Pertanika J. Sci. & Technol. 9(2): 127-138 (2001)

ISSN: 0128-7680

Developments in Aeroengines

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ABSTRACT

This paper reviews developments in aeroengines over the past 70 years from Whittle's first turbojet engine to the current turbofans. Modern turbofan engines are now capable of producing around 440 kN (100,000 lb) of thrust, compared with 7kN (1600 lb) for the first turbojet engines, while over this period the specific fuel consumption has halved and the thrust-to-weight ratio has increased significantly. The performance and reliability of these engines have revolutionised both civil and military aeronautics throughout the world. Some of the technical advances that have made these developments possible are described and possible future trends are discussed.

Keywords: Aeroengines, turbofans, turbojet engines, thrust-to-weight ratio

INTRODUCTION

January 16, 2000, marks the 70th anniversary of Whittle's patent for "Improvements in aircraft propulsion". This invention lead to the start of the jet age in which the gas turbine replaced the piston engine in all but the smallest aircraft. The high thrust-to-weight ratio, efficiency and reliability of modern engines has resulted in a spectacular increase in the number of people who now take flying for granted, and improvements in performance have led to a decrease in the real cost of air transport.

Frank Whittle was a cadet in the Royal Air Force when he filed his patent for the jet engine in 1930. From 1934 to 1936, he took the Mechanical Sciences Tripos at Cambridge University. During this period, he allowed the patent to lapse because the Air Ministry would not pay the £5 renewal fee. In 1935, Hans von Ohain, a research student in Germany and unaware of Whittle's patent, took out his own patent on the jet engine. The first bench-test of a liquid-fuelled jet engine was in England in 1937, but the first flight-test of a jet engine took place in Germany in August, 1939, weeks before the outbreak of the Second World War (1939 to 1945); von Ohain's (petrol-fuelled) engine powered a Heinkel He 178 fighter. Twenty months later, Whittle's engine took to the air in England in a Gloster E28/29 experimental aircraft.

Both these pioneers had to battle government bureaucracy in their respective countries as well as having to surmount numerous technical problems in developing the early engines (see Whittle 1979 and von Ohain 1979). As part of the war effort, drawings of the Whittle engine were given by the British Government to the United States in 1941. In October of that year, a complete engine was delivered to General Electric (GE) in Lynn, Massachusetts, and production of the engine started in the US shortly afterwards. The "big three" aeroengine manufacturers (GE, Pratt & Whitney and Rolls-Royce) all based their early designs on Whittle's engine (Meyer-Homji 1998).

In 1948, Whittle received an award of £100,000 from the British Government for his invention and for the development of the jet engine; in the same year he was knighted. He emigrated to the USA in 1976 and lived there till his death in 1995 at the age of 89. Von Ohain, having worked for the losing side in the war, was largely overlooked. He emigrated to the USA in 1947 and later became Chief Scientist at the Wright-Patterson Air Force Base in Dayton, Ohio; he died in 1998 at the age of 87. In this paper, I shall outline the principal developments of the jet engine, from its early days to the present, including some of the technical advances that have made these developments possible. Finally, I shall discuss some possible future trends.

J Michael Owen

FROM WHITTLE'S ENGINE TO THE PRESENT

A simplified diagram of a Whittle-type engine is shown in Fig. 1. It comprises four basic components: a compressor, a combustor (or combustion chamber), a turbine and a propelling nozzle. Air is drawn into the compressor through the air intake, fuel is burned in the combustor, the hot gas drives the turbine and the exhaust leaves the engine through the nozzle. The turbine, which is directly coupled to the compressor, provides the power to compress the air; the gas leaving the nozzle provides the thrust to propel the aircraft.

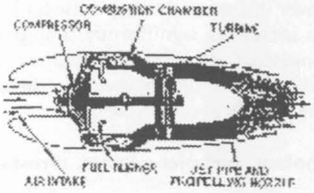

Fig. 1. Simplified diagram of Whittle engine (the Jet Engine 1986)

By Newton's Second Law of Motion, the force F exerted on the fluid is equal to the rate of change of momentum; by Newton's Third Law, the thrust exerted on the engine is equal and opposite to the force on the fluid. Neglecting the mass flow rate of fuel burned (which is relatively 40 small compared with the mass flow rate of the air, $\dot{m}$), it follows that, for an unchoked nozzle,

$$F = \dot{m}(V - U) \tag{1}$$

where U and V are the relative speeds of the air entering and leaving the engine respectively. The propulsive efficiency, η, of the engine is defined as a ratio of the power output to the rate of change of the kinetic energy of the air, and it can be shown that

$$\eta = \frac{2U}{U + V} \tag{2}$$

As U is the forward speed of the aircraft, it is necessary to reduce the jet speed V to increase the propulsive efficiency. However, equation (1) shows that, for a given mass flow rate, reducing V will reduce the thrust. This problem can be avoided by using a bypass engine to increase m and hence the thrust, as discussed below.

The development of Whittle's engine became bogged down in the early 1940s, and Rolls-Royce took over its development in 1943. The Rolls-Royce Welland, a modified version of the Whittle W2B engine, entered service with the RAF in 1944 when it was used to power the Gloster Meteor, a twin-engined fighter. The W2B engine, which had a double-entry single-stage centrifugal compressor driven by a single-stage axial turbine, produced a thrust of around 7 kN (1600 lb).

Turbojets, as these engines became called, were developed in the post-war years to power both military and civil aircraft. The world's first jet-powered airliner, the ill-fated De Havilland Comet, entered service with BOAC (the forerunner of British Airways) in 1951. The Comet, which was fitted with four Rolls-Royce engines, had a short life: it was grounded in 1954 after several aircraft had crashed as a result of fatigue failure of the fuselage (caused by cracks originating from the *square* windows). It was to be eclipsed in the 1960s by the successful Douglas DC8 and Boeing 707. The Pratt & Whitney JT8, which powered the larger Boeing 727 and 737, became the biggest-selling commercial aeroengine in history (Robins 1994).

The Rolls-Royce Dart was a development of the Whittle engine, and in 1946 it was used as a turboprop engine in the Vickers Viscount. Both the airliner and the engine were success stories: the last Dart was made in 1986 but Rolls-Royce anticipate sales of spare parts for a further 40 years: 80 years of sales!

The introduction of "bypass engines" in 1962 marked a significant development for aeroengines. The Rolls-Royce Conway, a low-bypass-ratio engine (see Fig. 2) was used to power both military and civil aircraft. It is interesting to note that Whittle had anticipated bypass engines in 1940 when he took out patents on a "thrust augmentor".

The *core* of a bypass engine is the turbojet, which is surrounded by an annular bypass duct. A fan, or low-pressure compressor, upstream of the core engine blow air through the bypass duct, consequently increasing the thrust of the engine. This overcomes the disadvantage of the turbojet engine in which, as stated above, the propulsive efficiency decreases as the thrust increases. In a bypass engine, the increased mass flow rate, enables the jet speed V to be reduced, thereby increasing η and F (see equations 1 and 2). The other big advantage is that the relatively low-speed bypass air, which surrounds the high-speed jet from the core engine, reduces the high-pitched exhaust noise associated with turbojets. This results in a quiet, powerful and efficient propulsion unit.

The Conway is a twin-spool low-bypass-ratio engine with a ratio of bypass to core air flow rate of only 0.42. In a twin-spool engine, a high-pressure (HP) turbine drives the HP compressor and a low-pressure (LP) turbine drives the LP compressor or fan. The two shafts, connecting the turbines to their respective compressors, are concentric and rotate at different speeds. In a three-spool engine (see Fig. 3), there is an intermediate-pressure (IP) turbine-compressor spool; this involves three concentric shafts, each rotating at a different speed.

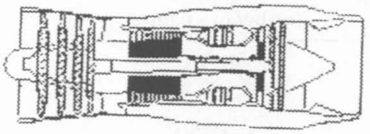

Fig. 2. Twin-spool low bypass ratio engine (The Jet Engine 1986)

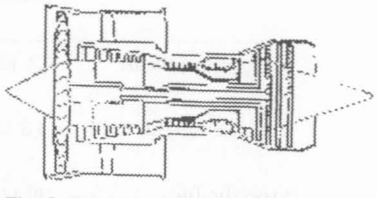

Fig. 3. Triple-spool high-bypass-ratio engine (The Jet Engine 1986)

Multi-spool engines allow better speed-matching of the compressor and turbine stages than is possible with a single-spool engine. The power per stage of a compressor or turbine is proportional to its rotational speed: the faster the speed, the smaller the number of stages required for a given overall power. However, the maximum rotational speed of a compressor blade is limited by stress considerations: the large blades found in fans and LP compressors cannot be rotated as fast as the small blades found in HP compressors. It is, therefore, desirable to rotate the fan and LP compressor at slower speeds than the HP compressor. A triple-spool engine consequently provides better speed-matching than a twin-spool one; it is also shorter, stiffer and lighter.

In the 1960s, the Pratt & Whitney JT9 twin-spool high-bypass- ratio (HBR) engine dominated the civil and military transport market. Rolls-Royce, in an attempt to catch up with its US competitors, began to develop the RB211, a triple-spool HBR engine (see Fig. 3). Apart from having to overcome the technical problems associated with triple-spool engines, Rolls-Royce also attempted to use a carbon-fibre composite material for the large fan blades. This proved a "development too far", and delamination of the composite blades, as a result of impact damage from ice particles or from bird ingestion, made the new material unsuitable. Technical and financial problems led to the demise of the company, which was nationalised from 1971 to 1987. Like the phoenix arising from the ashes, Rolls-Royce recovered and the RB211-family of triple-spool engines has been a technical and a commercial success which led to the development of the Trent family of engines.

Table 1 shows how much has changed over the years since the Whittle engine was introduced. Compared with the W2 engine, the Trent produces nearly 60 times the thrust and three times the thrust-to-weight ratio for around half the specific fuel consumption (SFC). Each second during take-off the Trent 892 "breathes" 1.2 tonnes of air and burns nearly two gallons of kerosene. Another impressive fact is that the turbine-entry temperature of this engine is around 350° C higher than the melting point of the material from which the turbine blades are made.

Advances in military engines have also been spectacular. Thrust-to-weight ratios of current military engines are around five times (and future engines are expected to be up to ten times) higher than those for the Whittle engines. Turbofan engines, although more efficient and lighter, have larger diameters than turbojets, and the compromise is to use low-bypass-ratio turbofans in combat aircraft.

TABLE 1
Comparison of basic data for Whittle W2 (turbojet) engine and Trent 892 (turbofan) engine

	Whittle W2 (turbojet engine)	Rolls-Royce Trent 892 (turbofan engine)
maximum thrust	7.1 kN (1600 lb)	407 kN (91,500 lb)
engine weight	3.8 kN (850 lb)	c. 72 kN (c.16,000 lb)
specific fue consumption	10.115 kg/h/N (1.13 lb/h/lb)	0.0765 kg/h/N (0.575 lb/h/lb)
air mass flow rate	12 kg/s (26 lb/s)	1200 kg/s (2650 lb/s)
turbine entry temperature	1050 K	1750 K
overall pressure ratio	4.4	40.8
thrust-to-weight ratio	1.9	5.7

Some of the technical advances that have made these developments possible are described below.

SOME SIGNIFICANT TECHNICAL ADVANCES

Figs. 4 and 5 show how the performance of engines has improved over the years. Apart from the giant strides made by pioneers such as Frank Whittle and Hans von Ohain, design changes are usually incremental, and most technical improvements occur after the expenditure of considerable time and money in research and development. Aerospace engineering is a high-cost, high- profit sector: the rewards go to those who take a long-term view on investment.

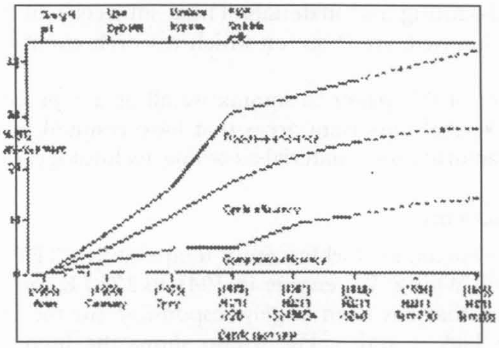

Fig. 4. Improvement in SFC with year (Robins 1994)

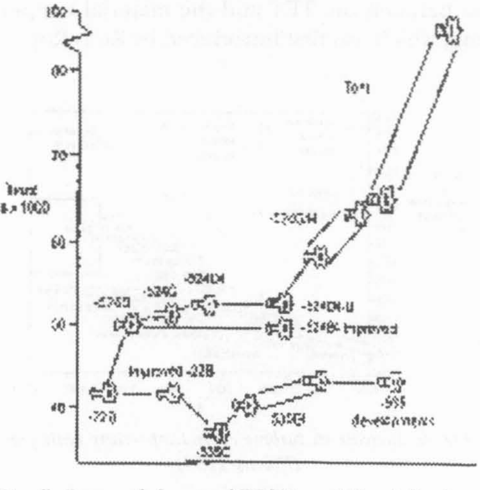

Fig. 5. Range of chursts of RB211 and Trend Engines (Robins 1994)

A significant trend in all research, development and design is the increasing use of computational methods. Growth in computing power and improvements in modelling, particularly in computational fluid dynamics, has quickened the pace. However, the more sophisticated the computational code, the greater is the need to validate its output using reliable experimental data. Gas-turbine research is becoming increasingly directed towards code validation using data obtained from engine tests or from experiments on models of engine components. In Europe and the US, this has led to closer collaboration between the manufacturers and those universities that are interested in advancing the design methodologies.

Some indication of where international research attention is focussed can be deduced by the distribution of technical papers presented at the annual ASME Gas Turbine and Aeroengine Technical Congress, the biggest event of its kind in the world. At the 43rd Congress in Sweden in June, 1998, a total of 597 papers was presented in 17 different subject areas. In "order of importance" (based on the number of papers) were: turbomachinery (including aerodynamics); heat transfer; combustion and fuels; structures and dynamics; manufacturing and materials. These subjects, which accounted for over 60% of the papers submitted, are those on which research attention has been focussed in the recent past.

It is not the object of this paper to summarise all or any of this specialist research. There are, however, several important areas that have resulted in the improvement of performance: manufacturing and materials; cooling technology; fan technology.

Manufacturing and Materials

Fig. 6 shows how the maximum turbine entry temperature (TET) has increased from around 1050 K for the Whittle W1 engine in 1941 to 1750 K for the Trent in 1994. It is the increase in TET that has been largely responsible for the improvements in SFC and thrust shown in Figs. 4 and 5. Fig. 6 also shows the increase in the maximum operating temperature of the materials used to manufacture turbine blades and nozzle guide vanes (the components subjected to the most adverse conditions) over the same period. The difference between the TET and the material temperature has occurred as a result of blade cooling, which was first introduced by Rolls-Royce in the Conway engine in 1962.

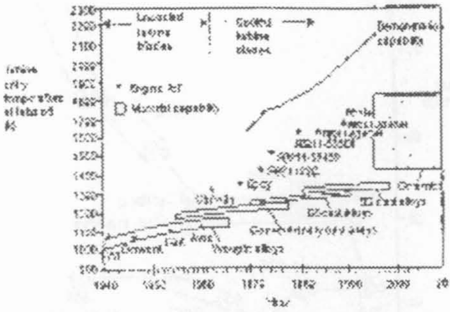

Fig. 6. Increase in turbine entry temperature with year (Robins 1994)

Wrought and conventionally cast nickel alloys were used extensively for turbine blades until the 1970s when directionally-solidified (DS) and then single-crystal (SC) cast alloys were introduced. In the "lost-wax" or "investment casting" technique, an automatic process is used to produce DS and SC blades with high accuracy and good surface finish. The blades are cast with complex internal cooling passages, and the single crystal eliminates grain boundaries, which reduce the life of conventionally cast blades. Turbine discs, which also operate at high temperatures and high stresses, are forged from nickel alloys. These alloys are employed in the final stages of HP compressors, whereas titanium is used at the front end of the compressor and in the fan blades.

Composite materials are now used to replace casings of engine components previously cast from steel or titanium. Sandwich constructions create structures with a high strength-to-weight ratio and stiffness, and they can also be used to suppress engine noise.

Manufacturing methods include electron-beam welding, electro-chemical machining (ECM) and electro-discharge machining (EDM). Particularly, novel techniques are used to manufacture fan blades as described below.

Cooling Technology

Only about one third of the increase in turbine entry temperatures shown in Fig. 6 has resulted from improvements in materials; most of the increase has occurred as a consequence of improved cooling technology. In a modern engine, around 20% of the compressed air is bled off for cooling and sealing purposes. The internal air system, as it is referred to, is used to provide cooling air for the nozzle guide vanes and turbine blades, which are exposed to the highest gas temperatures. The internal air system is also used to prevent the ingestion of hot mainstream gas over the surfaces of the highly stressed discs, to which the blades are attached, and to control tip clearances on turbine blades and to seal bearing chambers. This cooling air is expensive: work has been done in compressing the air, and the designers' aim is to minimise the amount of air used without reducing the life of the cooled components.

Fig. 7 shows how the cooling of turbine blades has evolved over the years. In the 1960s, "convection cooling" was used: the blade acts as a single-pass cross-flow heat exchanger in which the compressed air, flowing radially through the cooling passages, removes the heat convected to the blade from the mainstream gas, flowing axially. As a consequence of the improved manufacturing techniques described above, it is possible to include film-cooling holes in which some of the cooling air leaves small holes in the blade to create a film of cool air over its surface. Modern blades use serpentine passages, which turn the blade into a multi-pass heat exchanger. Film cooling, in conjunction with internal ribs and fins, is used inside the internal cooling passages to maximise the heat transfer coefficients without incurring too big a penalty in pressure drop.

The pressure loss that occurs inside the combustor means that the pressure at the HP nozzle guide vanes (NGVs) is lower than at outlet from the HP compressor. It is the

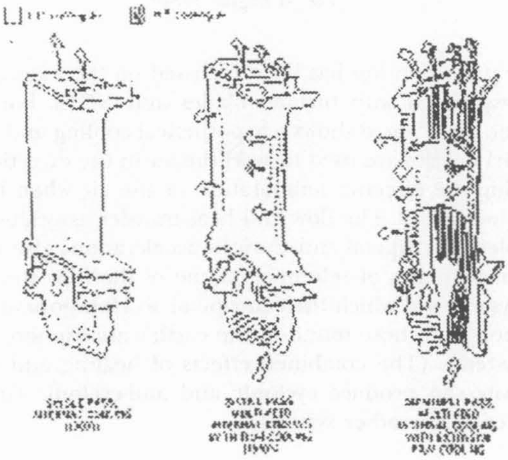

Fig. 7. Evolution of turbine blade cooling
(from "The Jet Engine" 1986)

pressure difference that drives the cooling air through the internal passages in the NGVs and blades. Improvements to the design of combustors has reduced the loss, which in turn has reduced the available pressure difference for cooling purposes. In addition, as the compression ratio has increased over the years, so also has the outlet temperature from the compressor: the temperature of the cooling air of modern engines is around 900 K. These trends have made life more difficult for the designer of the internal air systems.

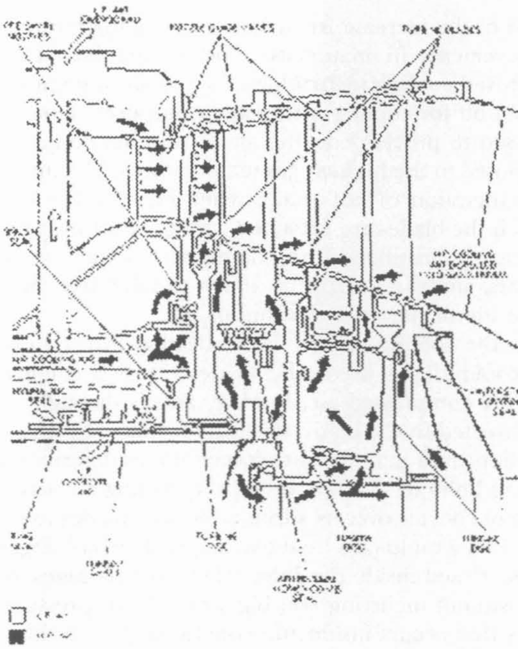

Fig. 8. Cooling and sealing of turbine dised
(The Jet Engine 1986)

Most of the research attention has been focussed on the external and internal flow and heat transfer associated with turbine blades and NGVs, but there is increasing interest in the turbine discs. Fig. 8 shows a hypothetical cooling and sealing arrangement for the discs. Pre-swirl nozzles are used to swirl the air in the direction of rotation of the disc, thereby reducing the effective temperature of the air when it enters the cooling passages in the turbine blades. The flow and heat transfer associated with these systems are extremely complex: centripetal and Coriolis accelerations give rise to flows that are not found in stationary frames of reference. Some of the flow structures that occur in these rotating-disc systems (in which the centripetal accelerations are in excess of 10^4 g) have more in common with those found in the earth's atmosphere than they have with flow in stationary systems. (The combined effects of heating and rotation in a sealed rotating turbine cavity can produce cyclonic and anti-cyclonic circulations similar to those found in the earth's weather system!)

Fan Technology

Fig. 9 shows the evolution of fan blades from the early (solid) RB211 design to the (hollow) Trent 800; the success of the turbofan engine has been helped by major improvements in the manufacture of the fan blades. After the disappointing performance of carbon-fibre fan blades in the 1960s, the development of the wide-chord hollow blades by Rolls-Royce in the 1980s was highly successful. Rolls-Royce has never had a service failure of conventional fan blades in over 40 million hours of operation, and there have been no service failures of wide-chord blades in over 10 million hours of operation (Baldwin 1993).

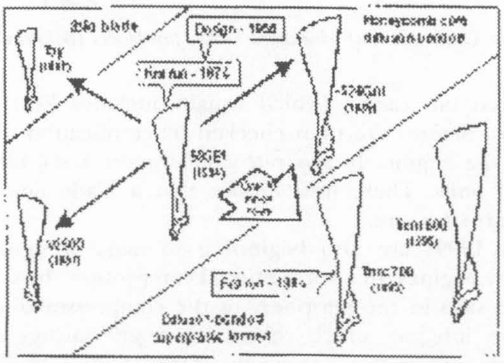

Fig. 9. Evolution of Rolls-Royce fan blades (Baldwin 1993)

In the Trent, at take-off the fan can pass over a tonne of air per second and can produce up to 80% of the engine thrust. The fan is nearly 3 m in diameter and the large blades rotate at up to 4000 rev/min, creating a "centrifugal force" equivalent to the weight of a steam locomotive. The blades have to resist "foreign object damage", such as bird ingestion. In one incident, RB211-535E4 engines on a Boeing 757 were struck by a flock of Canada geese near Chicago – some seven birds, each around 3 kg, were ingested. The wide-chord fan blades withstood the impact, which was some eight times greater than the requirements for certification, and the engine did not have to be shut down in flight.

The wide-chord blades are diffusion-bonded as a "flat pack", comprising two titanium outer panels and a centraltitanium membrane (see Fig.10). The flat pack is twisted and then inflated with high-temperature argon, which causes the central membrane to deform superplastically (with elongations around 1000%) to create an internal ribbed core. This patented "diffusion-bonded superplastically-formed" (DB-SPF) fan blade has high strength and also has good resistance to fatigue and foreign-object damage. The wide chord has allowed a reduction in the number of fan blades, without sacrificing aerodynamic efficiency, and this has resulted in a significant reduction in weight. The DB-SPF fan blade is considerably lighter than the Pratt & Whitney 4000 hollow titanium blade and the General Electric GE90 composite blade, and the improved fan blades and the triple-spool construction of the Rolls-Royce turbofans have resulted in much lighter engines than those of their competitors.

The wide-chord blade owes much of its development to computational modelling techniques. Finite-element methods are routinely used by all the major companies to analyse the effect of "bird strikes" on the rotating blades. In the unlikely event of a blade

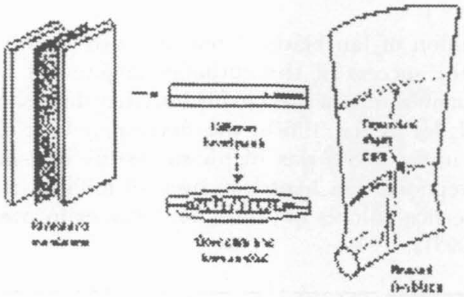

Fig. 10. Construction of wide-chord hollow fan blades (Baldwin 1995)

failure, the reinforced fan casing (which usually includes Kevlar) would contain a released blade. These designs are then checked by certification tests in which (dead) birds are fired into the engine. In separate containment tests, blades are released by means of exploding bolts. These tests ensure that a blade failure cannot result in damage to the aircraft structure.

"Blisks" (Gibson 1999) are also beginning to make a significant contribution, particularly to military engines. In a conventional compressor, the roots of the blades are located in machined slots in the periphery of the compressor discs. With a blisk, the blades and discs are integral, which results in weight savings of up to 30% with consequent improvements in thrust-to-weight ratios. Linear friction welding (LFW), developed by MTU and Rolls-Royce in the 1980s, is now used to manufacture the blisks. The blade root is oscillated against the disc periphery, and the frictional heating raises the interface to the required temperature for bonding to occur. Unlike conventional welding, in which the molten metal may create defects, LFW is a "solid-state" process in which the joint is as strong as the base material. It can also be used to bond blades and discs made from different metals.

This technology will be used to manufacture the three-stage LP compressor of the EJ200 engines for the Eurofighter Typhoon. It will probably also be used in the engines for the proposed Joint Strike Fighter, a European-US collaboration that could result in the production of around 3000 aircraft. There are plans for the development of a wide-chord fan blisk, in which the wide-chord technology of the civil turbofans will be married to the blisk technology of the military engines. This marks a reversal of the usual trend of the transfer of technology from the military to the civil sector.

THE FUTURE - OPPORTUNITIES AND THREATS

The big economic and environmental drivers for modern engine designs are high power-to-weight ratios, high reliability, low cost, low specific fuel consumption, and low noise and emission levels.

The 4th European Propulsion Forum ("The influence of new materials and manufacturing processes on the design of future aeroengines") was held in Bath in 1993, and the principal conclusions were summarised by Air Commodore Geoffrey Cooper (1993). For turbofan engines, bypass ratios of 9:1 are being developed and 15:1 ratios are being considered. The improvements in performance of these ultra-high-bypass-ratio engines is, however, offset by increased engine weight and nacelle drag.

Overall pressure ratios up to 60 are also being discussed. As the compressor provides the cooling air for the turbine blades and discs, it would be necessary to use heat exchangers to lower the temperature of this air, increasing weight and complexity. Turbine entry temperatures may increase by a further 350°C with a resulting 15% reduction in fuel consumption (Robins 1997), but this will require significant improvements in both cooling technology and material developments.

As far as materials are concerned, the search for suitable ceramics has become as elusive as the quest for the holy grail. For years, ceramics have offered the chance of a "quantum leap" but the disadvantages have so far outweighed the advantages. Ceramic turbochargers have been produced by the Japanese automotive industry, but the brittleness and poor shock resistance present problems for aeroengines. Thermal barrier coatings, using thin layers of insulating material, have been used in combustion chambers and on nozzle guide vanes, but there are problems with their use on rotating turbine blades. Although the coating protects the underlying metal surface, loss of part of it can result in rapid failure of the exposed metal.

Composites are likely to play an increased role in aeroengines. Lightweight polymer matrix composites (PMCs), which have a potential of operating at temperatures up to 350°C, have applications in low-pressure compressor casings. Metal matrix composites (MMCs), such as titanium reinforced with silicon carbide fibres, have high stiffness and strength-to-weight ratios, but they also have service limitations at high temperature. Ceramic matrix composites (CMCs) should be capable of operating up to 1400°C, and carbon matrix composites could be used up to 2000°C operating temperature if the oxidation problems can be overcome.

With respect to future aircraft, the Boeing 777 may carry payloads up to 3.3 MN (750,000 lb) with a range of 14,000 km, and the possibility of using twin engines each capable of producing up to 510 kN (115,000 lb) of thrust is being considered. For Rolls-Royce, such a large engine presents no serious problems: the Trent 8104 has already produced thrusts on the testbed of 490 kN (110,000 lb). For GE and Pratt & Whitney, however, the problems are more serious, and both companies are demanding a "propulsion exclusivity" contract with Boeing if they are to recoup their development costs (Kandebo 1999).

There is also talk of a possible replacement in the next decade for the technically advanced but commercially unsuccessful Concorde. Boeing and other companies are considering a 300-seat Mach 2.4 aircraft with a range of 8000 km. The engines would operate on a variable cycle: a turbofan for take-off and landing, and a turbojet for supersonic cruising.

Ozone depletion by NO_x emissions from engines operating at high altitude is a difficult problem to solve. According to Dennis Bushnell (1999), Chief Scientist at NASA Langley Research Center, water deposition in the troposphere and stratosphere also poses a problem for fossil-fuelled aircraft. The water deposition increases cloud formation and affects the earth's radiation balance, which is a problem that even hydrogen-fuelled engines cannot solve.

It is possible that all these problems could be overcome by a new propulsion system. As Sir Ralph Robins (1997) said: "There may be another Whittle out there, with an idea which will make us all look like the piston engine people of the 1930s and which, like Whittle's machine, will change all of our lives". Let us hope that Sir Ralph is right and that this new pioneer will start another revolution in the aeroengine world of the new millennium. Until then, the jet engine remains the best bet.

ACKNOWLEDGEMENT

The author thanks Rolls-Royce plc and Aerospace International for giving permission to reproduce their figures in this paper.

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