Int. J. High Technology Ceramics **4** (1988) 93–102

1

Engineering Ceramics: Applications and Testing Requirements

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1 INTRODUCTION

The inclusion of structural ceramic components in gas turbine engines allows the use of significantly higher operating temperatures than is possible with metallic components. Such utilisation of ceramics offers improvements in thermal efficiency which can be translated into decreased specific fuel consumption, decreased weight and consequently lower stresses in rotating components and higher thrust to weight ratios. Furthermore, ceramic components may be less costly than their complex air cooled counterparts and could reduce dependence on critical imported materials used in metallic superalloys. The emergence of the non-oxide silicon based engineering ceramics in the early 1960s held the promise of the realisation of these goals. These materials are strong, as well as being resistant to oxidation and thermal shock; however despite considerable expenditure on various ceramic engine programmes, there has been only limited success in the use of ceramics for structural components in the hot section of demonstrator engines. If ceramics are to become a reality the major problems of reproducibility, uniformity and reliability must be addressed. Although major strides have been made in understanding the behaviour of engineering ceramics, the successful introduction of ceramic components into gas turbine engines requires a comprehensive mechanical property database to be established to enable the development of both 'zero-time' (athermal) and time-dependent behavioural models.

The high stiffness, damage intolerant behaviour of ceramics, coupled with the requirement for testing at very high temperatures, poses particular problems in the development of test methods for these materials.

2 POTENTIAL APPLICATIONS IN GAS TURBINE ENGINES

2.1 Design goals

Since the introduction of the gas turbine engine, there has been a continuing demand for improvements in performance. For military engines the major objective is increased thrust to weight ratio and improved fuel efficiency. Over the last 45 years, thrust to weight ratio has increased from 3:1 to 10:1 with concurrent increases in turbine inlet temperature from 800°C to 1400°C (Table 1). These improvements have been made possible by weight reduction through design, the use of light-weight alloys and the introduction of nickel based superalloys with sophisticated turbine blade cooling techniques. The thrust to weight ratio target in the year 2000+ of 20:1 can only be achieved by employing turbine entry temperatures of 2000°C+.

TABLE 1
Development of Aero Engine Requirements

	1940	*1987*	*2000+*
Thrust/weight	3:1	10:1	20:1
Compression ratio	4:1	30:1	40:1
Turbine entry temperature (TET)	800°C	1400°C	2000°C

The thermal efficiency curves in Fig. 1 show that the target cannot be achieved by increasing the pressure ratio alone.

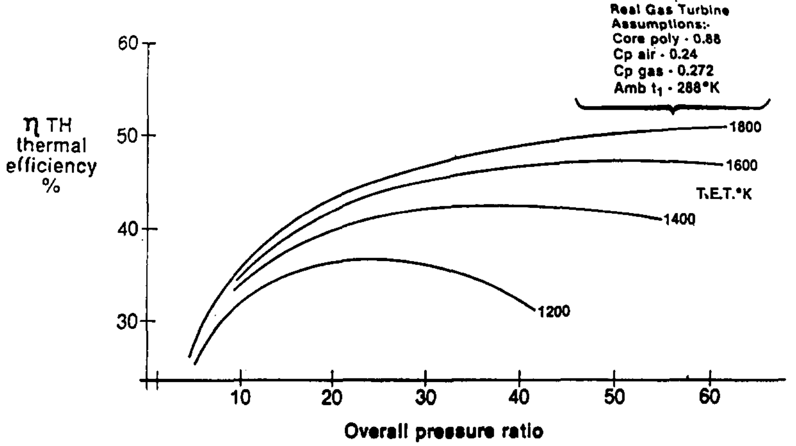

Fig. 1. Effect of cycle pressure and temperature on thermal efficiency.

Future requirements for increases in turbine entry temperature can be met either by increasing the amount of cooling air from the current figure of about 20% or by introducing uncooled ceramic components. Since there is an increasing penalty in efficiency by providing progressive amounts of cooling air to maintain the surface temperature of metallic components at well below their melting temperature (~1300°C), there is a drive towards the introduction of ceramic components into engines with the design capability required in the year 2000+ (Fig. 2). The goals are: high thrust to weight ratio; improved fuel consumption; reduction in first costs and maintenance costs and longer life.

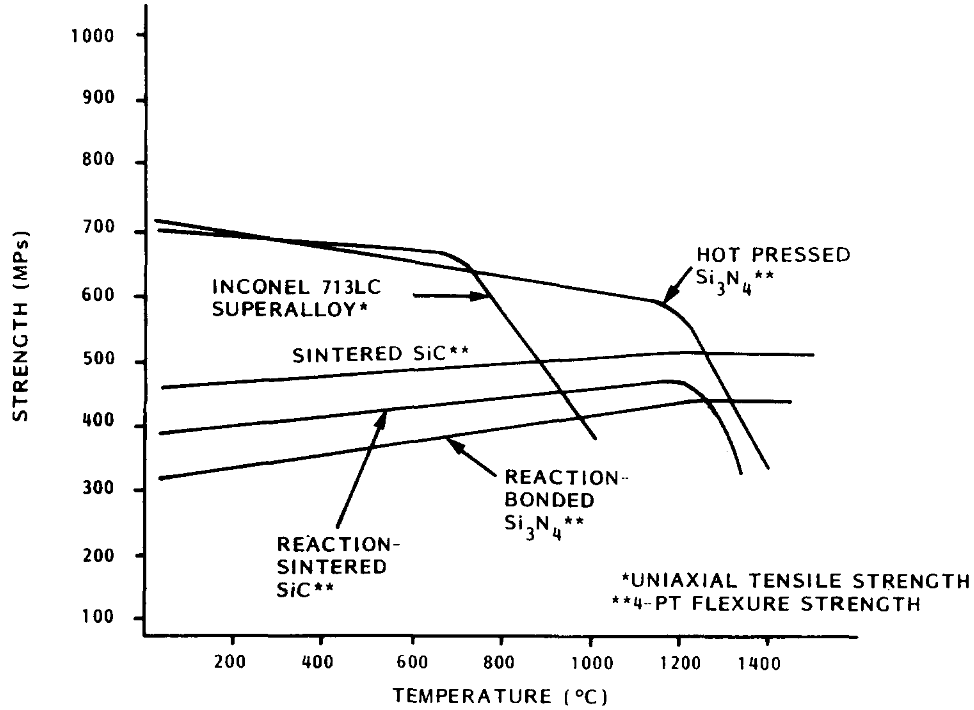

Fig. 2. Strength of ceramics and nickel based superalloys.

2.2 Ceramic material requirements

A wide variety of silicon-based ceramics have emerged in recent years which have potential applications as components in gas turbine engines. Silicon nitride and silicon carbide in their various forms are the most promising candidates for near-term applications. The available materials represent a large family with wide property variations and different responses to the gas turbine environment. The property differences between materials of a particular type arise out of differences in purity, microstructure, phase differences, contamination and structure stability (Larsen *et al.*, 1985).

Although these materials have superior high temperature properties to nickel super-alloys, the brittle and unpredictable behaviour of these materials has prevented their widespread introduction into critical areas of the gas turbine engine. Two different approaches can be taken to address these problems. The first is to combine improvements in processing techniques to reduce strength-limiting flaws caused by impurities, inclusions and pores, together with the use of statistical methods to predict probabilities of survival in any given application.

The flaw-sensitive nature of these materials can be ameliorated to some degree by the incorporation of toughening second phase materials (Schioler & Stiglich, 1986), however the goal of total flaw insensitivity can only be achieved by the use of continuous fibre reinforced ceramic matrix composite technology (Davidge, 1986).

Recent work at UTRC (Prewo *et al.*, 1986) has demonstrated the viability of this approach but as yet there are no fibres available which have the necessary temperature capability to exploit this technology to the full.

In summary, the material requirements are the ability to withstand stresses at high temperatures in hostile environments for extended periods of time whilst maintaining a tolerance of existing or newly created defects.

2.3 Components

There is potential for the widespread use of ceramic components in the hot section of a gas turbine engine. The final choice of component will depend on a combination of factors including design payback, probability of success, difficulty of manufacture and effect of failure on downstream components. The components comprising the hot section can be grouped on a generic basis into combustion, static and rotating aerofoils, shrouds, reheat and exhaust components.

2.3.1 Combustor components

The long-term objective is to maximise efficiency by burning the fuel stoichiometrically. This will entail very high component temperatures without the benefit of cooling air. The solution to this problem will lie partly in design and partly in material development.

The material requirements are low thermal conductivity, thermal shock resistance, erosion and corrosion resistance. The mechanical stresses are likely to be low, consisting mainly of combustion gas pressure and attachment stresses. In the short term, the need is likely to be satisfied by non-structural fibrous insulating tiles supported on a structural backing.

Ultimately, self supporting hybrid structures composed of dense load-bearing and fibrous insulating materials will be required.

2.3.2 Rotating aerofoils

Rotating turbine blades experience high mechanical and thermal stresses coupled with erosion and corrosion in a hostile environment: the demands on these components are consequently very high. They must be resistant to creep, thermal shock, erosion, corrosion/oxidation, cyclic fatigue, vibration and impact. Preferably they should be of low density, so as to minimise centrifugal loading on both the blades and the disc. These components are so critical to the engine that it is unlikely that a monolithic ceramic material will satisfy all these demands and the development of some form of composite ceramic will be necessary.

2.3.3 Nozzle guide vanes (NGVs)

In contrast to the rotating aerofoils, NGVs only experience mechanical stresses due to gas loading and contact stresses at attachment points (Fig. 3).

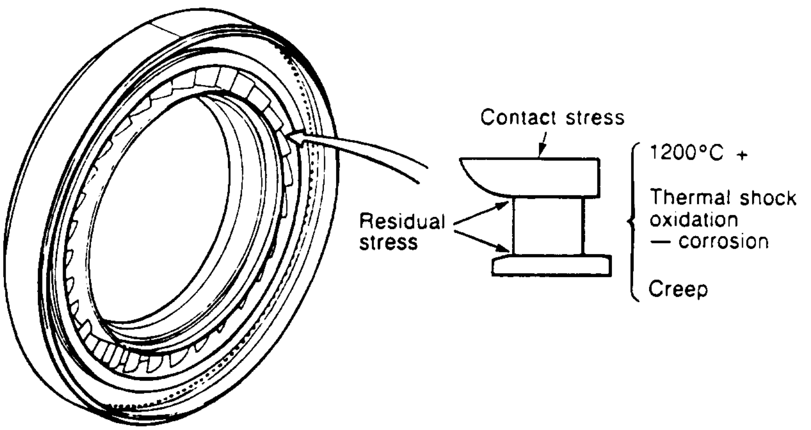

Fig. 3. Nozzle guide vane environmental considerations.

The major requirements for this component are thermal shock resistance, thermal cycling resistance, oxidation, corrosion and erosion resistance and impact resistance. Again, this is a critical component in the engine and failure could have severe consequences for components downstream. Consequently a composite ceramic approach to this component is also required.

2.3.4 Shroud rings

A source of efficiency-loss in turbine engines is the leakage of gas past the tip of the turbine blades. To reduce these losses, a shroud ring is fitted which controls the gap between the static casing and the rotating blades. The replacement of the metal component by a ceramic one has several advantages. The low thermal expansion coefficients of engineering ceramics allow better control of the tip clearance. The materials have a higher uncooled temperature capability than their metal counterparts and are more erosion resistant. The major concerns are thermal shock resistance, corrosion resistance and the ability to withstand impact from foreign object damage (FOD). The replacement of a metal shroud ring by a ceramic one in a helicopter demonstrator engine resulted in an improvement in SFC by over 2% simply by improved tip clearance control (Benger, 1986).

2.3.5 Re-heat components

Re-heat is a method of augmenting the thrust of a turbine engine by burning fuel in the exhaust section and utilising the oxygen from unburned cooling air to support combustion. In order to stabilise the flame, an eddy-current generator is placed in the combustion region. This component is known as a flame holder and can be in the form of an annulus or a series of radial fingers (Fig. 4). It has to withstand quite severe thermal shocks since the

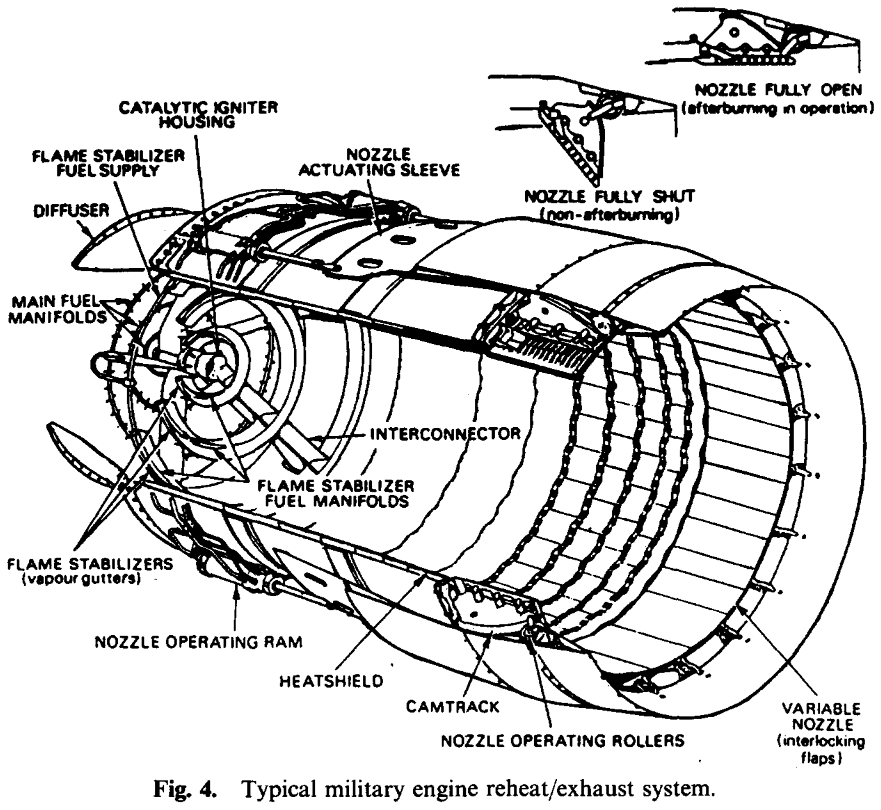

Fig. 4. Typical military engine reheat/exhaust system.

temperature rise once the re-heater is switched on is very rapid. The mechanical loads are quite low, with contact and bending stresses being the most severe.

Apart from thermal shock resistance, the major requirements are for oxidation/corrosion resistance, impact and erosion resistance and the ability to withstand high frequency vibrations induced by the combustion process.

2.3.6 Exhaust components

These consist of the exhaust cone, the jet pipe and the nozzle. Currently, the gas temperatures encountered in this section are between 550 and 850°C, rising to 1700°C in the re-heat mode. The metallic components are air-cooled and there are significant gains in efficiency to be made if this cooling air can be eliminated.

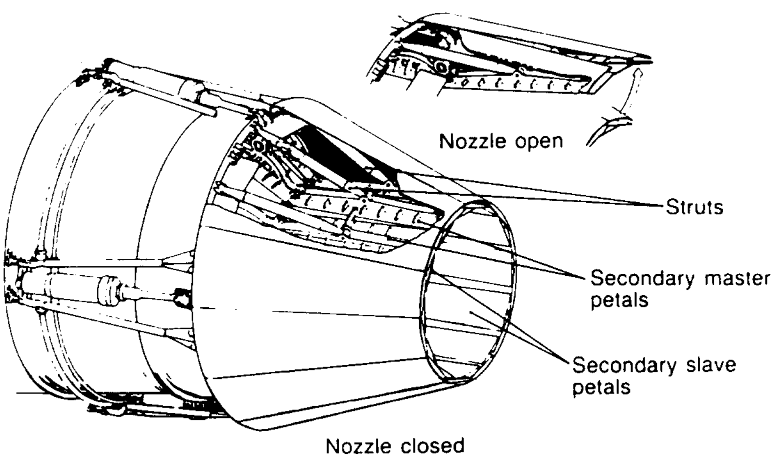

Fig. 5. Convergent/divergent nozzle.

The exhaust temperature in stoichiometric burning engines is likely to rise to 1850°C. A prime function of the jet pipe is to insulate external components from the exhaust so that in order to eliminate cooling air, the jet pipe material must be insulating. Since the structure is load bearing to some degree, it must also be relatively strong and stiff. These partially conflicting requirements could be met by employing hybrid structures consisting of a dense lightweight backing coupled with a low density fibrous insulating layer covered with hard dense skin to provide erosion resistance.

The variable exhaust nozzles also have to withstand fretting and abrasion as the elements slide over each other during operation (Fig. 5).

3 DESIGN METHODOLOGY

One of the prerequisites for the successful introduction of ceramic components into gas turbine engines is the development of design methodologies which will result in the ability to predict the behaviour of components in service. There are two major factors involved in the development of such methodologies: they are the statistical nature of the 'zero time' (athermal) failure criteria and an understanding of the mechanisms of time-dependent failure phenomena such as creep, stress rupture, stress corrosion and the generation of new defects.

To date, design studies carried out on gas turbine components have involved the fast fracture data only. An example of this approach has been reported in the CATE programme publication *Ceramics Applications in Turbine Engines* (Helms *et al.*, 1986). The techniques developed during this programme consisted of combining 2&3D finite element stress analysis on specific components with linear elastic probabilistic analysis using measured material properties in test bar form to arrive at an estimate of the survival probability of the components in service. At the heart of these techniques is the need for reliable duty cycle data to enable the accurate computation of thermal and mechanical stresses coupled with reliable mechanical property data on well characterised and reproducible material. In order to develop the capability to life ceramic components adequately, realistic models of time-dependent processes such as creep and sub-critical crack growth must be developed and incorporated into the design model.

4 TESTING REQUIREMENTS

The testing of engineering ceramics fulfils two major requirements. The first is for materials development; that is the generation of data to allow material systems to be optimised in terms of chemistry, microstructure and properties. Secondly, there is the generation of a material property database which will allow predictive models to be developed and the generation of data for design purposes. Because of the diverse needs of these requirements the approaches used can be quite distinct from each other.

4.1 Materials development testing

The material property feedback loop is a vital element of material development. The main requirement here is for the test method to be able to pick up trends in a series of materials so that optimisation for any particular application can be accomplished. In the past, the main test method for engineering ceramics has been modulus of rupture (MOR) testing in a three- or four-point bend. This method can be used over a range of temperatures and on a comparative basis to chart material improvements. The essence here is the speed with which data can be generated and fed back into the development system.

Clearly MOR is not the only property of interest. Other techniques which might be described as aids to material development include measurement of fracture toughness, hardness, wear resistance, creep resistance, static fatigue (sub-critical crack growth) and oxidation/corrosion resistance. The main feature of all these techniques is the relative ease with which fairly unsophisticated data are generated to serve as a coarse sieve for optimising or choosing materials with fairly widely differing properties.

4.2 Database generation

In contrast to the above, the generation of database properties must be much more accurate and must not only reflect intrinsic material properties but also take account of the turbine engine environment. Figure 6 shows the range of environmental factors which must be considered when designing tests for lifing/design database generation. To life this component adequately in terms of both 'zero-time' and time-dependent failure criteria, the materials response to both static and dynamic loading over a range of operating temperatures and stresses in a corrosive environment must be accurately known.

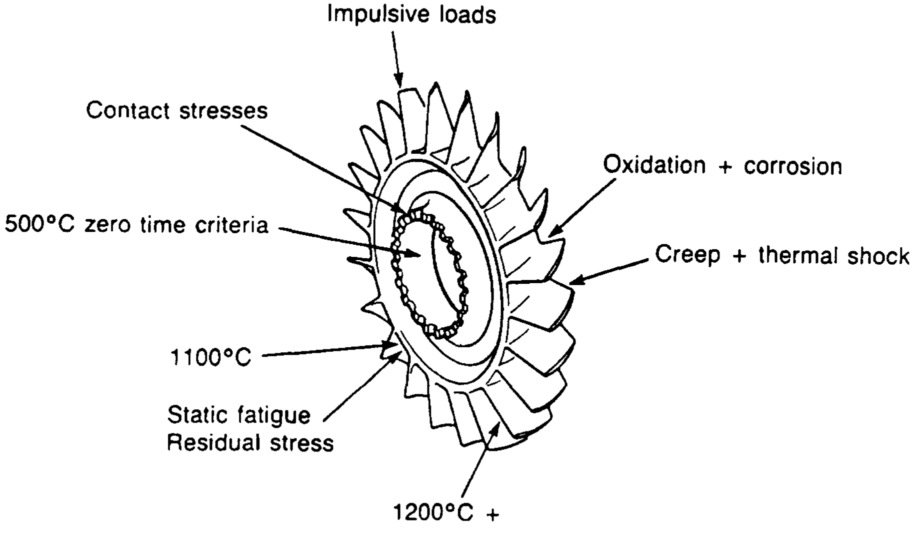

Fig. 6. Environmental considerations for a ceramic bladed disc (BLISC).

The main requirements for the generation of reliable data are that the material be consistent from batch to batch and that the test techniques developed are capable of providing reproducible data. The difficulties in achieving reproducible results with ceramic materials are not trivial. The high stiffness, brittle behaviour of the materials means that measuring true uniaxial properties without introducing secondary bending stresses is difficult. An additional problem is the difference in response to mechanical/thermal stress between essentially isotropic monolithic ceramic materials and highly anisotropic continuous fibre reinforced ceramic matrix composites. The fact that these materials are intended to operate at very high temperatures has been the driving force for the development of test equipment capable of operating at temperatures up to 1600°C. The difficulty in maintaining constant temperatures often over long periods of time is compounded by the need to measure small strains accurately at these temperatures.

Finally there is a clear need for the development of international standards for testing ceramics so that published data can be reliably used for design and lifing of ceramic gas turbine components.

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