THE FUTURE COSTS LESS – HIGH TEMPERATURE MATERIALS FROM AN AEROENGINE PERSPECTIVE

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Abstract

Aeroengines are sophisticated products resulting from over 50 years of research and development. During this time materials science has been a pacing technology, however the performances of current materials are reaching limits. The returns of research and development are diminishing, while the associated costs are continuously escalating. In todays highly competitive, cost driven marketplace this necessitates the definition of clear priorities for development work if future materials and engines are to satisfy the requirements of the market.

This paper addresses the changing market scenario for both civil and military aeroengines, addressing in particular the impact of economic circumstances upon the current and future technological drivers. In the light of this discussion, potential areas of future materials development will be discussed in terms of both performance and cost benefits.

Introduction

At the last Seven Springs conference in 1992, Jim Williams spoke about some of the rapid changes occurring in the Aerospace industry as a consequence of the collapse of Communism and the so called peace dividend. Since then these changes have continued and have been accelerated by the worst recession since the 1930s. The Aerospace market drivers have changed and consequently the perception of needs and priorities for materials have also changed. In this paper I will firstly review the business scene and then examine the consequences for aeroengine manufacturers, the high temperature materials industry and future materials requirements. My view will be from a European perspective, however, the conclusions should be universally relevant.

Military Aerospace

The global military market has seen a steady decline in turnover during the last fifteen years, partially as a result of the end of the Cold War, to a 1994 value only one third of that in 1980 (figure 1). In the aeroengine field there has been a dramatic reduction in demand for spares, as a result of reduced flying by the world's military and this trend has been exaggerated by the improved reliability of modern equipment. Another consequence has been delays and downsizing of new development programmes and significantly fewer new programme starts. Figure 1 also illustrates the difficulties in forecasting the military sector; predictions made in 1989 for the recovery of the market being seriously in error by 1995. In spite of this, military aeroengines remain a major market with a global annual turnover of around $5bn.

The downturn in military aircraft activity, together with national defence budget constraints, has led to an increasing emphasis on the cost of peacetime operation of military aircraft, thus putting pressure on both the lifetime and first cost. The historic demand for high

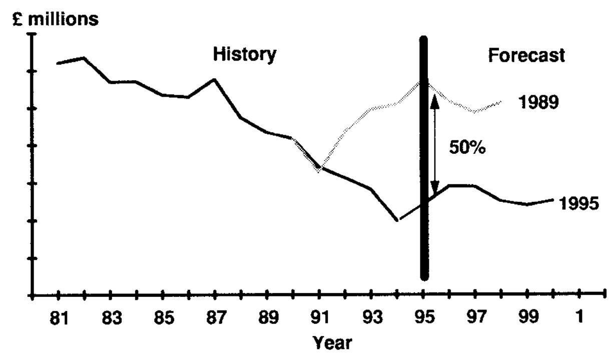

Figure 1: Military Aeroengine Business Turnover and Forecasts

technology levels and increased thrust to weight in military engines is still present, however this is now tempered by the requirement to achieve a reduction in total aircraft weight and hence cost. New product developments are rare and will continue to reduce in frequency. Consequently, technology demonstrator programmes such as JAST in the USA and AMET in Europe will be increasingly important in focusing the development and maintenance of technical capability.

Civil Aerospace

After a profitable period in the mid 1980s, the world civil engine business is now recovering from a difficult period of overall nonprofitability, during which time world air traffic fell for the only time since records began in 1929 and airline losses totalled over $15bn (figure 2). This inevitably had an impact on new aircraft orders; airlines being unwilling to commit themselves to large expenditure when confidence was low. The result was a reduction in new aircraft orders to their lowest level since 1983. In addition, due to bankruptcies and the difficulties experienced by airlines, orders were cancelled at a rate

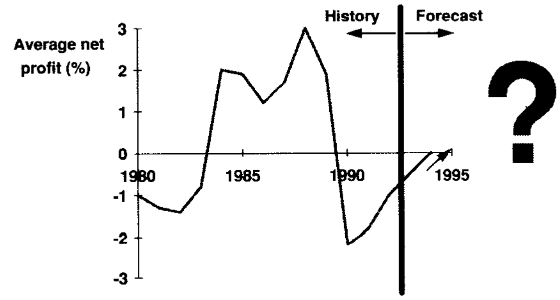

Figure 2: World Airlines – Profit Margins

Superalloys 1996
Edited by R. D. Kissinger, D. J. Deye, D. L. Anton,
A. D. Cetel, M. V. Nathal, T. M. Pollock, and D. A. Woodford
The Minerals, Metals & Materials Society, 1996

comparable to that for new aircraft orders. In 1994 aircraft cancellations amounted to $10.6 billion, whilst new orders totalled only $18 billion. Nevertheless the industry is now emerging from recession and growth in traffic has resumed. Indeed the market for new engines is anticipated to grow by a factor of 2 over the next 20 years to meet the requirements of fleet replacement and new business. This is illustrated in figure 3 which shows the historic and predicted sales figures for the period 1988 to 2014.

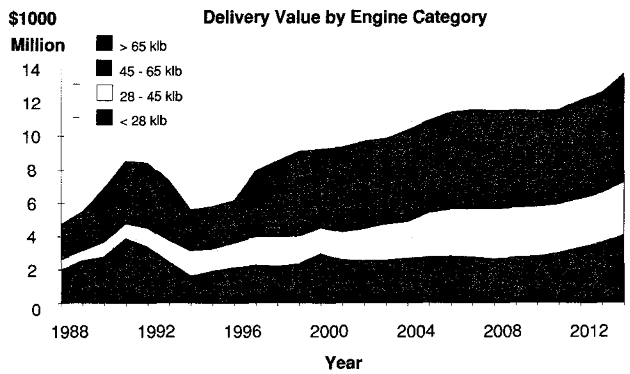

Figure 3: Market History and Forecast for Civil Aeroengines

Airlines do, however, remain under severe financial constraints, translating to an unrelenting pressure on aircraft purchase prices and operating costs. Although they achieved record profits in 1995, it is estimated that total airline profits for the period 1994 to 1996 will only equal about 85% of the losses in the previous three years and, as long as fuel prices remain relatively low, acquisition costs will be the major economic driver for the industry.

Figure 4 illustrates that during the period since 1972 the cost of new aircraft has risen at a rate generally twice that of inflation. This is due to the increased functionality of modern aircraft and includes a significant element attributable to more expensive materials and processes. While this period has also seen a continued increase in air traffic, the average airfare ticket price has remained broadly at the same level, representing a drop in real terms to one third of its 1972 value. This decreasing airline seat mile yield drives price pressure throughout the aerospace supply chain and consequently requires manufacturers to reduce their costs to maintain profitability. The net effect of this cost reduction requirement is a cascade of restructuring and cost cutting from the airlines down throughout the supply chain.

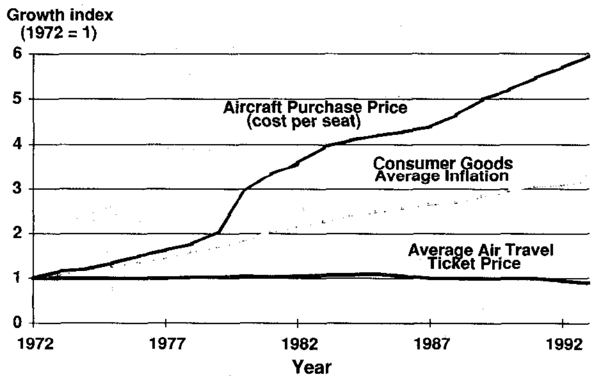

Figure 4: Illustration of the Inflation Rates of Air Travel Elements

The civil aeroengine market is becoming increasingly mature, with three major manufacturers producing similar products competing for market share. In such an environment there is a clear need to retain a competitive advantage. Historically this has centred around reduced fuel consumption with rapid gains being made in the early years largely through technology advances enabling higher operating temperatures and increased bypass ratios. This gave higher thermal and propulsive efficiencies. Today this improvement is slowing down as the industry and the technology become increasingly mature. For example the three engines offered for the Boeing 777 all give essentially the same fuel burn performance. In these circumstances the airline customer will discriminate on the basis of weight, reliability, quality of customer support and, most importantly, the financial package on offer. It is also possible that the customer will be technology averse, where it is perceived that new technology may cause unreliability or other problems. New technology must show an overall business benefit or it will not be applied.

Business Drivers

In the environment described above, the development of new technical capability has to be accurately focused on the needs of the business. Even the blue skies fundamental research needs to have a potential application driving it. Performance dominated military requirements no longer drive the development of new technology with civil engines benefiting from the spin off. Todays drivers are dominated by the civil engine market and the severe financial pressures experienced by the airline business. This shift to a civil dominated market demands dramatic reductions in both costs and product development times. While improved performance is still desirable, future competitive advantage is increasingly dependent upon unit cost and time to market.

This necessitates the adoption of effective business processes. Systems integration and the adoption of concurrent engineering principles are vital throughout the supply chain to enable the delivery of the right product at the right time and the right cost. It will also be necessary to ensure that the required technology is available prior to product validation as the simultaneous development of both technology and product carries too high a risk when timescales are reduced to a minimum.

The finance of research and technology is increasingly difficult, because of the costs to the business of restructuring and of concessions to secure the future market coupled with the reluctance of financial institutions to invest in long term programmes. A careful balance must therefore be achieved between cost and performance, technology push and product pull. Detailed cost benefit analysis is required together with a disciplined investment plan to select areas for research and technology investment before the initiation of work. This should result in fewer more promising development areas leading to reduced costs and development times. In this situation it will be essential to maintain some blue skies longer term research, particularly in universities.

Wherever possible technologies should be identified as dual use, that is applicable to both military and civil markets. The duplication of effort can thereby be minimised and development funding attracted from both military and civil sectors. Collaboration between competitors on projects of mutual benefit must also become more widespread enabling increasingly high development costs to be shared. This principle is well established at the engine project level (e.g. CFM International and IAE), in future we must find ways to make it work more effectively at the materials level. In most cases, materials are not product discriminators. We, therefore, need to find better mechanisms to share development, scaleup and database costs and to realise the benefits from industry standard materials.

The reduction in product development times will necessitate a parallel reduction in timescales for materials development. Together with the desire to reduce costs this will see the increasing importance of rapid prototyping, and modelling techniques both to guide research, cutting down on the amount of empirical testing required, and to better exploit materials in service.

Materials Supply Industry

The effects of these economic pressures have been felt throughout the materials supply industry. Here again the position today is one of upturn, with the future promising a period of growth as airlines return into profit, after a period of decline. Figure 5 illustrates these trends in superalloy billet volumes and selling prices.

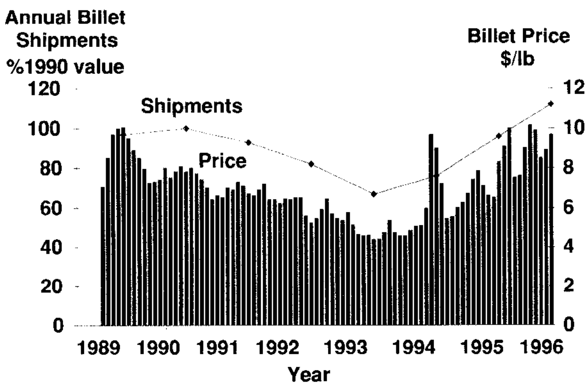

Figure 5: Tonnage and Price Trends for Superalloy Billet Supply

The industry responded to the recession with a period of consolidation, a number of mergers took place and manufacturing capacity was reduced, with some companies leaving the business. Companies also rationalised their operations and contracted down to their core businesses. The recession lead to a general loss of confidence in the aerospace market, as a result of which suppliers attempted to reduce their dependence upon aerospace through diversification into other product markets to enable them to survive through the lean periods. This process can be expected to continue.

The above issues have impacted upon the ability and willingness of the industry to respond to the recent upturn in orders. There is a reluctance to return lost capacity in what is still seen as an uncertain market, and significant difficulties exist in replacing lost personnel and expertise. With the rapid increase in the market there is also a problem with supporting the growing demand. The speed of the pick up has lead to problems of raw material supply up the food chain and an increase in lead times.

Economic pressure and the difficulty of competing in such an investment intensive, low volume industry, results in the requirement to cut costs. Joint ventures with risk and revenue sharing partners are increasingly required to expand limited resources. If investment in new processes is to be made a strong business case in terms of predicted volume usage must be made. In the light of these considerations there is still a future for conventional processes producing conventional materials with development focused on improved economics.

Materials Issues

Advanced materials have been a pacing technology throughout the development of the gas turbine. Higher temperatures and lower densities have been the twin driving forces for the materials community.

Current alloys have been developed over fifty years to the point where further advances are becoming increasingly difficult and expensive to achieve, at a time when resources are ever more limited. Nickel base superalloys are now operating at temperatures of up to 85% of their melting point (figure 6). It is clear that the melting point of Nickel imposes a natural ceiling to their potential and hence further improvement is limited. Continuing incremental development of these alloys is possible but this will require a deeper fundamental understanding of both the materials properties and processing routes, together with the increasing importance of computer modelling techniques. We will need better science to beat the laws of diminishing returns.

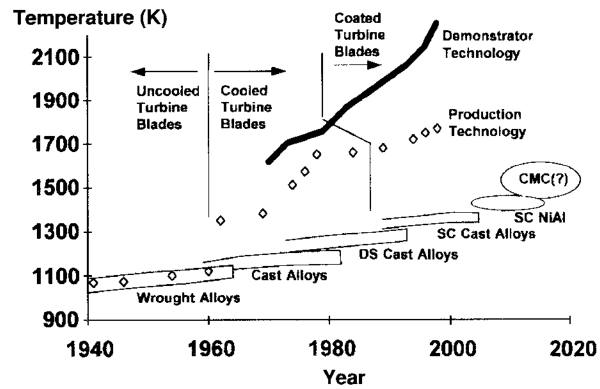

Figure 6: Progress in Turbine Materials and Technologies and Associated Increases in Turbine Entry Temperatures (K)

New materials are now becoming available which offer a step change in capability. However before these materials can displace conventional alloys they must demonstrate the ability to deliver cost effective performance benefits to the whole engine system.

Both of these approaches; the evolutionary development of existing alloys and the revolutionary development of new materials are discussed in greater detail below.

Evolutionary Development of Existing Materials.

Efforts to further exploit conventional superalloys continue although significant increases in temperature capability and strength beyond that of e.g. todays 3rd generation SX alloys will be difficult to achieve at acceptable cost and density.

It seems likely that further developments will concentrate largely on the adaptation of existing materials to niche applications and the production of cheaper alloys with performance parity. Such cost reductions are important in a situation where raw materials account for approximately 30% of the cost of turbine disc and 20% of a blade.

Further incremental advances in performance will require an improved understanding of material behaviour and the application of computer modelling techniques coupled with better processes and control. The growth of computing power has made the development of models of phase diagrams and processes such as melting, casting and forging a practical reality. Coupled with the prediction of properties from compositional and microstructural data this is enabling the prediction of the behaviour of a component from its chemical composition and processing route in a virtual design process. This in turn enables a move away from traditional empirical processes, reliant upon experience and experimentation, and hence dramatic reductions in cost and timescale, as a result of the need for less testing.

A detailed understanding of material properties and improved processing can also contribute through allowing more complete exploitation of existing properties and the safe employment of standard, cheaper, materials to higher stress levels. It may also be possible to control life cycle costs through the development of better life prediction methodologies.

Revolutionary Materials

There are two major classes of potential successor materials to the Nickel based superalloys, the intermetallics and the ceramic matrix composites.

Several barriers however exist to the implementation of any new material. It must be possible to demonstrate a cost effective performance benefit in a realistic time frame. There is a need for an existing manufacturing base, cost effective processing route and adequate design and lifing methodologies.

Intermetallics

Two main categories of intermetallics are available as superalloy successor materials. Titanium aluminides for use at lower temperatures and nickel aluminides for higher temperature components. Both offer the potential for cost competitive improvements in performance through significant density reductions, however the reluctance to accept the risk of designing with a material which is intrinsically brittle must be overcome.

The Gamma titanium aluminides are rapidly emerging as practical engineering materials which may be processed in a variety of conventional and, therefore, low cost processes. A combination of alloy modification and process refinement has increased ductility and defect tolerance to the point where none fatigue critical applications can be contemplated and are being demonstrated. Raw materials are inherently low cost for this system and there is no doubt that they will find significant applications in future engines.

The case for nickel intermetallics is much less mature. Again, there is low density and potentially low cost, however the ductility problem is more intractable and good strength and temperature capability are difficult to achieve without reinventing the superalloy.

Ceramic Matrix Composites

Ceramic matrix composites (CMCs) offer potentially significant temperature advantages over metals, together with a density typically one third that of Nickel. Currently they have a temperature capability of 1000 to 1200°C although this will need to be significantly increased if they are to see wide application. To date CMCs have been employed for high temperature components at low structural loads, for example the reheat systems in military engines and are now being considered as a problem solving material for niche applications such as turbine shroud seals. Here their excellent temperature capability can be exploited in order to avoid the need for cooling of metal components in difficult geometries. This can yield a cost benefit for the overall engine even where the use of CMCs is not justified on a component for component basis. CMCs may be employed for this kind of application within the next 25 years, enabling in service experience to be gained, facilitating ultimate wider application throughout the combustor and for static aerofoils. The use of CMCs in rotating components is, however, not currently envisaged due to their limited strength.

Despite the raw materials themselves being cheap a significant cost barrier does exist, largely due to processing difficulties, a component typically costing 1.5 to 2 times that of a metal part. Fibre manufacture, moulding and processing are all expensive requiring a large equipment investment. Machining is also problematic requiring a near net shape route and constraining production to simple shapes. These problems are compounded by the fact that the material has no scrap value.

There is a need to establish a large scale manufacturing base if a mature manufacturing process is to be developed with the consequent reduction in costs. The business case for investment in such a manufacturing base must however be justified by volume projections for the market and currently this is not the case. Indeed it is unlikely whether the aerospace industry itself would ever require the volumes necessary to constitute a sufficient market. In addition the generation of other applications and markets will be difficult before the manufacturing base is in place and the viability of the technology has been demonstrated.

Summary

The military engine scene has seen a steady decline in turnover since the early 1980s, with an increasing pressure to reduce first and operating costs in addition to the traditional requirement for increased thrust to weight ratio. As a result aeroengine technology is becoming increasingly driven by the cost based requirements of the civil market. The airlines, aided by the three cornered battle for market share between Rolls-Royce, General Electric and Pratt and Whitney, are putting ever increasing pressure on unit price and operating cost guarantees. Against this background, competitive advantage from further reductions in specific fuel consumption, via higher operating temperature and lower specific thrust is becoming increasingly difficult and costly to achieve, hence, increasingly, it is cost and timescale which will win contracts. The aeroengine has become a commodity and its supplier base must adapt to this reality. In the light of current economic constraints it is clear that the historic investment in materials research and development cannot be sustained. A balance must be struck between technological innovation and economic necessity. New technology must be able to demonstrate the potential for a clear competitive advantage before its adoption. In this context modelling techniques based upon a deeper physical understanding will become increasingly important to optimise material and manufacturing processes and reduce development costs and cycle times.

The result is that while new step change technologies are being developed the incremental development of existing alloy systems will remain vital. Past predictions of usage for new materials are now looking optimistic and superalloys will remain the high temperature material of choice for the foreseeable future. It is essential, however, that materials provide increased value to the OEM, this means both lower cost as well as increased functionality. Continued investment in materials science and engineering is vital if we are to achieve these goals and, increasingly, we will have to share this investment if we are going to be able to afford it.