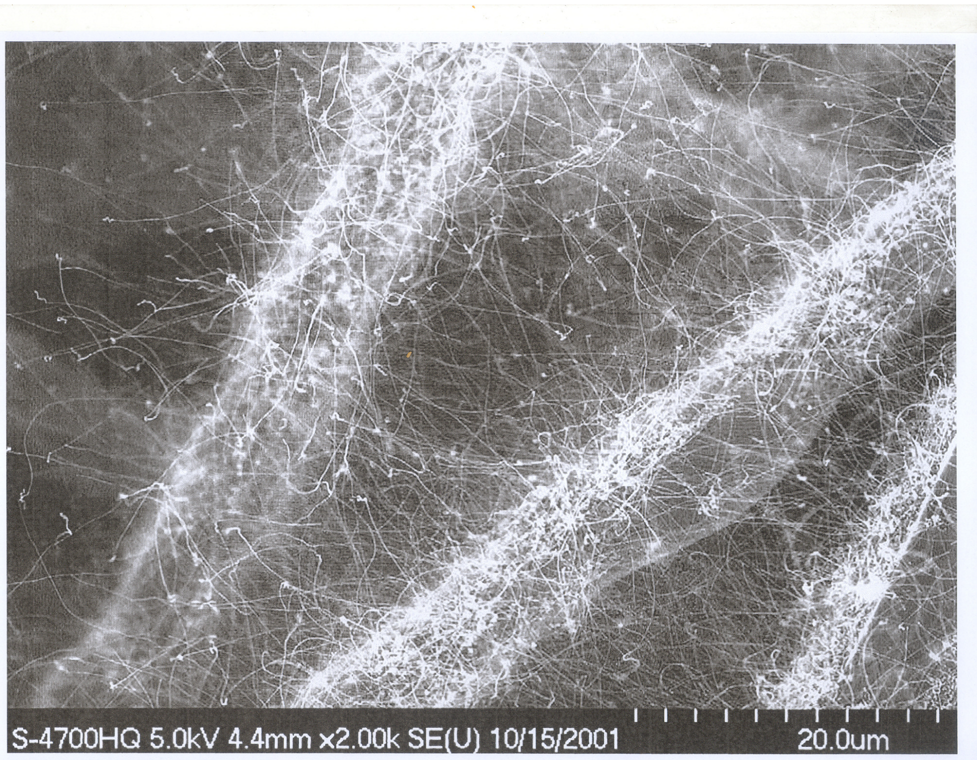


Fig.7 SEM Image of Carbon Nanotubes Grown on a Carbon Fiber [Ref.25]

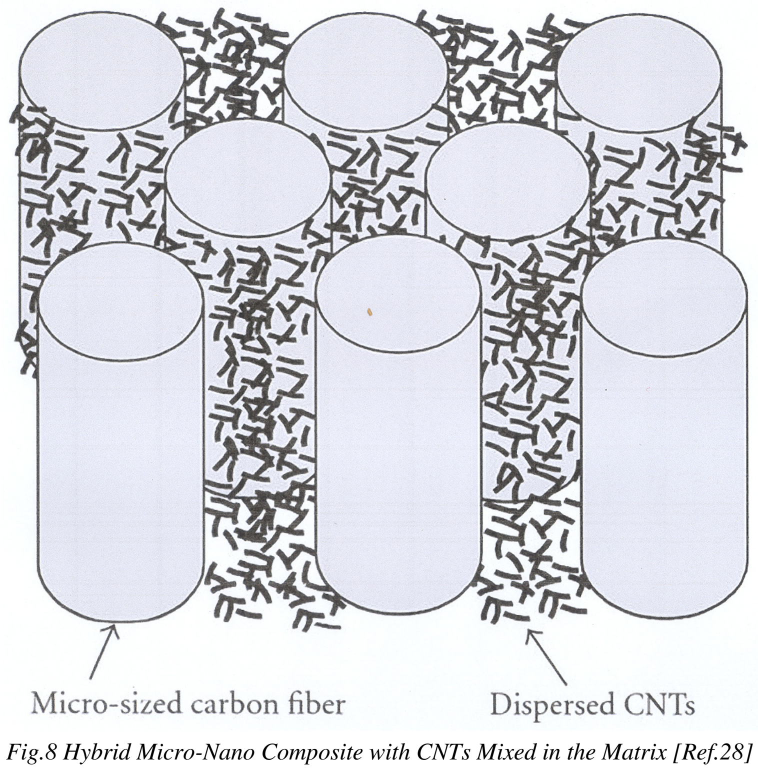


Fig.8 Hybrid Micro-Nano Composite with CNTs Mixed in the Matrix [Ref.28]

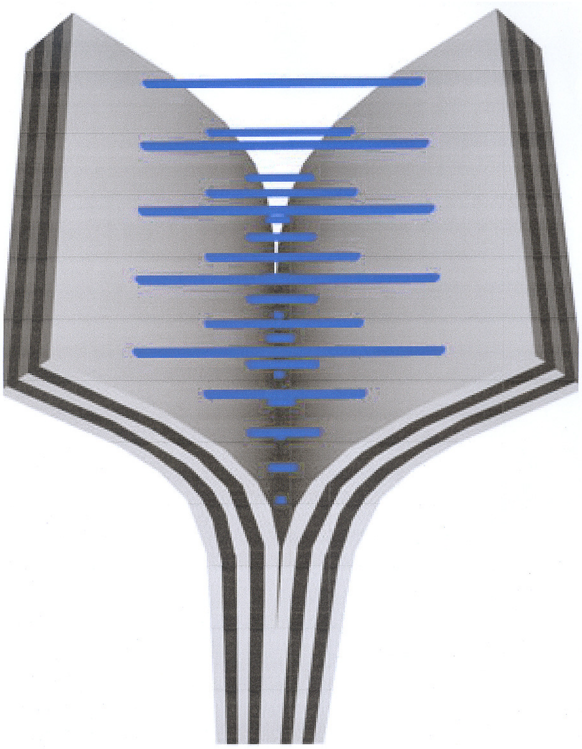


Fig.9 Carbon Fiber Reinforced Polymeric Composite Plies Stitched Together with CNTs [Ref.29, 30]