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Composite Materials, Metals, And Ceramics Used in the Boeing 787- Materials Overview

Pramodkumar Nedumpilli Ramakrishnan

Student Member of Vijaybhoomi University Research Incubation Programme

Abstract: ***This paper aims to provide an overview of the new materials that are currently in use in the Boeing 787 Dreamliner. The 787 stands at the pinnacle of today's aviation sector and is an engineering marvel, renowned for its groundbreaking innovation and exceptional technical capabilities. Most notably, advanced composites have never been used to this extent in a passenger jet before, representing the first step of ushering in a new era of composite use within the aviation sector. This paper aims to provide a thorough overview of the new materials in 3 sections: composites, metals, and ceramics. This study will detail why the aircraft's components are made of a newer material, delve deeper into the properties of that material, highlight some of its disadvantages, and explore the industrial techniques used to enhance the quality of components used in the 787. This study will help in providing valuable insights on the practical applications and drawbacks of the new materials, illustrating their potential use even beyond the aviation industry,***

Keywords: Boeing 787 Dreamliner, Composites, Titanium, Ceramics, Carbon fiber

1. Introduction

The history of aircraft is a testament to humanity's relentless pursuit of conquering the skies. It began in 1903, when the first powered flight was made by the Wright Brothers. Ever since then, aircraft have developed rapidly, going from simple biplanes to complex jet - powered machines with Boeing being essential in this revolution. Since its founding in 1916, Boeing has created enduring aircraft, such as the Boeing 707, which transformed air travel in the 1950s, and the Boeing 747, also known as the "Queen of the Skies, " which rewrote the rules for long - haul travel. And now, Boeing is revolutionising the materials used in the entire airline industry with its most recent and groundbreaking airplane - the Boeing 787. This plane challenges the limits of exactly how much of an airplane can be made of composite materials and metals like titanium and has novel features and designs that allow it to be much more efficient than other aircraft.

The Boeing 787 Dreamliner has 3 variations, the 787 - 8, 787 - 9, and 787 - 10. The 787 - 8 is the smallest out of the 3, with a length of 57m, wingspan of 60m, height of 17m, and a total carrying capacity of 248 people. The 787 - 9 and 787 - 10 vartistions get progressively bigger, and their technical specifications are listed in Table 1.1 -

Table 1.1

	787 - 9	787 - 10
Passenger capacity	296	336
Range (km)	14, 010	11, 730
Length (m)	63	68
Wingspan (m)	60	60
Height (m)	17	17
Engine	GEnx - 1B / Trent 1000	GEnx - 1B / Trent 1000

The reason why the B - 787 was chosen as the plane to study is due to the many major changes it has from traditional aircraft design, which were successfully implemented in actual flight. For example, the 787 boasts an expansive use of titanium and carbon composites throughout the structure of the aircraft and employs transformative manufacturing techniques in order to make the 787 as efficient and light as possible.

2. Research Questions

This paper is based on the following questions -

- Why have new materials been used in the B - 787?
- What are the material's properties?
- What are the materials advantages in aeronautical applications?
- What are some of the disadvantages and implications of using the material?

3. Research Methodology

This paper will answer the research questions by firstly, analysing and defining the types and amounts of materials used, secondly, by highlighting the properties of the materials, and lastly, by relating the materials' properties to their use, thus, explaining their advantages and disadvantages. The paper is divided into 3 main categories: Composites, Metals, and Ceramics.

4. Discussion

Figure 1.1 shows the composition of materials in the 787 by weight.50% of the 787 weight consists of carbon fiber reinforced plastics and other advanced composites. Each aircraft contains approximately 32, 000 kg of CFRP composites, made with 23 tonnes of carbon fiber. It is an impressive 80% composite by volume. [1] Composite use as well as titanium use has been significantly expanded compared to the previous generations of Boeing planes. The B - 777, the predecessor of the 787, for example, was made up of roughly 9% titanium by weight, 12% composites, and over 50% aluminium.

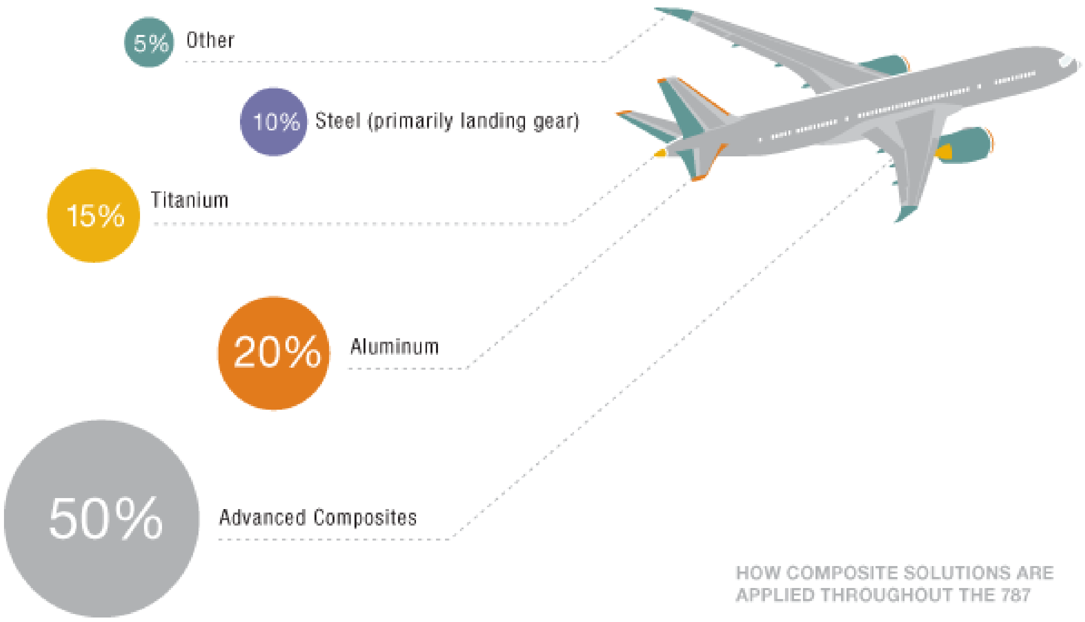

Figure 1.1: Material composition of 787

1) Composites
Composite materials are advanced materials created by combining two or more separate components, such as fibers or particles, together within a matrix. These components combine to form a new material with improved qualities that typically outperform its constituent elements. Composites are well - known for their high strength - to - weight ratios, durability, and adaptability. They are widely used in a variety of industries, including aerospace, automotive, construction, and sports equipment, where their customisation makes them invaluable for the creation of lightweight, high - performance goods.

a) Properties
Carbon fiber laminates and carbon fiber sandwiches are used throughout the aircraft. These composites are used to make the fuselage, wings, tail, doors, rudder, elevator and parts of the interior. The use of composites is beneficial in part because it greatly reduces maintenance due to fatigue as compared to aluminium alternatives. The characteristics of carbon fiber that make them ideal for use in these parts are as follows -

- Strength - The strength of carbon fiber ranges from a tensile strength of roughly 3 - 7 GPa and a Young's modulus ranging from 200 - 500 GPa [2]. Strength is one of the key components that are deliberated upon when prospecting materials for certain components, and the high strength of carbon fiber makes it the perfect material to be used in areas with high tension loads such as the fuselage. The components made from this material are durable, they do not break when large amounts of stresses or strains are applied on them and they last a long time, reducing an aircraft's maintenance and repair costs.
- Weight - The density of carbon fiber composite that contains 30% epoxy resin and 70% carbon fiber is about 1.75 - 2.00 g/cm^3 [11]. Comparatively, the density of aluminium is 2.7g/cm^3 [12]. This means that carbon fiber composites weigh almost half of what aluminium would weigh if the same volume of material would be used. This has considerable advantages in aerospace applications. It allows the aircraft to keep their weight down which directly translates to increased fuel efficiency.
- Corrosion resistance - Carbon Carbon bonds are extremely strong and, therefore, very resistant to oxidation and corrosion. In the same way, Carbon fiber composites are made from chemically stable material and this very resistance to corrosion. They are highly inert to agents like acids, alkalis, salts and solvents.
- Thermal Properties - Pitch - based carbon fibers, have an axial thermal conductivity and tensile modulus as high as 900 - 1100 W/m/K and 960 GPa 900 - 1100 W/m/K, respectively [3]. Carbon fiber molecules are closely packed together, which reduces the scope of thermal transfer by convection. Carbon fibers also do not have delocalised electrons which significantly impacts heat transfer by conduction. This makes carbon fiber composites good thermal insulators. The tensile modulus and thermal conductivity, however, may vary upon the type of carbon fiber composite used.

In total, the Dreamliner contains 70, 000 pounds (33 tons) [13] of carbon fiber reinforced plastic of which about 45, 000 (20 tons) pounds is carbon fiber. Boeing was also successful in eliminating 1, 500 aluminiums sheets and 40, 000 - 50, 000 fasteners by manufacturing a single piece carbon composite fuselage instead of building traditional aluminium fuselages.

b) Carbon sandwiching and laminating processes
The process of laminating involves employing a resin to bind layers of fibers together. This hardens into a composite structure after curing. These resins are compatible with reinforcing materials like glass fiber carbon fiber. The laminate properties are mainly dependent on a combination of the following items -

- The adhesive properties of the matrix system bonding the fibers and layers together.
- The fiber type used within each layer.
- The geometry or fiber angle in each layer.
- The ratio between matrix and reinforcement.
- The cure temperature.
- The compression pressure during the cure process.

A sandwich construction is where a low density core is surrounded or "sandwiched' by 2 layers of a laminate material. The formula below where *L* = length of span; *F* = load (in Newtons); *b* = width of test bar (in mm); *t* = thickness of test bar (in mm); and *y* = distance covered by a load *F* during flexure, measured from the initial position, shows that the bending or flexural modulus depends on the t^3 of the material [10]:

$$\text{Bending or flexural modulus} = \frac{L^3F}{4bt^3y}$$

This means adding a low density core, often in the form of honeycomb, foams or woods will increase the thickness, and prevent bending of the material much more than the laminate structures alone. This increase in thickness is a very cost efficient way to increase the stiffness of a component.

c) Disadvantages

Composites possess many qualities that make them an attractive material to be used in a plane; however, there are a few drawbacks that could restrict their further use -

- Costly Production - The high cost of producing carbon fiber is one of the material's main drawbacks. Complex and energy - consuming processes, such as the manufacture of precursor materials, carbonization, and weaving, are used to create carbon fiber composites. The overall cost of carbon fiber is increased by the price of electricity, raw materials, and specialised equipment, making it much more expensive than conventional materials like steel or aluminium. Its high cost may prevent its widespread application and usage as it increases the cost of buying a plane, making it less attractive to potential customers.
- Brittleness - Although carbon fiber is well known for having a remarkable strength to weight ratio, it is also more brittle than metals like steel. Due to its brittleness, it may not be as durable in applications that frequently include impacts, vibrations, or flexing. Carbon fiber may not be the best material in circumstances where structural components must sustain high impact pressures since it is susceptible to cracking or fracturing when subjected to severe stress.
- Environmental Impact - Although it is a less spoken about topic when discussing material choices, global warming and environmental impact are some of the terrible byproducts of the aviation sector which are further amplified by the use of carbon composites. Its production involves energy - intensive processes which emit carbon and rely on non - renewable petrochemical - based precursor materials like PAN. Furthermore, due to the complexity and high expense of recycling carbon fiber as compared to their metal alternatives, disposal and pollution concerns over the material have greatly increased.

2) Metals

One of the key materials used to make the Boeing 787 is titanium. "Titanium has been used extensively throughout the 787" as stated by Being themselves, replacing conventional aluminium alloys in components to reduce overall weight and increase strength. Titanium makes up 14 percent of the total airframe of the 787 and is used to make fasteners, components of the jet engine, and the tail cone.

a) Properties

The use of titanium alloys in the 787 can be justified by the following properties:

- Non - magnetic nature -
  All the fasteners used in the 787 are made of titanium and are non - magnetic, which minimises interference from and to magnetic fields generated in the aircraft. This is due to titanium's low magnetic permeability. Its magnetism remains unchanged regardless of it undergoing hot processing or cold processing, unlike austenitic stainless steel, which retains magnetism after going through the process of cold processing. Titanium is not susceptible to outside interference and won't even trigger metal detectors. [4]

- Low density -
  Titanium has low density compared to alternatives like aluminium. Specifically, the density is about 40% less as compared to its aluminium counterpart. This low density allows large amounts of weight saving when large amounts of titanium is used in an application. (for example an aircraft). The reason for this low density is that titanium atoms are relatively light, but their electron shells are quite wide, which allows fewer atoms to be packed within a certain volume. This, when compared with the formula, Density = Mass/Volume, shows how a smaller mass atom in a greater volume results in the lower density of the material.

- High melting point -
  Titanium has a higher melting point than steel, making it ideal to use for the tail cone. The melting point of titanium is around 1, 700 degree celcius, making it one of the highest melting points of any known metal [5]. In comparison, aluminium has a melting point of around 660 degrees celsius [15]. This high melting point is due to the extremely strong chemical bonds between titanium atoms. Titanium is made up of, predominantly, metallic bonding which leads to the need of high amounts of energy in order to break these bonds.

- High specific strength -
  Titanium is an exceedingly strong material; in fact, it's one of the strongest metals on the periodic table. Commercially pure (99.2% pure) titanium has the tensile strength of around 434 MPa or 63, 000 psi [14]. This high strength comes in combination with it being light, having an extremely high strength - to - weight ratio. Titanium is as strong as steel but 45% lighter, and twice as strong as aluminium.

- High compatibility with composites -
  Titanium alloy has an electrode potential that is highly matched with carbon fiber, which can avoid galvanic corrosion that in turn leads to a lesser chance of failure of titanium alloy components [6]. Titanium is also very compatible with graphite fibers in polymeric composites. aluminium and graphite have a strong galvanic potential, which corrodes the aluminium away in a case where the aluminium comes into contact with the graphite in the

presence of moisture. This can be solved by segregating the composite using methods such as a layer of fiberglass, although it is better if titanium is utilised as a cautious option: specially in areas that are difficult to inspect or repair.

- Small thermal expansion coefficient -

The formula for calculating thermal expansion stress is,

$$\frac{\Delta L}{L} - = \alpha_L \Delta T$$

where ΔL is the change in length of the given material, L is the given length, ΔT is the change in temperature, and α_L is the coefficient of linear thermal expansion of the given material. The coefficient of thermal expansion of steel ($12 \times 10^{-6}{}^{\circ}C^{-1}$) [16] and nickel alloy ($13 \times 10^{-6}{}^{\circ}C^{-1}$) [16] is greater than that of titanium ($8.5 \times 10^{-6}{}^{\circ}C^{-1}$) [16]. Hence, with the same temperature increase, the thermal expansion of steel and nickel alloy is greater than that of titanium. The thermal fatigue performance of titanium alloy is therefore naturally better than its counterparts. Even though titanium's coefficient of thermal expansion is higher than that of graphite, it is far lower than that of its closest competitor in the aerospace industry, aluminium [7].

- Inert properties -

Titanium and its alloys are highly inert and have excellent corrosion resistance properties. They do not react with bases although titanium metal may react with acids and halogens at extremely high temperatures. This is due to the fact that much like aluminium, titanium tends to form a film of passive oxide coating, this formation of oxides on the surface of titanium protects the underlying material from corrosive agents like acids and bases. Titanium has a high oxidation potential due to its electronic configuration and is classified as a transition metal. This anti - corrosive property of titanium makes its use attractive in various industries and applications like jewellery, aerospace, medical, architectural, automotive, and chemical.

b) Application

Titanium alloy fasteners are used throughout the 787 and the aerospace industry for that matter, due to their low density, high ratio and corrosion resistance. Common types of fasteners include bolts, studs, screws, nuts, washers, pins and rivets [7].

The Boeing 787 specifically employed Ti - 5Al - 5V - 5Mo - 3Cr, a next - generation high - strength titanium alloy with higher strength than that of other alloys. Because of its corrosion resistance, the use of titanium in landing gear structures drastically lowers landing gear maintenance and replacement costs. It also has high strength all the while being less dense, which is suitable for its applications in this area.

VST 5553 (Ti - 5Al - 5Mo - 5V - 3Cr) was also proposed as a high - strength beta alloy with enhanced processability and a superior mechanical property combination over its predecessor VT22 and competitor alloy Ti - 10 - 2 - 3, both of which are widely utilised for structural airframe applications. The alloy has been thoroughly evaluated as a candidate alloy for large - size structural die - forgings since the notion was suggested nearly ten years ago. The main advantage of VST 5553, is that it can have higher strength after aging with cooling from the solution treatment temperature. VST 5553 forgings are being used in the Boeing 787. The company behind this ("Корпорация ВСМПО - АВИСМА" or commonly known as VSMPO), has developed two processing techniques for this alloy, and demonstrated the benefits of both for their use in aerospace applications [8].

c) Disadvantages

However, the fact is that there are still problems associated with more large - scale use of titanium. The main problem preventing more widespread use of titanium in any industry for that matter is its high cost. Titanium utilisation has to be significantly justified for each application due to its greater cost than aluminium and steel alloys. These high costs arise due to the following reasons: 1) high amounts of energy is required to separate the metal from its ore, 2) ingot melting consumes a lot of energy and because of its high reactivity, it must be done in an inert atmosphere with a water - cooled copper retort or hearth.3) Machining becomes exceedingly expensive, taking 10 - 100 times longer than the machining of traditional aluminium alloys, increasing both the cost and time taken to produce. However, we are seeing cases where titanium is making its way into more widespread use, with the most relevant example being that Apple has recently announced the IPhone 15 Pro, which features a titanium shell encasing the entire phone.

3) Ceramics

The Boeing 787 Dreamliner uses a total of 2 engines per plane. The most popular engines that power this plane are the Rolls Royce Trent 1000 or the General Electric GEnx engine. Out of all Boeing 787 orders, the GEnx represented the most popular choice accounting for 53% of all orders. The Trent 1000 came in a close second with 33%. The remaining 14% of orders remain undecided. Both these engines make use of ceramics in a variety of ways to improve the engines overall performance and efficiency.

a) Rolls Royce Trent 1000

The Trent 1000 that powers Boeing 787 Dreamliner is 20% more efficient than the Boeing 767 aircraft it replaces. It has the highest bypass ratio of any Trent engine produced with it being 10: 1. The bypass ratio (BPR) of a turbofan engine is the ratio between the mass flow rate of the bypass stream to the mass flow rate entering the core. The Trent 1000 produces a total of 62, 264–81, 028 lbf of thrust.

The Trent 1000 uses ceramic in the combustion system to improve efficiency and lower the emissions that arise due to combustion. The combustion system refers to the area where fuel injectors mix fuel with air and ignite it to produce hot combustion gases that power the engine. The Trent - 1000 uses ceramic tiles to line the interior of the combustion area. The tiles, being excellent insulators of heat, reduce the need of cooling around the combustor. This means less air is diverted from the compressors to cool down the hot components around the engine. With the need of less ‘cooling air’, there is more space available in the combustor itself for the fuel to ignite in. This means that the same amount of fuel can burn in a larger volume, which lowers the peak temperature. It is very well known that NO formation increases with temperature. As the combustion air temperature increases, the NO concentration increases. It also appears that thermal NO formation is *highly* dependent on temperature. In fact, the thermal NOx production rate doubles for every 90 K temperature increase beyond 2100 K [9]. This is why as peak temperatures drop due to a larger volume, a reduction in NOx emissions is observed.

The tiled combustor is intentionally designed in a way that increases durability and reduces maintenance costs. The area exposed to high temperatures is lined with 2 - by - 6 - inch, overlapping, heat resistant ceramic tiles. This lining grows and shrinks with temperature variations, shielding the metal rings of the combustor from the full effects of the heat and reducing cracking stress. Low conductivity ceramics are also used to maintain the integrity of the metals in the blades themselves.

b) Ceramics in the General Electric GEnx engin

The GEnx provides up to 15% better specific fuel efficiency than the engine it replaces. It is made to stay on the wing 20% longer while utilising 30% less parts, which lowers maintenance expenses. GEnx's emissions are also upto 95% below the legal maximums, guaranteeing clean compliance for years to come. It is GE's self proclaimed "quietest and most user - friendly commercial engine to date."

GE is testing the GEnx jet engine with CMC parts that include inner and outer combustor liners, high - pressure turbine stage one shrouds, and stage two nozzles. A vital enabler of next - generation aviation engines, Ceramic Matrix Composites (CMCs) are made of silicon carbide (SiC), ceramic fibers and ceramic resin, manufactured using a sophisticated process and further refined with proprietary coatings. CMCs have one - third the density and weight of metal alloys, but can withstand temperatures up to 2, 400 degrees Fahrenheit, at which almost any metal alloy begins to soften. This heat resistance due the the use of CMCs in the GEnx engines allow the turbines to expel less air from a jet engine's flow path to cool the components in the hot sections of the engine. By keeping more air in the flow path instead of cooling the parts, the engine runs more efficiently at higher thrust. This process is the same as the one described for the Trent 1000 Engine.

Thermal barrier coatings (TBCs) also represent an important component of a jet for general aviation purposes. TBCs are advanced ceramic coatings applied to metallic surfaces such as gas turbine blades and other components to provide thermal insulation from the hot gas flowing through the turbine blades. TBCs work on a two - layer coating system; the first consists of an oxidation and corrosion resistant layer, the so - called adhesive layer, followed by an insulating ceramic top layer, the so - called top layer. This protects the blade from oxidation and corrosion from high temperature gas and enables an increased service life.

"The transition from nickel alloys to rotating ceramics inside the engine is a really big leap, " Jon Blank, Executive, CMC and Coatings Materials for GE Aviation, told GE Reports. The use of CMCs signals a revolutionary change in jet engine design from its predecessors, with GE having invested over $1 billion in the development of CMCs over the past two decades. According to estimates from Boeing, the lighter and newly developed engines from General Electric Co and Rolls - Royce Plc will result in airlines saving about 20 percent on their fuel costs.

5. Limitations and Future Research Areas

The paper analysed the use of materials with a very narrow lense, focusing solely on their use in the B - 787. This limits the discussion of their application to a single aircraft, not providing a complete overview of the materials' potential implementations. However, the valuable insights gained about the materials used, the ways in which they were used, and the properties that made them the best fit, can, as a future scope of research, help in determining new applications for these materials in other areas, both, within and outside the scope of the aviation sector.

6. Conclusion

This study explored the justifications for why certain materials are used in B - 787, and provided an overview of the material composition of the plane. It detailed the properties of carbon fiber composites, titanium, and ceramics for which their subsequent use in the fuselage, tail cone, and engine are ideal. This study highlighted the manufacturing and designing techniques that have been applied to complement the characteristics of the materials used, which results in the development of better functioning components. Finally, the study brought to light some of the disadvantages of these revolutionary material changes away from conventional aircraft design.

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