Advanced aerospace materials: past, present and future

With the Intergovernmental Panel on Climate Change (IPCC) reporting that up to 15 per cent of total greenhouse gas emissions could be caused by aviation by 2050, it is important to review how the past, current and future use of advanced materials and design could help prevent this scenario. Sir David King, Dr Oliver Inderwildi and Chris Carey, **of Oxford University's Smith School of Enterprise and the Environment, discuss improvements being made to existing materials, and review the new materials that we could soon see flying on aircraft.**

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A material advantage?

Since Orville and Wilbur Wright first decided to power their *Flyer* with a purpose built, cast aluminium engine to meet the specific requirements for power to weight ratio, new materials have been necessary to improve and advance aviation. This improvement in material properties has helped us to travel quickly and inexpensively around the world, by improving the performance and operations of modern aircraft.

With aviation expecting to join the EU emissions trading scheme in 2010 there is now an economic driver to reduce emissions in addition to the social and technical pressures to reduce its environmental impact. With aviation there are two main ways to reduce emissions – by reducing the overall fuel burnt and increasing engine efficiency. To reduce the amount of fuel burnt you can reduce both aircraft weight and its parasitic drag (drag due to the non-lift component i.e. the fuselage).

For a large turbojet aircraft a weight reduction of 1,000kg cuts fuel use by about 1.1-1.5 per cent. To improve engine efficiency, the engine has to run at a higher turbine inlet temperature, with a 50°C increase relating to a 1 to 1.33 per cent increase in engine efficiency, allowing less fuel to be burnt for the same thrust output. As CO_2 emissions are in a 1:1 ratio with fuel burn, these reductions relate directly to a decrease in carbon dioxide emissions. Since fuel costs are the largest operating expense for airlines, technologies which reduce fuel use have a favourable effect on the bottom line.

Losing weight

During the pioneering period of aviation (1903-1930) the minimum weight possible was of utmost importance due to the poor performance of propulsion systems *(the Wright Flyer had about 8hp)*. This led to the use of wood covered with varnished fabric, which had limited strength and loading capacities. Aluminium alloys became the baseline for aircraft structures after corrosion issues were overcome in 1927. Initial advancement concentrated on the refining of aluminium alloys and the development of new materials, such as composite systems which consists of two or more phases on the macroscopic scale. The mechanical performance and properties of the combined system are superior to those of the constituent materials. These materials were first applied on civil aircraft with the Boeing 707 in 1957, with approximately 20m^2 of polymeric composites in mainly tertiary roles, such as cabin structures.

Increasing use of composite materials was limited, with only a three per cent increase observed from the A300 to A310. However much larger structural parts, such as the vertical stabiliser (8.3m by 7.8 m at the base), were now being fabricated entirely from carbon composites. This gives a weight saving of more than 400kg over an aluminium alloy structure, resulting in approximately 0.5 per cent reduction in fuel burn per hour. Aluminium/lithium alloys, first proposed in the 1950s, were also introduced to reduce the density of components *(one per cent of lithium reduces the density of aluminium alloys by three per cent)*. Production issues initially restricted their use but they are now utilised in a variety of structural applications.

The Smith School of Enterprise and the Environment is a unique interdisciplinary hub where academics from around the world work with the private sector and government to pioneer solutions to the major environmental challenges of the 21st century. Its work on aviation is part of the "Future of Mobility" project being undertaken by the school to give a comprehensive perspective of the future of transportation and mobility up to the year 2050 *(http://www.future-of-mobility.org)*.

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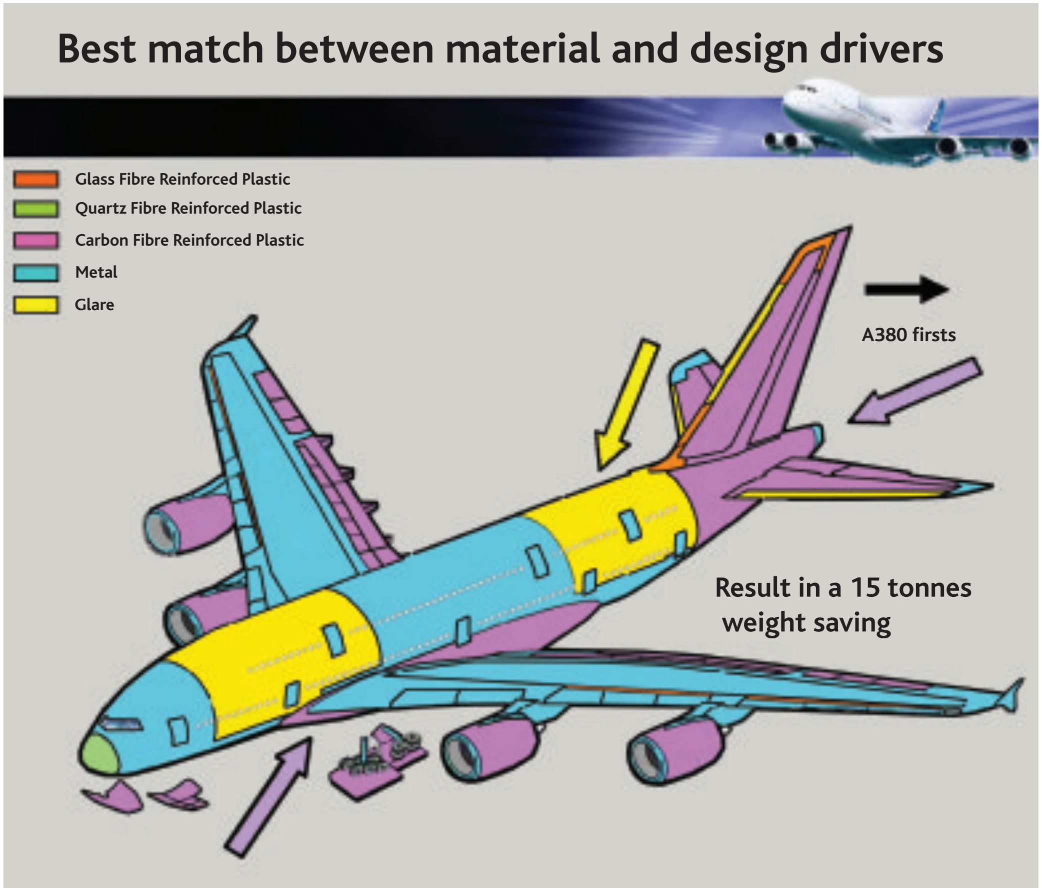


Figure 1. Airbus A380 material composition *Source: Airbus*

The latest development in the field of aerospace materials arises from the use of application-specific materials. The A380, which at 61 per cent has the lowest percentage of aluminium by weight of all flying Airbus models, has 20 different alloys and tempers compared to the six utilised on the A320/330 aircraft. The A380 also saw the application of a new material, GLARE, for fuselage skins which shows improved fatigue and impact properties at a lower density than incumbent materials.

The composition of the A380 *(Figure 1)* illustrates the variation in materials used in modern airliners, in order to ensure that the best material is used for the application, allowing for weight reduction. Significant increases in the amount of composite systems have occurred, with the 787 and proposed A350 XWB each having a primarily composite structure (over 50 per cent), with carbon fibre reinforced polymer being used. These material developments have led to the overall reduction of aircraft weight, which is reflected in the reduction in fuel consumption per revenue passenger mile *(Figure 2)*. Whilst advanced materials are not solely responsible for this reduction, they have contributed significantly to this overall improvement in fuel burn.

Getting hotter

The introduction of turbines required a development of a new family of materials to cope with the high temperatures and stresses present in the turbine, particularly the so-called 'hot' or combustor/turbine stages where temperatures can reach over 1500°C in modern engines. Initial engines, such as Sir Frank Whittles W1, used a variety of stainless steels but these were soon replaced with the first super alloy systems, nickel-chromium alloys such as Nimonic and Inconel. The development of high strength materials, resistant to the corrosive environment in the jet turbine, called for improvements in production as well as new materials and alloys.

Development of vacuum induction melting (VIM) technology allowed a much greater control over the composition of superalloys, which increased the component reliability. Commercial production of titanium was also an important development: Not only did it find many applications in turbine components, such as the compressor stage, it also allowed for the development of ducted bypass fans. These work by using excess energy produced during combustion to bypass an amount of air past the core of the engine giving an overall increase in thrust and improvement in specific fuel cost (SFC) at the cost of top speed and overall engine weight.

The mid 1950s also saw a radical change in the technology of turbine blade production – the use of investment casting. This process allowed the casting of fine channels within the blade, which, with laser drilling, allowed air-cooling of the turbine blade, increasing blade-operating temperature.

The casting of the blade led to the next leap in turbine technology, the removal of grain boundaries. Standard cast blades contain a large number of grain boundaries where a number of undesirable events occur. The introduction of directionally solidified (DS) blade (produced by slowly withdrawing the blade from the furnace in one direction) gives no grain boundaries perpendicular to the major stress axis. This improves reliability and maximum temperature by up to 25°C and therefore engine efficiency.

This was further developed to single crystal (SX) casting *(first used in Pratt & Whitney's JT9D-7R4 in 1982)* where the use of directional solidification and crystal removal (via a helix) led to the production of turbine blades containing no grain boundaries, again increasing maximum operating temperature by 25°C. Thermal barrier coatings (TBC) is another technique used to reduce the relative temperature of engine parts by applying ceramic coatings to hot section parts. The mid 1980s saw the application of polymeric composite materials in engines, in many non-core applications such as fan blades and casings. These have the benefit of reducing the overall mass of an engine and therefore the aircraft, improving efficiency.

The majority of these advancements have led to a vast improvement in engine efficiency by increasing the turbine inlet temperature. *Figure 3 overleaf* shows the turbine inlet temperature of a selection of Rolls-Royce turbines and corresponding material developments, where a significant proportion of the temperature increase can be attributed to advanced materials.

What does the future hold?

The improvement and development of materials for aviation applications is developing on three main fronts: the development of new materials; the improvement of current material properties by refining composition and novel processing methods for new applications; and the application of current materials in new and novel structures.

New materials

New materials can be defined as materials which have yet to be applied in an 'as-designed' application in aviation. Some of these materials, particularly metal matrix composites (MMC) and ceramic matrix composites (CMC) have seen some in-flight testing and are approaching military use but have yet to gain wide ranging acceptance by OEMs for various reasons. The following discussion briefly introduces a number of materials that have a potential for applications in next generation aircraft.

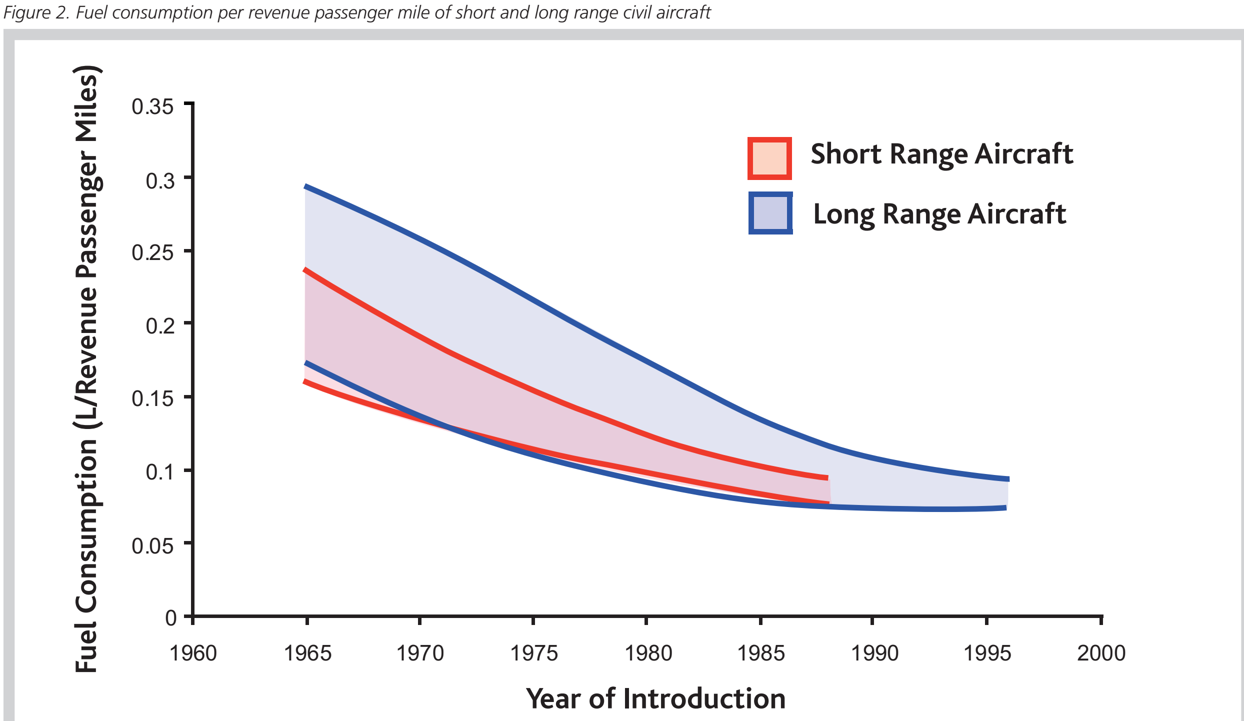
Ceramic matrix composites (CMCs): While consisting of purely ceramic constituents, CMCs utilise a ceramic matrix with reinforcing ceramic fibres and are accepted as a composite system. This creates a material with the excellent thermal properties and with improved mechanical properties, overcoming the limitations of monolithic ceramic (i.e. toughness) and displaying other benefits. The possible applications of CMCs in aviation are generally in the hot section of the aero engines and include turbine disks, combustor linear, turbine aerofoils, transition duct convergent flags and acoustic liners. The use of CMCs would allow an increase in turbine inlet temperature from the current 1200°C to 1500°C, which would lead to a 6-8 per cent increase in fuel efficiency.

Metal matrix composites (MMCs): These consist of an aluminium or titanium matrix with oxide, nitride or carbide reinforcement and have many advantages over monolithic materials. But they are not as tough, are more expensive and are difficult to machine. A major issue for MMCs is their production and manufacturing cost and current research is focused in this area. Possible applications include highly loaded surfaces such as helicopter rotor blades, turbine fan blades and floor supports.

Nanocomposites: As with macro-scale composites, a number of matrix/-reinforcement combinations are possible with CMC, MMC and PMC all under investigation. Nano-composites utilise the huge surface area per mass and high length-to-width ratios of nanoscale objects to improve material properties. Current development issues include producing the necessary quantity of nanoparticles at a commercially attractive price and various production issues, such as filler dispersion.

Shape memory metals (SSM): When SSMs are heated they revert to a pre-deformation shape. They usually consist of copper/nickel based alloys, though other materials can be used. The simplicity of SSM actuators is that they can be used for hybrid applications such as variable jet intake and morphing

Figure 2. Fuel consumption per revenue passenger mile of short and long range civil aircraft



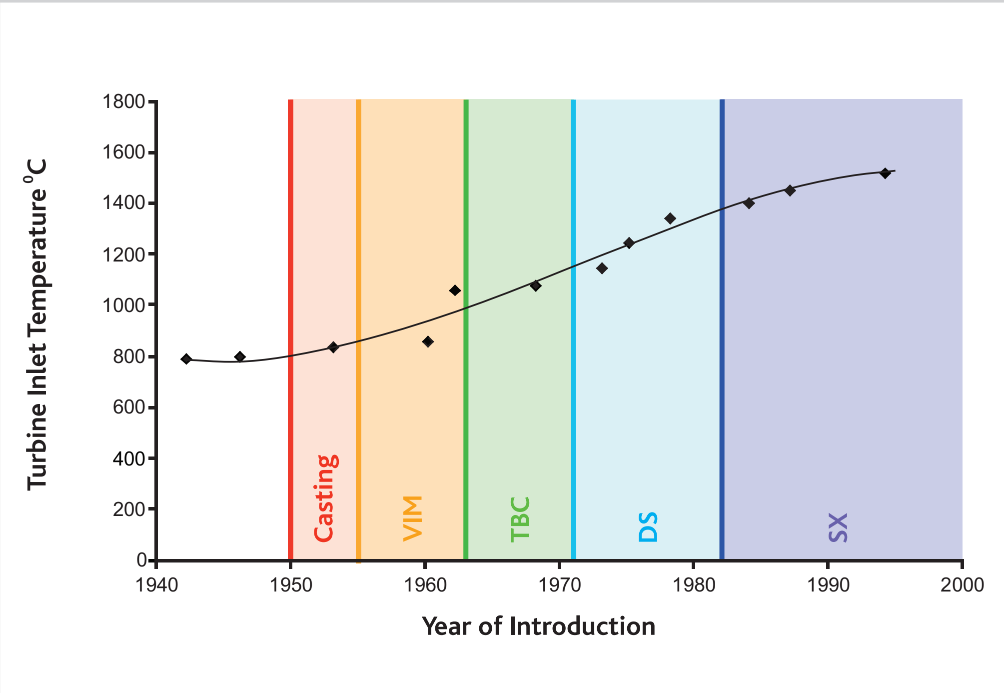
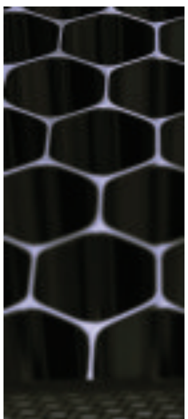


Figure 3. Turbine inlet temperature for a selection of Rolls-Royce turbines with major material developments indicated.



variable geometry chevrons *(Figure 4)* where traditional systems are too large and complex when compared with the savings possible.

Material Improvements

A continuing trend in material development is the improvement in processing and production of incumbent materials to either improve physical properties or to allow their application in new areas and roles.

Aluminium alloys: As the most common of aviation materials, it is unsurprising that a large number of developments are in the pipeline for aluminium alloys. These include further refinement of current alloys to improve specific strength and corrosion resistance, as well as developing alloys for specific manufacturing processes such as friction stir welding and laser welding. These advancements will continue the trend for much larger numbers of alloys in aircraft (the A380F has three planed alloys for wing panels) leading to lighter structures with location specific properties.

Super-alloys: Current research in this area is focused on fourth generation super-alloys containing ruthenium to improve microstructural stability and increase high temperature creep strength.

Titanium: The main area of research with titanium is in improvements to the production process to lower costs. A number of development projects are being carried out with the potential to reduce the cost of final titanium products by very significant amounts, in the region of 30 per cent or more.

Steels: Advances in steel alloys have concentrated on improvements in ultra-high strength and toughness. The AerMet family of alloys are a significant development in this area, with similar specific strengths (UTS/density) to common Ti alloys, but with a vastly improved ductility and much higher yield strength. Applications are in safety critical structures, such as transmission gears and parts which require the structural efficiency that steel can offer.

Ceramics: Ceramics exhibit superior thermal properties and major progress has been achieved in improving the mechanical properties so ceramics can now compete with metals in applications for which they where previously unsuitable. Development of ceramic materials has led to the use of these highly thermal stable materials in a variety of applications, such as main shaft bearings, engine seals and thermal barrier coating on turbine blades. The use of ceramics in these applications allows engines to work at a higher temperature, increasing their thermodynamic efficiency.

New structures

A number of new structures have been investigated for a variety of materials and are at varying stages of development. Some, such as fibre metal laminates, have already been applied to aviation, whilst others are still at the laboratory stage.

Lattice: One area of particular interest is lattice block, which works on either pyramidal or tetragonal truss arrangements and is produced using investment casting. These structures weigh approximately 15 per cent of a solid plate of the same external dimensions, whilst still exhibiting good strength and damage architecture.

Foams: Another major development in the use of aluminium alloys is the production of foam or cellular systems. These are produced by a number of methods such as direct foaming using gas and investment casting, but all methods produce a material containing a number of voids. The size, density and structure of the void produced depends on a number of variables, and particularly the production method. The Smith School of Enterprise and the Environment believes that foam structures will replace honeycomb structures and could lead to higher performance at reduced cost. The use of low density super-alloy foam in noise abatement applications, replacing acoustic liners, would allow for an increase in engine burn efficiency, again reducing fuel burn and emissions.

Laminate structures: A number of laminate systems are under investigation with a variety of constituents. The laminate structure prevents catastrophic failure and exhibits improved impact characteristics. One such material is fibre metal laminate, which consists of layers of composite and aluminium and provides high impact strength and directional strength at a low density. A number of different composites have been investigated, such as aramid, glass fibre and carbon fires with a variety of metal layers such as aluminium, titanium and steel. New approaches are investigating asymmetrical lay-up approaches, such as CENTRAL, tailoring the panel properties to the application requirements.

What now?

All these developments have created one of two things, either a lighter overall weight for parts of the same properties, in the case of structural materials, or a higher thermodynamic efficiency of the engine with higher temperatures within the engine. If we consider the latest aircraft to be launched, the A380, a single kilogram of weight saved equates to a 50ml reduction in fuel burn per hour. This might not sound much, but assuming a 75,000 hour life of the aircraft, it equates to 3,750 litres of fuel. The hypothetical replacement of steel within the A380 (approximately 11,500kg) with titanium alloy would reduce the overall weight by 5,750kg, saving 288 litres of fuel per hour (22 million litres over the life time) equating to a two per cent drop in fuel burn and emissions.

With turbine material improvements, an increase in turbine inlet temperature from the current 1,200°C to 1,500°C would lead to a 6-8 per cent increase in fuel burn efficiency, equating to a 588 million litre reduction in fuel use over the life of the aircraft. This is *the equivalent of approximately 300 A380s filled with fuel.* And with Jet-A1 prices exceeding $1.10/L last year, these developments offer significant economic, as well as environmental, benefits in the operation of airliners – even when the economic and environmental cost of producing advanced materials is taken into account, as discussed in the last issue of *Aviation and the Environment.*

Figure 4. Variable Geometry Chevrons

"The use of low density super-alloy foam in noise abatement applications, replacing acoustic liners, would allow for an increase in engine burn efficiency, again reducing fuel burn and emissions."