CERAMICS IN GAS TURBINE ENGINEERING

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The strength and oxidative stability of ceramics are maintained far beyond 1000 degrees C and have always interested gas turbine designers. Their brittle fracture behaviour, however, is a severe problem which has limited designers to the use of metallic alloys which, although not always stronger than ceramics, possess some measure of ductility which reduces their liability to catastrophic cracking, or failure in impact or under other types of stress concentration loading (Ref. 1).

Cast metallic alloys with little ductility have been used successfully now for some years in engines, and combined with current tendencies to improve efficiency by higher temperature operation, and the associated penalties of cooling of structural members, have led to a re-appraisal of the possibility of using ceramics in gas turbines. Among others, the Ford Motor Company in the U.S.A. has become interested in the use of silicon nitride and other ceramics in gas turbines (Refs. 2, 3 and 4), and designs of ceramic turbines have been proposed (Refs. 5 and 6).

Among ceramic materials, silicon nitride, Si_3N_4, is outstanding (Refs. 7 and 8), because of its low thermal expansion coefficient (c.2 $\times$ 10^{-6}/degree C), only bettered by silica (which, however, may undergo deleterious phase changes in thermal cycling). This ensures a good performance in thermal shock environments. Silicon nitride is stable up to 1700 degrees C, above which it begins to decompose significantly, the N_2 rising to 1 atmosphere around 900 degrees C. It has good strength, even at elevated temperatures, and adequate oxidation behaviour. This desirable combination of properties is further enhanced in the case of 'reaction sintered material' by a fabricability (Ref. 9). Firstly, when made by reaction bonding silicon powder in nitrogen at high temperatures, it can be machined while only ten per cent reacted and soft to precisely the dimensions and shape required, which are maintained to within 0·1 per cent on further nitridation to the hard strong ceramic. Secondly, the absence of firing shrinkage or warpage simplifies the construction of large or complex shapes; and thirdly, processes have been developed which allow silicon powder compacts and Si_3N_4 shapes to be joined, both unusual capabilities in ceramic materials. Several fabrication routes have been developed for a variety of shapes and textures of compacted silicon powder, and these include isostatic pressing, flame spraying, dough-moulding, slip casting and foaming (Ref. 9).

These yield materials with densities up to $2{\cdot}8 \times 10^3$kg/m^3 (theoretical 3·18), which have various amounts of void fraction. In another form of the material, hot pressed silicon nitride, the full theoretical density is achieved and exceptional strength values, up to 1250 MN/m^2 (c. 180 000 lbf/in^2) have been obtained. This last material would be more widely used but for the difficulty in hot pressing silicon nitride powder in carbon dies at about 1600 degrees C to complex or precise shapes, which makes it a costly procedure; and some difficulties also exist with poor high temperature strength and variability in strength, but these will probably be resolved. The volume cost of reaction-bonded material as compared with nickel alloys is probably only about 50 per cent greater, and with increasing utilization and more economical processing, is certain to fall substantially below £10 per lb. An attractive feature of such ceramics is their low density, similar to aluminium, which might be very important in the design of lift engines for helicopters and VTOL aircraft.

All of the hot components of the gas turbine are candidates for the employment of silicon nitride ceramics. The possibilities for combustion chamber structures have been reviewed (Ref. 10) and useful experiences within an 8-inch diameter 'colander' combustion flame stabilizer in Rolls-Royce's Bristol facilities recounted by Godfrey and Taylor (Ref. 11) have been extended by slitting the shape to reduce thermal stress effects with very encouraging results at a combustion gas mean temperature of 1910 degrees K. Experiences with the development and testing of nozzle guide vanes employing a compressive type fixture have been encouraging (Ref. 11), although only simulated engine testing of the blade shapes was used. These studies, while promising, demonstrated that thermal stress and mechanical stress distribution were important factors and would require adequate design consideration and analysis for ceramics to be used with success. Another problem which is somewhat more intractable is impact damage by debris ingested into the turbine, or produced within it by scaling or sooting. Some kind of filtering or centrifugal separation of such projectiles may avoid this difficulty, which in the case of metallic blades sometimes only causes cratering of the ductile blade surface, whereas in brittle materials there is a very much greater tendency for cracking to spread catastrophically from the impact's local stress concentration.

If extended surface matrix heat exchangers are used to improve thermal efficiency, a likely development already being examined in automotive gas turbines, some degree of filtering is afforded, but not without the risk of some damage to the heat exchanger.

The area of rotary regenerative heat exchangers is one in which ceramics, such as the Corning devitrified glass ceramic material, have already been investigated over a period of years by Leyland (ex-Rover) Gas Turbines Ltd., with promising results. As the upper temperature limit of these glass-ceramic materials is around 1000 degrees C there would be great value in the use of extended surface matrix silicon nitride material. Such forms are currently the subject of development and at the Admiralty Materials Laboratory and elsewhere plastic-bound silicon processes have been developed to yield thin Si_3N_4 film matrices. At the AML a dough-moulding/rolling process has been used to yield flexible ribbons of silicon powder compact in thicknesses down to 75μm (0.003 in.) which can be wound and nitrided to produce the required matrix configuration. The upper use of temperature of such a matrix is likely to be conditioned by the oxidation behaviour of thin silicon nitride layers, and the small but appreciable expansion coefficient also makes gas sealing a little more complex.

Another area of potential usefulness is tribology. Silicon nitride bearings (Ref. 12) are attracting attention because of their good performance in hot corrosive environments such as sea water (Ref. 13), and are of potential value in hot situations. Their use up to temperatures of 900 degrees C unlubricated has shown it to be possible (Ref. 12) and they have also been demonstrated to be attractive materials for gas bearings (Ref. 14). At the AML a small Si_3N_4 fan has been operated at temperatures over 1000 degrees C for long periods on a Si_3N_4 journal employing a simple 8-hole (406 μm, 0·016 in.) distribution of air at c.50 kN/m^2 (0·7 lbf/in^2) from the journal, an annular clearance of c. 60μm and an unfinished (rough) as-nitrided surface finish. There is undoubted potential for the use of silicon nitride in gas turbine bearings, where the need to avoid overheating of oil lubricated bearings is often a restricting factor in design.

Notwithstanding the promise of some of these developments, the brittle fracture behaviour of these materials requires sophistication and intelligence in design, combined with a feeling for the problems in designing with brittle materials. While stress concentrations may be a source of failure if their existence is not appreciated or their magnitude is underestimated, postive advantages exist in the high compressive and temperature strength behaviour of ceramics. Work at the Fulmer Research Institute has shown that the unusual variability in strength of ceramics is much less marked in reaction-bonded Si_3N_4 materials, and safety factors of less than 3 may be acceptable. For design with ceramic materials to be improved, thermomechanical stress analysis of components needs to be studied in detail with regard to thermal stress concentration problems, the former being important because of the relatively poor thermal conductivity of reaction-bonded silicon nitride. Improved knowledge of relevant mechanical properties such as creep and fatigue need to be developed. In fatigue tests at room temperature, and over 10^8 cycles, work at the AML has suggested that the performance of Si_3N_4 ceramics can be superior to that of metals (0·7 of UTS), but nothing is yet known about high temperature behaviour. Structural compositional factors affect mechanical properties, and need to be investigated in material characterization studies.

Finally, it may be said that all hope has not been lost of useful developments in the most basic and difficult engineering problem with ceramics: that of brittle fracture. Composite materials appear on the basis of current work at the AML, with the reinforcement of silicon nitride ceramics with high strength fibres, to be exceptionally easy to produce, and recently some indications of toughening have been seen in our experimental work with Si_3N_4 containing SiC/W fibres (overall diameter 75–100μm) produced by Fuller Research and Development under AML contract. In a few experiments, the incorporation of SiC fibres appeared to have restricted the facile propagation of cracks typical of brittle material, and the stress/strain curve resembled that of a ductile metal, with appreciable area underneath it. The advent of such encouraging developments in engineering practice is at least several years away, and much work needs to be done on optimising this process to yield useful engineering materials, but it affords a promise of help in problem areas to those exploring the promising but difficult field of high temperature engineering with ceramic materials.

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