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Gas turbine technology

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Abstract

Gas turbine engines power most commercial flights operating today. Yet many people are ignorant of the cutting-edge technologies used in the creation and operation of these engines. This article explains some of the principles involved with emphasis on the selection of materials for fan blades and turbine blades, which have to operate reliably in exceedingly hostile environments.

(Some figures in this article are in colour only in the electronic version)

Simple theory, outstanding performance

The number of commercial flights has escalated rapidly since the middle of the last century: currently it is believed that as many as three million people may be in the air at any given moment. Clearly flight is a technology that we have all embraced and are happy to exploit. The ease and efficiency of transport over large distances, combined with the unrivalled levels of safety within the industry when compared with any other mode of transport, give air travel a distinct advantage. On the safety front, recent US figures actually show that you are twice as likely to die as a result of an incident involving an animal-drawn carriage as opposed to an aircraft. These facts—and perhaps the exhilaration experienced during flight—mean that it has become common practice for us to climb aboard 100 tonnes of complex machinery and intricate electronics in an understandable effort to experience faraway destinations.

However, once seated in a cosy window or aisle seat, already wondering what delights will lie below the foil wrappings of the in-flight meal, it surprises me how little thought people generally give to the technology that they are relying on. There seems to be little attention given to the 30 000 components hanging together under the wing that propel us upwards and onwards, and to the fact that a decent proportion of these components are operating above their melting point (I based this on personal experience of passengers I have sat next to and chatted with, and perhaps left slightly scared and bewildered).

When boarding the aeroplane the only part of the engine clearly visible is the fan set. I am sure most people climb aboard without a glance in the engine's direction, yet the fan blades are not components that should be disregarded in blasé fashion. At full speed the 3 m diameter array rotates at 3300 rpm, and if a blade were released it would have enough kinetic energy to launch a small car over a seven-storey building. I have flown eight times within the last year and on each and every occasion I marvel at the performance of the engines and airframes. It is amazing to me that the sensation of acceleration we experience, as the 100 tonnes of aeroplane reaches almost 300 km h^{-1} in under 20 seconds, is generated by only two engines that are simply throwing hot air backwards at high speed.

During these moments at take-off I usually experience a strange mental confrontation: like many people there is always a small sense of unease and a heightened awareness of strange noises and cabin movement. However, it is about then that I remind myself of the sound

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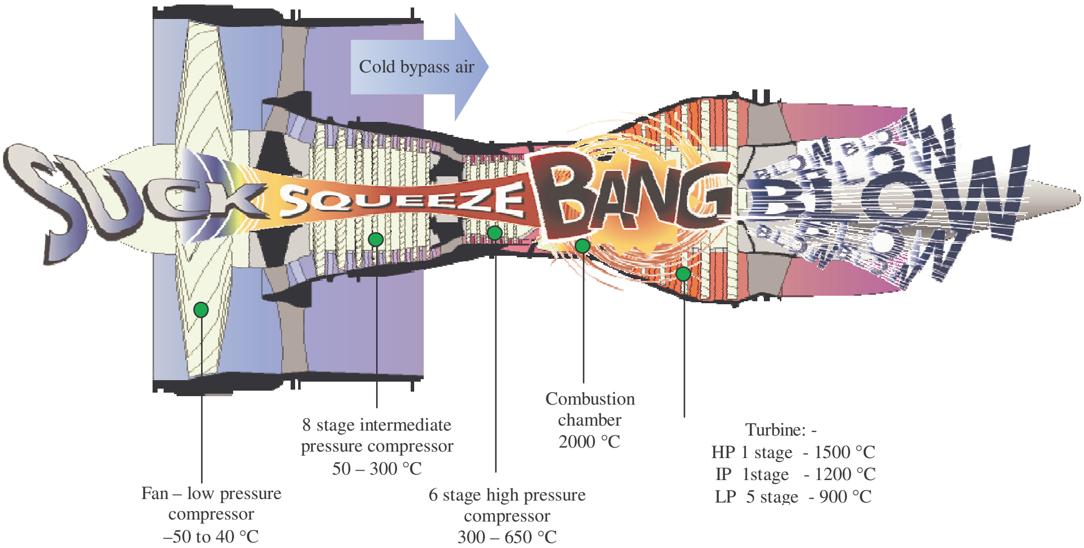

Figure 1. The principle of gas turbine operation: suck, squeeze, bang, blow.

engineering and unshakeable physical principles that support this undertaking. Having worked within Rolls-Royce, and fortunately spent time within various departments (stress, thermals, materials and 'lifing'[1], design etc), I have gained an appreciation of the engineering effort, in terms of performance, safety and reliability, that supports the nine tonnes of rotating machinery below the wing, and am as a result always confident and happy to be onboard.

As suggested above, the fact that we now take flight for granted has only come to pass due to the continued drive of aero-engine manufacturers to improve engine performance. Over time there have been very clear trends in improved engine efficiency, power and safety, all achieved at a relatively low cost to you the traveller. Within the following paragraphs I hope to briefly describe to you the workings of this simple machine, and discuss some of the technology and ingenuity that successfully drive it millions of miles a year.

Suck, squeeze, bang, blow

The principle of gas turbine operation is relatively simple (figure 1):

- **Suck:** air is sucked in through the fan at the front of the engine
- **Squeeze:** the air is then squeezed to many times atmospheric pressure
- **Bang:** within the combustion chamber fuel is mixed with the air and is ignited
- **Blow:** the hot air expands and is blown out of the rear of the engine.

Sir Frank Whittle designed and built the first jet engine in 1941. Because of their major advantages in terms of power, efficiency at high speed and simplicity, jet engines rapidly became the preferred option for air travel. Rolls-Royce has had many firsts within the commercial gas turbine industry since Whittle's innovation, a trend that we maintain to this day. For example, Rolls-Royce produced the Dart, the first gas turbine in civil flight, and the Conway, the first Bypass engine. Our current products include the Trent series of gas turbines—engines that incorporate many cutting-edge technologies and that have become synonymous with reliability and efficiency. The RB211 family of engines (the RB211-524G is used to power the Boeing 747, and is the precursor to the Trent family) has accumulated over 75 million hours of flying, a figure that equates to more than 46 billion km, or flying to the sun and back over 150 times. The Trent has helped us to secure a large proportion of new engine sales, and as such Rolls-Royce is now recognized as the second biggest aero-engine manufacturer, and currently lists 38 of the top 50 airlines amongst its customers.

[1] The term 'lifing' refers to the analysis of a material's fatigue properties, and the determination of a cyclic 'life' (cycles to failure) when it is subjected to a given alternating stress level.

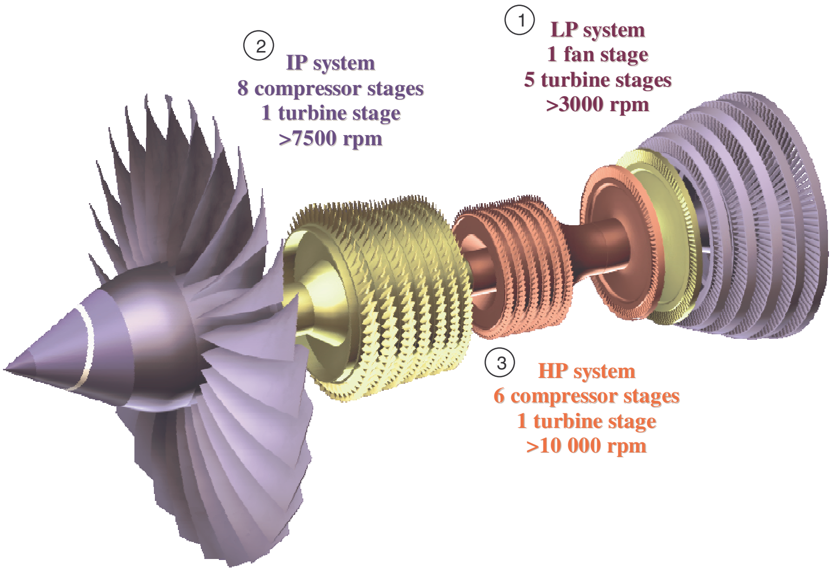

Figure 2. Rolls-Royce three-shaft engine configuration.

The Trent engine is a three-shaft engine (figures 2 and 3), a system that allows the designer to more efficiently match the thermodynamic and aerodynamic requirements throughout the engine. This is a significant step from the two-shaft engines originally employed by Rolls-Royce and which are still designed by our competitors. From figure 2 one can see that there are three systems:

- The low pressure system (one compressor stage, the fan, driven by five turbine stages).
- The intermediate pressure system (eight compressor stages driven by one turbine stage).
- The high-pressure system (six compressor stages driven by a single turbine stage).

Within the gas turbines generally seen on Airbuses and Boeings, the expanding hot gases provide only a small fraction of the engine thrust. In figures 2 and 3 one can see that the gas is passed through various stages of blading. Firstly, air that is pulled in by the fan through the core of the engine is compressed by the intermediate and high pressure compressor blades. After fuel injection and ignition the expanding gas exits the engine through various sets of turbine blades. These blades are turned (like the sails on a windmill) and, in turn, they rotate the fan and compressor blades at the front via shafts that pass through the centre of the engine. As such, it is the turbine blades that

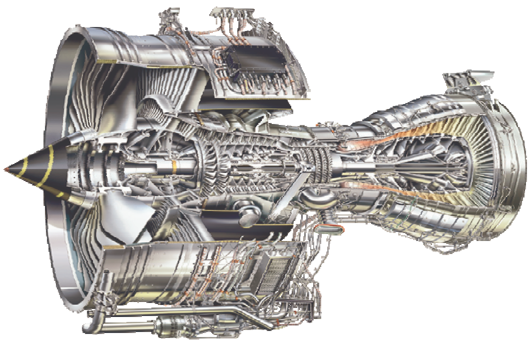

Figure 3. The Trent 500 engine, four of which are used on the Airbus A340.

turn the fan, which pulls the air through to develop the thrust. I mentioned the 'core' of the engine previously to emphasize the distinction between this region and the 'bypass' air (figure 1). In reality only about a quarter of the air pulled through the fan enters the core of the engine: the remaining cold air is thrown backwards, around the outside of the core to develop the majority of the engine's thrust (see figure 1).

The choice between a 'bypass' and a 'turbojet' (in which 100% of thrust is developed through the core of the engine) configuration is mainly a function of desired engine efficiency and manoeuvrability. High 'bypass' ratio engines are desired for commercial travel to maximize efficiency (see box): high jet velocity and

High by-pass or turbojet?

To understand this statement we may consider the flux of momentum entering and leaving the engine, and a general equation that defines its efficiency.

Flux of momentum entering the engine

$= \dot{m}_{\text{air}} V$

Flux of momentum leaving the engine

$= (\dot{m}_{\text{air}} + \dot{m}_{\text{f}}) V_{\text{jet}}$

where m_{air} is the mass flow of air, V is the velocity of air entering the engine, m_{f} is the mass flow of fuel and V_{j} is the velocity of air leaving the engine.

Thus the net thrust, F_{N}, that is available in flight is given by the difference between the two momentum fluxes, that is

$$F_{\text{N}} = (\dot{m}_{\text{air}} + \dot{m}_{\text{f}}) V_{\text{jet}} - \dot{m}_{\text{air}} V.$$

This equation tells us that for a high net thrust there must be either a high jet velocity, V_{j}, or a large mass flow, m_{air}.

Propulsive efficiency compares the rate of work done on the aircraft to the rate of kinetic energy increase of the flow through the engine. It may be approximated for the typical case when the mass flow (of fuel) is much smaller than that of the air, by [1]

$$\eta_{\text{p}} = \frac{2V}{V + V_{\text{j}}}.$$

From this second equation we can see that propulsive efficiency (and therefore net engine efficiency) is maximized if the jet velocity, V_{j}, is minimized. Therefore if we wish to maximize efficiency (i.e. low V_{j}) but maintain thrust (F_{N}) we must maximize the **mass flow** of air through the engine. Therefore we want high bypass engines for commercial and freight air travel.

manoeuvrability are not required because a large proportion of time is spent at a single altitude and speed. Military applications, however, will use turbojet type engines, such as the Olympus (Concorde) and the Pegasus (Harrier), because they desire many rapid changes in power, attitude and speed and care a little less about propulsive efficiency. However, as for many things in life, the decision on engine design is not necessarily as cut and dried as suggested above, but is a trade-off between many interacting parameters.

Although large bypass engines are efficient there are some tangible negatives. They are heavy bits of kit that provide considerable drag, and cost an appreciable amount of money to purchase and maintain. Furthermore, not all military aircraft scream around the skies at maximum power all day long: many military jets that spend significant amounts of time cruising around, needing a little extra only for the occasional chase, are usually equipped with low bypass engines. Fuel consumption is important to the military, not for cost, but for reasons of range and weapon load capability.

As a metallurgist I am concerned with optimizing materials to meet the various stringent requirements of the engine. Clearly the conditions vary dramatically throughout the engine, but there are at least a couple of underlying driving forces when choosing the material to do the job: weight and cost. It would be ideal to construct everything from a cheap material such as steel. However, with a density of 7.6 g cm^{-3}, employing steel, as a compressor disc material for example, would cost appreciably more in

Figure 4. A Trent 800 fan set comprising 25 blades. The fan has a diameter of approximately 3 m and the mass flow of air through the engine is approximately 72 tonnes/min, or 1.2 tonnes/second.

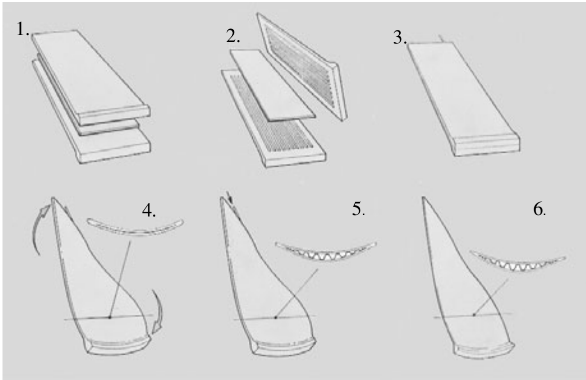

Figure 5. Trent fan blade production. Left: a six-step breakdown of wide-chord fan blade production for the Trent engines using the DB-SPF technique. The fan blades for the Trent engines are manufactured from three sheets of titanium (1). The two outer sheets will form the aerodynamic surfaces of the blade and the thicker root section. The middle, thinner, sheet will form the 'Warren–Girder' structure internally, providing the blade stiffness and impact resistance required. Once the pack of three plates has been formed a masking pattern is painted onto the internal faces of the outer plates (2). The plates are then re-stacked, with a small tube attached to the end, welded together around the edge, evacuated and heated above 950 °C (3). At this temperature diffusion occurs across the metallic surfaces in intimate contact within the pack and at its edges. Thus, after heat treatment the three plates are now a single unit. The pack is then shaped into its approximate aerofoil morphology (4), before it is inflated (5). To enable inflation the component is re-heated above 900 °C and argon gas is injected, at pressure, through the tube. After inflation the aerofoil cross section seen in images 5 and 6 is created. The girder configuration is developed because diffusion bonding is unable to occur across the 'masked' regions, and these unbonded areas are expanded during argon injection.

Right: stage 4 being completed. The operators are removing the shaped, diffusion-bonded pack from a furnace at ≈950 °C.

terms of fuel consumption than the current option and would impart significantly higher stresses on itself and the surrounding structures. Conversely magnesium- or aluminium-based alloys might be an ideal option with regard to weight, but given their relatively low tensile properties and a propensity to become liquid around 660 °C (a temperature encountered within the high pressure compressor section), they are not necessarily the metals of choice. The following sections detail two components that are key to efficient engine operation, and demonstrate the efforts made to maximize performance through material, chemistry, design and manufacture.

The fan blade

The fan blade sees temperatures from ambient to −50 °C (at cruise altitude), rotation at 3300 rpm with a tip speed of 1730 $\mathrm{km\,h^{-1}}$, and a centripetal force through its root equivalent to 900 kN (a figure usually quoted by the airline pamphlets as equivalent to the weight of 13 African bull elephants). Furthermore, this component must last for 80 million km (10 000 flights), displaying sufficient flexibility and damage tolerance to continue uninhibited operation within wind, rain, snow and the occasional bird impact. All of these parameters are met by a single piece of metal about 10 kg in mass, approximately 1.0 m high by 0.4 m wide (figure 4). In this instance a titanium alloy is used—titanium 6/4 (titanium + 6% aluminium + 4% vanadium)—a material that meets the mechanical requirements stipulated above, with the minimum mass possible (density about 4.5 $\mathrm{g\,cm^{-3}}$).

In addition, this material has the special properties necessary to incorporate the required complexity during the manufacture of the component. In an effort to achieve the blade stiffness required at minimum mass Rolls-Royce has developed a unique hollow fan blade (figures 4 and 5). This structure proffers a significant weight saving (50%) over the solid blade alternatives, reducing the engine's specific fuel consumption, thereby saving the airlines money. The internal structure of this blade can only be manufactured, with sufficient integrity, using the diffusion bonding, super-plastic forming

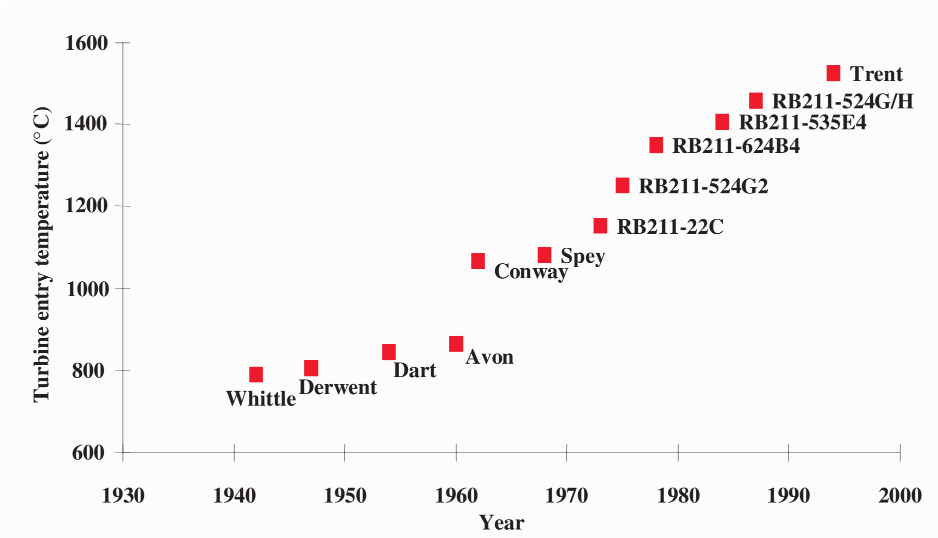

Figure 6. Development of turbine entry temperature (TET) with time.

(DB-SPF) technique (figure 5). Production of these components is an exacting and onerous task, one that Rolls-Royce has met by constructing a purpose-built facility for the job, a facility that maintains a cleanliness regime beyond that of the electronics/microchip industry.

Cleanliness during production is key because of the ‘stress raising’ effects that impurities and foreign particulates would have within the internal structure of the blade. Such point defects could initiate a fatigue crack that may propagate to failure under service conditions. When we consider the kinetic energy of a fan blade released at maximum revolution (remember the scenario of a small car launched very high...) it can be seen that the expense of such a clean facility is a necessary one. On this front, however, we can be reassured that extensive testing and modelling has been completed to demonstrate that, if such an event were to occur, the engine shrouds and casings would not be compromised and no high energy debris would exit the engine. Indeed the aviation authorities demand that a complete engine ‘blade off’ test is completed for all new engine projects—necessary, but a multi-million pound engine is fit for little else afterwards. To complete this test a small explosive charge is attached to the root of one fan blade within the set. Then, once the engine has been powered up to full speed, the charge is detonated and the blade released. High speed cameras film the event from a variety of positions and help to demonstrate that, apart from a large flame and some low energy material, nothing is released from the engine that might compromise an airframe’s integrity.

Turbine blades

A second key area of expertise for Rolls-Royce is within its turbine blade manufacturing facility. As stated earlier, there has been a clear trend in improved engine performance with time. In an effort to improve efficiencies, weight must be shed from the construction and operating temperature must be increased.

From the graph in figure 6 it can be seen that within 60 years the temperature of the gas

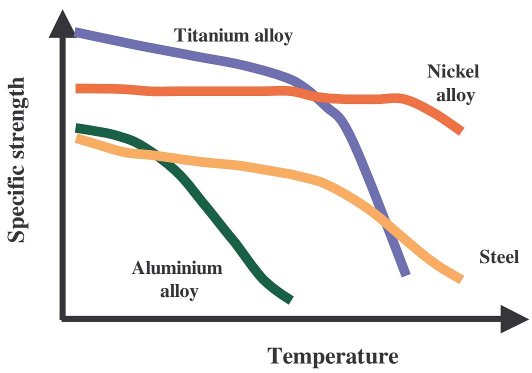

Figure 7. Specific strength versus temperature for a variety of common aero-engine materials.

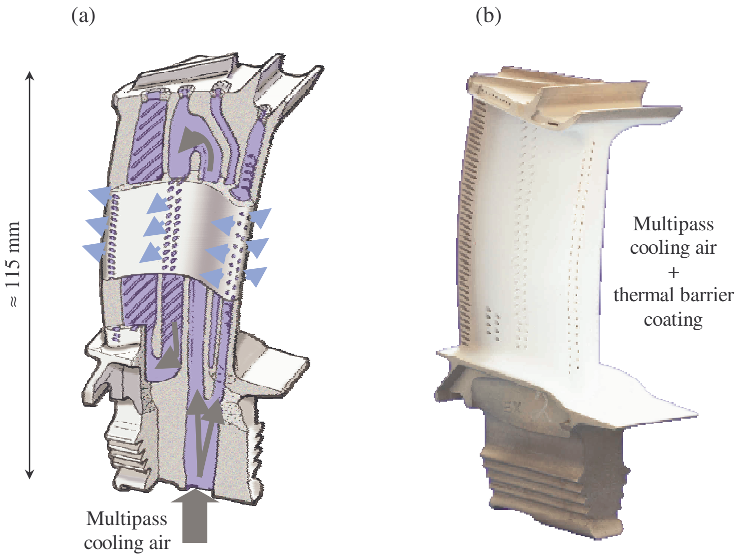

Figure 8. Gas temperature: (a) 1425 °C, (b) >1550 °C.

leaving the combustion chamber and passing over the high pressure turbine blades, i.e. the turbine entry temperature (TET), has risen by nearly 800 °C. To accommodate this advance significant changes have been made to the component's design, material and structure. Because of the high temperatures involved turbine blades are manufactured from nickel-based alloys. Figure 7 highlights how well nickel alloys maintain their mechanical properties with increasing temperature when compared with the alternatives. This curve takes account of the material's density, and indicates that even though nickel is practically twice as dense as titanium (about 8.4 g cm^{-3}—contrary to the requirements to reduce engine weight) it is the only material that retains sufficient integrity at high temperature. Indeed standard titanium alloys must be avoided towards the hot end of the aero-engine, not only because of their diminishing properties, but also because at temperatures in excess of 600 °C, and under friction, they can rapidly ignite and burn aggressively, covering the rearward stages in molten metal.

The turbine blades see the most aggressive conditions within the engine, but as with all components, they must readily deliver efficient performance, whilst incurring minimal overhaul and repair costs. The blades that Rolls-Royce currently manufactures can withstand a temperature of about 1550 °C, rotate at 10 000 rpm, remove 560 kW each from the gas stream (slightly better than your average Ford Focus) and last up to 5 000 000 flying miles.

Figure 8 demonstrates a couple of the technological advances that Rolls-Royce has employed in its successful turbine blade design and material definition, thereby allowing it to employ a TET above the melting point of the alloy (TET > 1500 °C, alloy melting point about 1350 °C). The key advances have been the manufacture of single-crystal blades, with internal cooling channels, and, latterly, thermal barrier coatings. Cooler air (air at 700 °C) is bled off from the compressor and passed through the turbine blades. Small laser-drilled holes in the surface of the blade allow the cooler air to flow over the working surfaces, protecting them from the hot gas stream. In a later development ceramic materials have been deposited onto the blade surfaces, further protecting them from the aggressive environment and allowing yet higher TETs to be achieved.

At high temperatures the major component failure mechanism is creep, i.e. over time under high temperatures and loads the blade will deform, lengthen and rupture. The creep mechanisms and elongation to failure are caused by atom migration and diffusion. A key path for this atom movement is along grain boundaries (these are areas of lattice discontinuities and therefore a relative increase in space). Thus, by removing this easy diffusion path

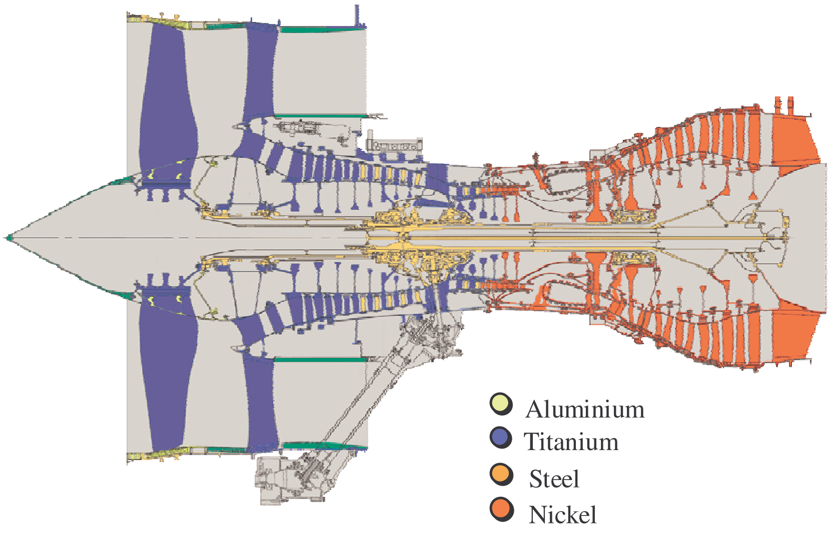

Figure 9. Engine materials.

for the atoms by developing single-crystal blades, we increase the creep strength of the material. This is a process requiring exact casting conditions and ingenious mould designs. The mould design must ensure that only a single grain, in a preferred crystallographic orientation, is allowed to grow.

Overview

One can see that throughout this conceptually simple machine the engine manufacturer has worked strenuously to maximize the potential of each component. The result is a machine combining a fantastic array of materials that generates the maximum performance at minimum weight with the current technology. Figure 9 is a general arrangement of a Trent engine that depicts the range of materials employed.

Materials technology continues to drive further advancements in aero-engine performance. There are additional innovations that cannot be included in current designs because of the prohibitive cost, both internally and to the airlines. Major improvements will probably result from material development, towards lighter and stronger materials. Innovations such as metal matrix composites and engineering ceramics are a real source of interest and continued research and development. In addition, research into burn-resistant titanium alloys, allowing them to be used further into the hot end of the engine, and nickel alloy compositions will further refine the engines' performance. During your next flight it is worth spending a moment to appreciate the cutting-edge technology that is sending you skywards, and to feel safe and contented that it is a technology backed by excellent know-how and millions of miles of experience.

Acknowledgments

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