Materials Requirements for High-Temperature Structures in the 21st Century [and Discussion]

James C. Williams, M. McLean, A. Cottrell, M. Harvey and T. Khan

Phil. Trans. R. Soc. Lond. A 1995 **351**, 435-449
doi: 10.1098/rsta.1995.0045

Materials requirements for high-temperature structures in the 21st century

By James C. Williams
GE Aircraft Engines, Cincinnati, OH 45215, USA

The continued improvement in efficiency of high-temperature structures depends on improved materials and on designs that utilize these materials more effectively. This paper discusses the possibilities available to achieve these improvements. While the results are applicable to any high-temperature structure, the discussion focuses on gas turbine engines. This is because some of the most demanding requirements correspond to this application and the author is more familiar with this area.

Possible materials can be separated into distinct classes: evolutionary and revolutionary materials. The former represent incrementally improved materials, mostly metals. The latter represent intermetallic compounds, and metal, polymer and ceramic composites. An attempt is made to estimate the extent of improvements that can be realized from each class of material. In addition, the barriers to realization of the gains are outlined. Where possible, next steps in overcoming these are described.

Finally, non-technical issues such as material cost and availability are addressed and the growing importance of these factors is discussed.

1. Introduction

High-temperature structures operate under additional design constraints, compared to those intended for service at or near room temperature. Examples of these constraints are time dependent inelastic strain (creep), thermally induced stresses and environmental degradation of material properties. The efficiency of high-temperature structures depends on the ability of the designer to compensate for these and other effects of operating temperature. Detailed knowledge of the service domain and materials behaviour helps minimize the complications due to elevated temperature service. This knowledge is also helpful in minimizing the amount of conservatism that needs to be incorporated into designs to compensate for service environment uncertainty and unanticipated time dependence of materials behaviour. There are ultimate service temperature limits imposed by expected structural life and by the capability of the materials used in the structure. These limits also are determined by the consequence of structural failure if the service life is not achieved. Clearly, when the consequences of premature failure are economic, the implications are quite different than when there are possible safety related issues. The level of design conservatism reflects these differences. Among the most demanding structural applications for high-temperature materials are those in aircraft engines. The basis for this statement is a combination

Phil. Trans. R. Soc. Lond. A (1995) **351**, 435–449
Printed in Great Britain

TEX Paper

of several factors: the operating temperatures are high, the expected structural lifetimes are long, the consequence of structural failure is extreme, and the weight critical nature of the product forces the design margins to be as small as possible, consistent with product safety.

Despite these significant constraints, there has been a steady improvement in the capability of aircraft engines with each successive product generation. There are several quantitative parameters that can be used as measures of performance of aircraft gas turbine engines. Perhaps the most important of these are thrust normalized by weight (thrust-to-weight ratio or T/W) and thrust-normalized fuel consumption (specific fuel consumption (SFC)). This paper summarizes the gains made in these performance indices over the past 40 years or so and examines the prospects for continued improvements. The past increases in materials capability are based on multiple generations of improved metallic alloys and on major improvements in processing technology. The future opportunities for continued improvements are much more limited and the rate of progress, going forward, cannot be sustained by improvements only in metals. The alternatives to metals have many other uncertainties and associated questions. Among these are cost and the existence of an industrial base capable of making materials such as ceramic and metal matrix composites in production quantities, assuming they can be made to work technically.

Today, as a combined result of the overcapacity for producing aircraft engines and their natural maturation as a product, these high technology machines have assumed many of the characteristics of a commodity. That is, they are selected by customers who assign a large weight to price in the decision process. The effect of this recent change in the market place is the further slowing of introduction of new technology and a greater focus on cost. This has the effect of restraining R&D budgets and dramatically reduces the ease with which new materials can be introduced into production engines. This is not to imply that no new technology is being developed or introduced into new or derivative engines. It is clear, however, that cost plays a much greater role in the early decision process regarding areas selected for investment in materials technology development.

The intent of this paper also is to describe the current environment for new technology introduction and discuss the effects it has on the future directions for engine materials technology. Some specific actions can be taken to increase the affordability of materials technology development. Included are the earlier use of cost models to estimate affordability and more productive pre-competitive cooperation between traditional competitors that have common needs. More discussion of this will follow.

2. Past materials developments and gas turbine engine performance characteristics

In addition to T/W and SFC, there are several other metrics that are useful to assess the performance of an aircraft engine. These metrics include the compressor exit temperature (T_3) and the turbine inlet temperature (T_{41}). These temperatures are related thermodynamically to the overall pressure ratio of the engine cycle. Cycles with higher overall pressure ratios are more efficient and thus desirable in modern turbofan engines. Another metric is the mass of air that the fan moves relative to that which passes through the engine core (the compres-

Table 1. *Representative gas turbine characteristics as a function of time*

service date	T_3/°C (°F)	T_{41}/°C (°F)	overall pressure ratio	by-pass ratio
1955	379 (715)	871 (1600)	10	< 2
1965	427 (800)	938 (1720)	12–13	2–3
1975	593 (1100)	1343 (2450)	14–16	5–6
1995	693 (1280)	1427 (2600)	35–40	8–9
2015 (est.)	816 (1500)	1760 (3200)	65–75	12–15

sor, combustor and turbine). This metric is another indicator of the propulsive efficiency of the engine. This measure is called the by-pass ratio. Table 1 summarizes the changes in these parameters over the past 40 years as new generations of products have been developed.

The steady increases in T_3 and T_{41} shown in table 1 have been possible because of the availability of higher-temperature alloys for the rotating machinery in the compressor and the turbine section of the engine. In the case of turbine airfoils, these increases have been partly due to improved alloys and partly due to new processing methods. The transition first from conventionally cast Ni base superalloys with equiaxed grain structures to directionally solidified superalloys with only longitudinal grain boundaries and then to monocrystals with no large angle grain boundaries is the result of processing capability improvements. These transitions in structure allowed by processing advances also have enabled alloy chemistries to be modified to delete grain boundary strengthening elements such as Hf and B. These elements had been necessary to impart the required ductility, but they reduced the melting point of the alloy and thus reduced the creep strength. The variation with time of the temperature capability of turbine blade materials, including the effects of processing is shown in figure 1.

In the case of discs, the higher-temperature alloys have a higher volume fraction of the γ' strengthening precipitate and also contain higher concentrations of refractory metal additions, both of which increase the creep strength. The most recent generation of alloys also are made with powder metallurgy methods because this is the surest means of obtaining segregation-free, large forgings. In some cases special processing has been used to create larger than normal grain sizes to further enhance the creep strength. Such changes also affect other properties such as static strength, low-cycle fatigue strength and fatigue crack growth resistance. The key has been to obtain a balance of these properties that enhances the overall structural efficiency of the discs. This has been successfully done and powder metallurgy discs with controlled grain diameters of the order of 45–90 μm diameter are regularly used today.

Other improvements in processing such as the use of clean melting technology also has improved the performance of disc alloys by eliminating inclusions that can be the source of early fatigue crack initiation. As a result, the stress levels at which the clean-melted alloys can be used with high confidence is increased and the rotor weight can be reduced accordingly. Concurrently, the cost of these improved materials has been held in check, relative to the level of performance, by the use of improved processes. These processes have higher yields and greater

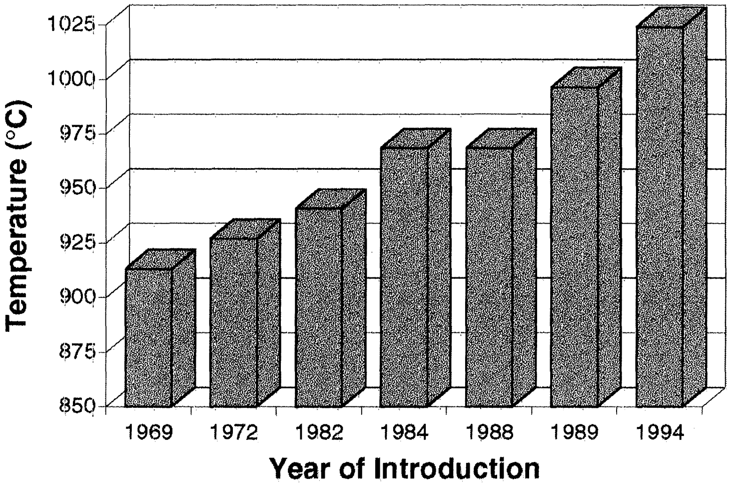

Figure 1. Bar chart showing the changes in temperature capability of cast turbine blade alloys as a function of time. The first three alloys in the series are equiaxed, conventional cast. The next one is a monocrystal alloy. The next is a directionally solidified alloy with comparable performance at lower cost. The last two are monocrystal alloys.

reliability as the result of the use of process modelling. Through improved process controls, made possible by concentrating on the critical process variables identified with modelling, the product of the process exhibits less variation and the occurrence of 'special cause' events is minimized. Finally, the increased use of net shape processing techniques such as casting and precision forging has reduced the cost of manufacturing components from these improved alloys. Without the improvements in processing capability, the cost of the improved materials would be much higher and their use would be much more limited.

3. Future generation metallic materials

The above summary describes, in general terms, the engine performance improvements that have been made and the role of materials as a key enabling technology. An important question with regard to expectations of future improvements is, 'How much more performance can be expected from metals?' Clearly, the rate of improvement is slowing and it is possible that the point of diminishing returns for metals is approaching. The more realistic challenges beyond the next one or two generations of metallic alloys may be the gains obtainable by tailoring existing alloys for particular application regimes and improving the life capability of existing materials. Schematically, this is depicted in figure 2, from which the concept of a performance asymptote or limit can be inferred. In this figure an index of material performance, e.g. creep strength, is shown as a time series. Clearly, the use of a smooth curve is only schematically correct, since the performance increments are achieved on a generation by generation basis. The more important point, however, is that the cost of each increment of performance is roughly the same, so the benefit/cost ratio is decreasing as the asymptote is approached. Barring a major (unlikely) breakthrough in high-temperature metallic alloy concepts, this asymptote is essentially fixed by material melting temperature. The time may be at hand that a logical and appropriate economic decision

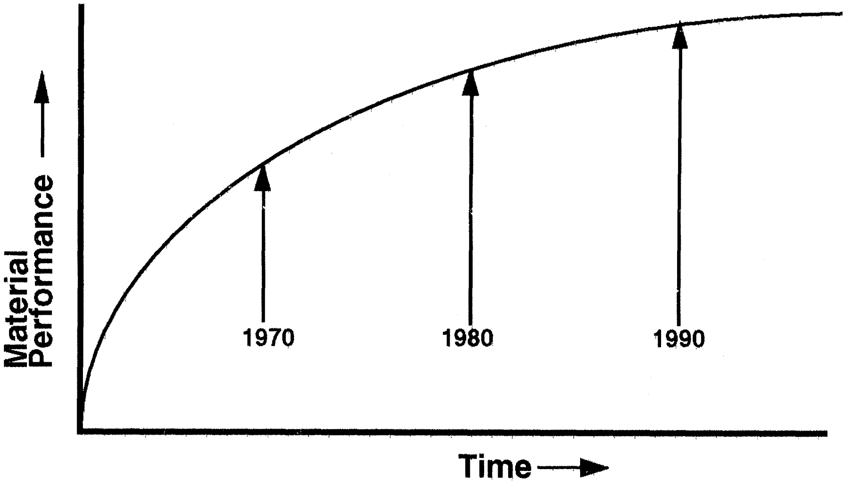

Figure 2. Schematic plot of evolutionary material capability as a function of time. The overall capability is approaching an asymptotic value, but each generation of material cost about the same to develop, making the benefit for unit cost less.

would be to concentrate future R&D efforts on adapting existing materials to serve well-defined niche applications.

One such application is the emerging high speed civil transport (HSCT) engine currently under development in the US. The operating temperatures for the turbomachinery in this engine are not much higher than that of current generation subsonic engines. The times at maximum temperature, however, are many times longer. The long time at high power levels, and therefore high temperatures, is required in the HSCT engine to sustain supersonic cruising speeds. These time–temperature combinations greatly exceed any experience that exists in the aircraft engine industry. Schematic time–temperature profiles for subsonic and HSCT engines are shown in figure 3. This application introduces time-dependence issues in materials performance that have not been addressed previously. These issues will require special attention from a materials standpoint but the maximum temperature capability requirement is not significantly increased in comparison to the recent subsonic transport engines (see table 1). The rotor materials for the HSCT engine thus will require tailoring of the properties to meet these requirements, but the upper boundary of the operating temperature domain need not be extended. These requirements, while challenging, do not call the asymptote (at least on a temperature axis) into question and there is a basis for optimism that the requirement can be met.

The asymptote suggestion also implies the following question: What can still be done to improve metals? This question is causing the engine materials community to more aggressively examine the viability of new classes of materials that have the capability of defeating the metals temperature barrier. These future materials have been separated into two classes, according to the magnitude of the potential performance increment. The classes are called evolutionary and revolutionary, respectively. High-temperature evolutionary materials are metals, almost by definition. Facing the evolutionary materials asymptote question becomes more pressing as the limits of metals are actually approaching and as

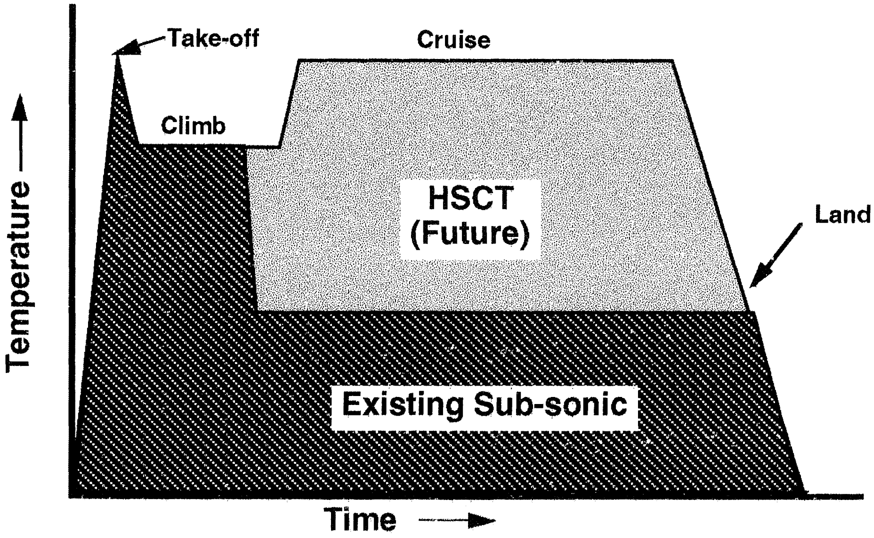

Figure 3. Schematic plots of turbomachinery temperature at various points in a flight cycle for typical subsonic transport engine and the proposed HSCT engine. Note the long exposures at high temperatures during cruise for the HSCT.

resources to explore alternatives become more limited. In the end, the decision will be one of comparing more certain modest gains obtainable from at least one more generation of evolutionary materials with the possibility of much larger gains obtainable from revolutionary materials but with higher risk. This question will be examined in more detail in the next section, but it is relevant to raise it here because these other materials are widely viewed as an apparent alternative to next generation metals. This is in part because of the diminishing benefit relative to cost that can be obtained from another generation of evolutionary metals.

Against this background, it is useful to examine the prospect for next-generation metallic engine components such as rotors (discs) and turbine blades. It appears that there is at least one more generation of turbine blade alloys that can be identified, developed and put into service. These will be investment cast monocrystal blades. The temperature capability and durability of this next alloy and of earlier generation alloys also can be enhanced through the use of ceramic thermal barrier coatings (TBCs). Between these two technologies, it appears that the gas temperature in the high-pressure turbine can be increased by about 100–125 °C in the foreseeable future while maintaining a constant cooling air flow. Conversely, the use of TBCs at a constant gas temperature allows the cooling flow to be reduced for improvement in SFC without raising the metal temperature. The impediment to development of TBCs is improving their current level of durability. If the temperature advantage that can be obtained through their use is incorporated into an airfoil design either through lower cooling air flows or higher gas temperatures, a breach in the coating due to spallation, either from impact or loss of adherence, will have serious consequences in airfoil life. The current generation of TBCs are durable enough to provide significant life extensions, but their use to accommodate increases in T_{41} is a higher risk proposition at present.

Regarding discs, the current T_3 limitations are mainly related to compressor rotor capability since these rotors are not cooled. The limitation for commercial transport applications is more closely related to the effects of dwell or hold time on fatigue crack growth (HTCG) than it is to creep strength. Fortunately, the effects of coarser grain size has a common benefit for both properties, so the use of processing methods that result in grain sizes in the ASTM 4–6 range improves both HTCG and creep strength. Low cycle fatigue (LCF) strength is reduced with increased grain size, but the limiting properties for most long-life commercial engine discs is fatigue crack growth or HTCG, not LCF. As T_3 increases in next-generation high-thrust commercial engines, creep may become a factor, but it is unlikely that LCF will be a life-limiting consideration. Thus alloys and processing methods that improve creep and HTCG will be the focus of most future disc development activities. It is likely that all next generation alloys that meet the strength requirements will be too solute rich to be producible by ingot metallurgy (also called cast and wrought) methods. This mainly is because of the difficulty in producing large, good quality ingots of these richer alloys. Thus powder metallurgy (PM), or its equivalent, will be the basic production method upon which higher temperature disc processing is built. This is an inherently more costly method which immediately raises questions in light of the new cost/performance paradigm. However, on the positive side, once the transition from cast and wrought to PM processing is a *fait accompli*, the incremental cost of special processing to achieve coarser grain size is small. There are several possibilities for higher temperature discs for use above 730 °C. The first is dual heat treatment (DHT) where the disc rim is selectively heat treated to have coarser grains than the bore. This yields better creep and HTCG in the hottest regions of the disc with minimal impact on LCF and tensile strength of the bore. The second method is a dual alloy disc (DAD) where the bore is made of a higher tensile strength, less creep- and HTCG-resistant alloy and the rim is made of a different alloy that has much better creep and HTCG resistance. Processes that prove technical feasibility of both of these approaches have been adequately demonstrated, but reduction to full scale production practice remains to be done. Both of these options raise the cost of discs. The DHT disc will cost less but will give a smaller increase in temperature capability than the DAD approach. Evaluating the trade-off of cost increment against performance improvement cannot be done in isolation. The author believes it is not likely that many applications will emerge where performance is so important that large cost increments will be acceptable. The question is whether, in the light of the newly recognized absolute cost constraints, there will ever be an application for DAD technology. Only the market place will answer this question.

Some actions that can be taken to reduce the barriers to implementing the next generation materials have been mentioned in the Introduction. Some of these are directly related to mitigation of cost barriers, others are more closely related to technical barriers, although this separation is somewhat artificial.

The first of these is the need to do a better job of pre-selecting the most likely materials and process candidates before initiating development. This implies that some rudimentary affordability analysis needs to be conducted before any technical work is initiated. Technologists of an earlier generation will not willingly accept this requirement, but this is a management issue that simply needs to be embedded in the organizational culture (it is an element of the new cost-driven realities). The net result of implementing this cost conscious practice is that fewer, more promising technologies will be under development at any one time. This permits more resources to be focused on the most likely candidate technologies, with the likelihood of early realization in practice being significantly increased. It also is important to remain alert to opportunities to introduce new materials in low risk or limited use as early as possible to raise the awareness of their existence and potential. Even limited, but real, service experience has a disproportionately beneficial effect on the confidence designers have in a new material. Another way to reduce the cost of developing a new material is to engage in joint development projects with other companies that have common requirements. In earlier times, many companies viewed this approach with disdain because of perceived loss of competitive advantage. In reality, there is a great deal of development activity that can be done jointly even by direct competitors without compromising any potential advantage. More cooperation is emerging, but there is room for much more.

The technical barriers to higher temperature materials implementation include the need for a better fundamental understanding of time dependent materials behaviour, especially HTCG. If the understanding is based on principles instead of empirical data and information, the time-dependent behaviour of a range of alloys can be compared and contrasted without the need to generate large quantities of empirical test data for each alloy being examined. Another area for continued improvement, which is technical in nature, but which has potential for major cost impact is the development and use of realistic process models. Better models permit definition of processes that improve product quality and uniformity. Included are both materials and components such as forgings and castings.

The point of this discussion is to make it clear that new technology, both in materials and in processing, will be introduced into a future generation of new and derivative engines, but cost will play a more central role in the decision process. Just as this cost focus represents new thinking, there is new thinking that needs to be done to make new technology more affordable so as to prevent stagnation of product improvement. Product improvement driven by technology has been the characteristic that has differentiated the aircraft engine industry from, for example, the auto industry. Thus it appears that finding innovative ways of sustaining continued product improvements in a more cost conscious environment will be a key challenge for the industry.

4. The future of revolutionary materials

As mentioned earlier, a revolutionary material is one that has a large change (step function) in any particular property of interest. These materials have captured a great deal of interest among structural designers because of their potential for large gains in structural efficiency. Over the past 10–15 years a lot of effort has been devoted to reducing revolutionary materials to practice for inclusion in high-performance production military and commercial systems. It is fair to say that progress in reaching this objective has been slow. Today the only examples of these materials in significant use are polymer matrix composites. Other candidate classes of revolutionary materials are metal and ceramic matrix composites, and intermetallic compounds. The balance of this section will examine the status of each of these material classes and outline the prospects and timing for reducing them to practice.

(a) Polymer matrix composites (PMCs)

These materials are in use in a number of production systems, both in the airframe structure and the engine. The largest volume of PMCs are used at or just above ambient temperature (less than 100 °C). There is a moderate amount of polyimide matrix, carbon fibre composite material (PMR-15) in use at temperatures up to about 275 °C, but this is small in an overall sense. Thus PMCs are not a mainstream topic of this article since they are not truly a high-temperature material. Nevertheless, a brief summary of the benefits and issues associated with the use of PMCs seems appropriate since this is the most mature class of revolutionary materials. PMCs are attractive because they provide major weight and durability advantages. They have specific stiffness and strength values of not less than twice that of metallic structures. They also have similar advantages in fatigue strength. They are considerably more costly to fabricate into components, compared to Al or Ti, and this has limited the extent of their use. Until quite recently, design methods to fully realize the benefits of PMCs have not been widely available. This deficiency has further limited their use in complex shaped structures. Compared to monolithic metals (as opposed fabricated metallic structures such as honeycomb core, metal face sheet), PMC structure is difficult and costly to repair. These two cost related factors are the subject of development effort and in time will be less troublesome. Today, however, these remain as issues that reduce the usage of PMCs. The industrial base for making PMC raw materials is reasonably mature, but the overcapacity, due in part to previous over-optimistic estimates of use levels, currently is creating major financial pressures for the materials suppliers. As a result there will be a shake-out in the supplier base, but the remaining companies should emerge healthier than they have been in several years.

(b) Metal matrix composites (MMCs)

Metal matrix composites have been in existence as a material concept for over 20 years. Laboratory quantities of these materials have been available for nearly as long. Today there are several distinct classes of MMCs. These can be distinguished by the nature of the reinforcement: continuous fibre, discontinuous fibre or particulate reinforced composites. There are markets identified for each of these classes of MMC, but the only class that will be discussed here are Ti matrix composites reinforced with continuous SiC fibres (known as TMCs). These composites have been shown to have very attractive properties as can be seen in table 2. These properties represent a two-fold increase in structural efficiency when compared to high strength Ti alloys. The reproducibility of the properties shown in table 2 has also been thoroughly demonstrated and TMCs are widely accepted as a technically feasible material system. These properties are very anisotropic, but this characteristic can be managed through better design methods that are available (but not widely used). The issue that has been restricting TMC use is cost and at present this barrier is great enough that these materials are not in use in any production system.

The principal issue that is impeding extensive use of TMCs in addition to cost is the lack of a production scale and style source of supply. In some regards this can be viewed as a chicken and egg situation. This epitomizes the dilemma that has plagued the reduction to practice of revolutionary materials. That is, the

Table 2. *One example of reproducible, longitudinal-orientation MMC properties*
(Material system: Ti 6Al 2Sn 4Zr 2Mo + Si, wt%; *ca.* 150 μm SiC fibres.)

ultimate tensile strength	1.9×10^3 MPa (276 ksi)
Young's modulus	226×10^3 MPa (32.8 msi)
fracture strain	0.95%
density (equivalent to Ti alloys)	4.43 g cm^{-3} (0.16 lb in^{-3})

cost becomes less as the usage volume increases, but there are few applications that are so performance limited that the early higher cost during the low-volume phase of reduction to practice can be justified. Without a well-defined market, capitalization to produce the materials in larger (lower cost) volumes typically is not available. There currently is a large cooperative programme in the US that is aimed at reducing the cost of TMCs. There are several aspects of this cost-reduction programme that make the outcome encouraging. Most important is the agreement among the users to focus on a single, lowest-cost process for making TMCs. This lowest-cost process will be selected after a careful evaluation phase. Further, the initial applications planned for production introduction are ones limited by low use temperature and stiffness. This increases the chances of success because it is less likely that an unforeseen problem will occur during service introduction. If the material cost targets are achieved, TMCs will likely see initial service in real products within the next four years. While this is encouraging, the overall time line from material concept to actual product use is considerably longer than was originally forecast.

(*c*) *Ceramic matrix composites (CMCs)*

CMCs are the most attractive material concept for defeating the metals use temperature asymptote defined by melting temperature. The fibre toughening of CMCs avoids many of the well-known brittleness issues associated with monolithic ceramics. However, it is essential that the toughness of CMCs that is derived from fibre-dominated behaviour is retained after long term, high-temperature service. This poses a potential problem that is still under evaluation and extensive study. The key to fibre dominated behaviour is retention of a fibre matrix interface that has intermediate strength. It is common for reactions to occur during elevated temperature service that either strengthen or weaken the interface, thereby changing the toughening behaviour. As service temperatures increase above the 1300–1350 °C range this matter becomes increasingly difficult. Today, it is accurate to say that there are no CMC systems that have the service capability for thousands of hours at or above 1300 °C. Development efforts are still underway to achieve this goal, but it is a daunting prospect. There are other issues that must be resolved before CMCs can reach their full potential at these very high temperatures. One is the availability of a high-temperature fibre that will have adequate creep resistance as service temperatures are raised. This limitation is less bothersome than the loss of fibre dominated behaviour because it gradually reduces the load bearing capacity of CMCs but does not result in the onset of potential for catastrophic failure. CMCs also have a limited industrial base for large scale production, although the situation is somewhat better than for TMCs. As in the case of TMCs, the absence of applications and little consensus among users regarding preferred processing methods contributes to the high cost of CMCs. A cooperative programme of the type described for TMCs would be useful as a means of cost reduction. There is growing interest in CMCs for low-emission engine combustor liners. If this application is realized, the situation could change and applications in real products could develop relatively rapidly.

(*d*) *Intermetallic compounds*

Intermetallics also have been the object of study for more than 25 years as potential replacements for high-temperature alloys. In fact, some of these materials have excellent high-temperature strength. The major barrier to the use of intermetallics has been the inability or unwillingness, in a risk sense, to deal with the low temperature brittleness of literally all intermetallic compounds. Most intermetallics become more ductile at elevated temperature, but the low temperature brittleness poses severe problems, some real and some perceived. An additional attraction of intermetallics is their low density, because many compounds contain one or more light elements such as Al or Si. The intent of this section is not to review the status of the various intermetallics that are currently the subject of a large number of development programmes around the world. Rather, it is to describe the barriers to implementation that a component made from an intermetallic must overcome to achieve production status. Several conferences have been held on intermetallics and the proceedings of these are an excellent source of detailed technical assessments of particular compounds (Darolia *et al.* 1993).

The brittleness of intermetallics makes them difficult to design with because of increased risk of unanticipated fracture in service and increased manufacturing losses because of cracking during processing. The pay-off from these low density materials justifies coping with these issues. As a result, there are several intermetallics that are being actively studied. Among the most promising and widely studied is the compound based on TiAl. There are several ternary and quaternary alloy variants of this compound under intense evaluation. At GE Aircraft Engines, an entire last-stage wheel of low pressure turbine (LPT) blades has been made from cast Ti–48Al–2Cr–2Nb and run in a factory cyclic endurance test of a large commercial transport engine. The blades have performed perfectly, demonstrating that the concern about low ductility is not performance limiting. These results are very encouraging and provide the impetus to consider a field evaluation of LPT blades. This is expected to commence in 1995. The TiAl LPT blades can be directly substituted for cast equiaxed Ni base alloy blades at about 50% weight reduction. Later, if this evaluation is successful, additional weight savings can be achieved by re-designing the disc and static structures because of the lighter rotor weight. Still the practical issue with TiAl is cost, because of the higher degree of difficulty of fabricating components. Casting helps reduce the cost, but TiAl castings will be more expensive until there is more experience in the industry. In the future, TiAl should be less expensive than cast Ni-base alloys if the prices of Ni and Co continue to escalate. It is an unusual opportunity to contemplate a simultaneous reduction in weight *and* cost. Many issues must be resolved before this is realized, but there is good reason to believe that this will eventually happen. There also is interest in forged (wrought) TiAl, but there is little reason for optimism regarding cost of this processing method. Here, the low ductility increases the number of forging steps and reduces the yields because of cracking. It appears that the first production application of TiAl, if it occurs, will be in cast form. It is conceivable that the first production introduction of low-risk cast TiAl components could occur as early as 1997.

5. The effect of business climate and product maturity on product development trends

The current business climate in the aircraft engine sector only sharpens the cost focus. It is clear that the prime means of differentiating a product in this market today is price, not performance. This is because of the maturation of subsonic engines and the current world overcapacity for aircraft engine production. Today, all engines in a given thrust class have comparable (but not identical) performance characteristics. The most certain means of increasing market share is to offer a competitive product at a lower selling price than that of the competition. This means that the cost of producing the product must be reduced and vigorously managed, both at the engine factory and at the raw materials and component suppliers plants. The concept of cost as the primary consideration represents a new paradigm in the engine industry. Adapting to this new way of life has produced some significant changes including new ways of working and significant reductions in work force size. In addition to competitive cost comparisons between engine makers, there has recently arrived an awareness of the importance of absolute costs. Several major airlines have recently said that they cannot foresee a realistic means of obtaining adequate return on investment from any aircraft that costs more than about \$200,000 per seat (in 1994 dollars). The basis for this is the analysis of anticipated revenues and operating costs including the cost of ownership. The significance of this position is not the accuracy of the \$200,000 figure, but the recognition of an absolute cost constraint in addition to a relative one that is the result of competitive analysis. This event will undoubtedly affect the rate that new technology can be introduced into future generation engines and airframes. In turn, this will influence the types of development projects that the engine manufacturers undertake and the rules of thumb that have been used to assess the value of new technology that enhances product performance. External factors such as large increases in fuel cost may change this matter, but for current planning purposes such increases do not appear likely.

Even the market analysis of the HSCT assumes very modest fare premiums (about 10–15%) in three-class service to make the market size large enough to allow the return of development cost. Such modest increases will not buy much technology beyond that needed to meet the range and emissions requirements. Thus the market in which commercial aircraft and engines operate appears to have permanently changed. The new competitive realities are based on cost , not technology. It is time that technologists recognize these realities and adjust their thinking and approach to their work.

6. Summary

This paper has described the development of aircraft engines as products of high technology. A few ideas that have been presented are worth repeating here in capsule form.

1. Materials have played a significant role in the performance improvements of aircraft engines during the past 40 years.

2. The temperature limits of metals are being approached, but the alternatives to metals raise several different, but equally difficult questions.

3. The development and implementation cycle for new materials is very long and needs to be reduced. This will reduce development cost and permit more rapid introduction of new materials.

4. The current market climate places an unprecedented emphasis on cost.

5. Performance parity with cost advantage will be the most certain way to win market share in future transactions.

6. The ability to introduce new materials will be paced by cost, more than anything else.

References

Darolia, R., Lewandowski, J., Liu, C., Martin, P., Miracle, D. & Nathal, M. (eds) 1993 *Structural intermetallics.* Warrendale: TMS-AIME.

Discussion

M. McLean (*Department of Materials, Imperial College, London, UK*). Doctor Williams indicated that ceramic matrix composites show particular promise for aero-engine applications. Does he envisage that they will be used with cooling? If not, what material temperature advantage is required over existing metallic materials for which blade cooling is likely to be more efficient?

J. C. Williams. Ceramic matrix composites (CMC) appear to be attractive for combustor liners, turbine blades, and static exhaust structural parts. Clearly the use of cooling would further enhance the temperature benefit in the former two cases. Today, there is no proven way to put cooling passages in CMCs. There at least two barriers. First, severing the fibre reinforcement would reduce the structural efficiency of the materials. Second, even carbides or nitrides have much lower thermal conductivity than superalloys. Consequently, there would be steep temperature gradients between cooling holes. This would only serve to exacerbate the thermal fatigue problem that is recognized in elastically heterogeneous materials such as CMCs.

Calculation of the increase in temperature capability to make an uncooled CMC part comparable to a current cooled superalloy turbine airfoil is not straightforward because of the differences in thermal conductivity and the anisotropy in this property that the fibres introduce. In superalloy blades cooling can provide as much as 500 °C ΔT between the metal temperature and gas temperature. Using this as a rough approximation, it is fair to say that there are no CMC systems today, either production or developmental, that offer this temperature. Of course, the durability required or expected in commercial engines today is an additional question mark when the use of CMCs is contemplated.

A. Cottrell (*Department of Materials Science, University of Cambridge, UK*). As befits the title of this Discussion, we are concentrating on the problem of raising the working temperatures of materials. But in, for example, gas turbine engines it can be just as important to aim at reducing the weight, the pursuit of which would lead the materials research in a quite different direction. Would Dr Williams care to comment on these possible alternative strategies?

J. C. Williams. It is always attractive to introduce lower density materials, or more accurately, materials which have better performance on a density corrected basis. However, the overall performance benefits of significantly reducing the operating temperatures in the hot sections of a turbine engine to permit use of lower density materals are fewer than those that can be gained by increasing the temperatures through incremental improvement of the currently used Ni-based alloys. The difficulty lies in achieving large enough reductions in the operating temperature to permit the use of lower density alloys based on Ti or even Al, while maintaining acceptable performance characteristics and not increasing the risk of fire. The remaining question is whether there are lower density materials with roughly Ni-based alloy temperature capability. There are a few, including C–C composites, ceramic composites and some intermetallic compounds such as NiAl and TiAl. Each of these classes of materials present several durability related questions that are so daunting as to currently preclude their use in any production engines. Engine tests have shown that the difficulty in applying these materials varies by material class, but the least likely appears to be C–C composites and the most likely is TiAl, at least for rotating components. There has been considerable work expended in reducing the weight of static structures, with the result that polymer matrix composites and cast Ti alloys are widespread use today. Al and Mg alloys may be possible for the cool, front end but these materials are not widely used in western world for large engines.

The greatest performance benefits have been realized through incremental improvements in the gas temperatures partly made possible through higher temperature materials and partly through the use of improved cooling technology. Lighter weight structures are attractive, but as a complement to higher temperature rotors.

M. Harvey (*Department of Materials Science and Metallurgy, University of Cambridge, UK*). Ram Darolia, also of General Electric, has published some interesting results with regard to nickel aluminide, NiAl, as a possible replacement for existing superalloys in blade applications. What is the current state of research at GE concerning this particular intermetallic?

J. C. Williams. There has been a lot of work done on NiAl at GE Aircraft Engines over the last six years. This work has focused on several aspects of this material including processing to make large monocrystals, alloying to achieve better creep strength and ductility improvements, manufacturing methods for making turbine airfoils and design methods that permit the use of limited ductility materials such as NiAl in turbine components. It is fair to say this work has taught us a lot and that we are now in a much better position to contemplate a demonstrator engine test of this material. We also have learned how much more difficult, compared to superalloys, it would be to reduce NiAl to practice in a production engine.

We have an engine test scheduled for mid-1995 which contains a turbine nozzle with NiAl vanes. Our previous effort gives us reasonable confidence that this test will be successful, but the next steps are less clear. The benefits of a 35% less dense alloy with several fold increased thermal conductivity are very clear. The cost of introducing this material and the associated durability risk are much less clear and need to be resolved before a production commitment could be made.

T. Khan (*Chatillon Cedex, France*). Which type of materials does Dr Williams have in mind while projecting T_3 (compressor air temperature) temperature of about 815 °C in advanced subsonic engines of the future? Could he give an indication in the type of research work which should be carried out to meet this goal.

J. C. Williams. First let me re-emphasize that, currently, there are no known materials solutions to permit an engine to operate for long times at 815 °C T_3 values. The best candidates for somewhat lower temperatures (up to 760 °C) are Ni-based alloys used in narrower regimes that the current 'one size fits all' approach. By this I mean the bore of a very high-temperature rotor could be made of a high strength, fatigue resistant alloy, the web could be a medium strength, creep-resistant, coarse-grained alloy and the rim might be directionally solidified or even monocrystal pieces made from airfoil alloys chosen for their extreme creep resistance, but low tensile and fatigue strength.

There has been discussion of W wire reinforced structures but I, personally, am not optimistic about the ability to eliminate reactions between the Ni alloy and W wire. Clearly, there are a number of serious technical barriers to achieving an 815 °C disc. Even if these can be overcome, the costs of such a disc may prove prohibitive. The gas turbine industry has provided other examples of technical successes that are commercial failures. As the industry matures, these must be avoided through cost-conscious, decision-making processes in the early stages of a development project.