Ceramics (II): Making Gas Turbines from Brittle Materials

Silicon nitride and silicon carbide ceramics used as structural materials could reduce both the energy consumption and pollution emissions of gas turbines. Heat engines made from these ceramics could run at higher temperatures than engines made of even the most exotic high temperature alloys presently available, and fossil fuels could be more efficiently burned than at present. During the last 15 years researchers have learned how to make these ceramics and then have improved them. On the basis of this knowledge, programs are now under way both in the United States and in Europe to demonstrate the use of silicon nitride and silicon carbide in operating gas turbines for highway vehicles, stationary electrical power generators, and remotely piloted aircraft.

In 1971 the Advanced Research Projects Agency (ARPA) began a multimillion dollar program under the direction of Maurice Sinnott (now at the University of Michigan, Ann Arbor) that was designed to leapfrog from the 1100°C maximum operational temperature possible with alloys to about 1370°C, through the use of silicon nitride or silicon carbide ceramics in operating gas turbines. According to Sinnott, at least three factors, in addition to the advancing state of the art, made the silicon-based ceramics look attractive: the possibility of operating at higher temperatures; the ready availability of silicon, carbon, and nitrogen as compared to the need to import elements used in high temperature alloys, such as nickel, cobalt, and chromium; and the prospects for low costs, especially of raw materials.

Ford Motor Company, Dearborn, Michigan, is the prime contractor for the ARPA turbine program, which is somewhat innocuously titled "Brittle Materials Design." Ford has as its goal an automobile-sized 200-horsepower (150-kilowatt) turbine in which all the hot flow path components will be made from ceramics. Hot flow path components include the combustor, nose cone, first and second stage stators and rotors, and regenerator. The demonstration turbine is to operate at temperatures up to 1371°C in the hottest part of the engine over a 200-hour duty cycle, which includes cold starts and rapid shutdowns. The latter two situations are conducive to thermal shock, a condition whereby rapid temperature changes cause ceramics to fracture.

Now in the fourth year of the program with two more years to go, the Ford team headed by A. F. McLean has succeeded in running a ceramic turbine for 100 hours at a maximum temperature of 1050°C. Metal rotors were used in the tests and were responsible for the temperature limitation.

No single ceramic is likely to be best for all the turbine components. Thus, the Ford engineers, while concentrating on silicon nitride, are looking at both reaction bonded and hot-pressed versions (*Science*, 28 March, p. 1185). The reaction bonded silicon nitride is especially important because of the possibility of fabricating complex shapes at low cost.

Because one cannot simply replace a metal part with the same part made from a ceramic, a major portion of the Ford effort has been devoted to designing the turbine so that the good properties of the silicon nitride will be incorporated and the bad aspects will be avoided. Fabrication methods have also had to be developed. For reaction bonded silicon nitride parts, injection molding (a process common in the plastics industry) and slip casting (a traditional ceramic process) have both been used. Ford has managed to increase the density and hence the strength of parts made by these methods. In the past, a difficulty has been that, if the powder shape is too compact, then the nitrogen cannot reach and react with all the silicon.

Bonding Rotors a Problem

The major problem has been with the rotors. Because the highest stresses are in the rotor hub, it has been made from hot-pressed material, which is denser and stronger than reaction bonded. The rotor blades, however, have been made from reaction bonded silicon nitride because it has superior creep resistance at high temperatures, and higher temperatures are encountered by the rotor blades than by the rotor hub. Work is under way to solve the problem of achieving a combination of strength, precise alignment, and freedom from defects in the bonding between the hub and the blades.

Westinghouse Research Laboratories, Pittsburgh, Pennsylvania, is a subcontractor to Ford and is charged with developing ceramic nozzle guide vanes (first stage stator) which will withstand 1371°C in a 30-megawatt test gas turbine. The eventual turbine will likely be a hybrid of metal and ceramic parts, with the combustor, first stage stator vanes, and first stage rotor blades being made of ceramics and the remainder from metals, according to R. J. Bratton, manager of the Westinghouse project. A possible application of such a turbine would be in a combined cycle power plant. The gas turbine serves as a first stage power generator whose hot exhaust gases are used to heat steam in the boilers of a second stage steam turbine generator.

A turbine of this size has a stator diameter of about 1.5 meters, as compared with perhaps 15 centimeters in an auto-sized turbine. The large size makes it uneconomical to test very many times, in part because of the high fuel costs. As a result, Westinghouse has placed a great deal of emphasis on theoretical modeling of stresses and heat transfer in the ceramic vanes and less on actual testing.

Both silicon carbide and silicon nitride are being investigated in parallel. The hot-pressed version of each is needed because of stringent materials requirements that cannot be fulfilled by reaction bonded ceramics. There is some evidence to indicate that silicon nitride is superior to silicon carbide for the turbine application, although less engineering data is available on the latter.

In a recent test at 1371°C, dramatic confirmation of the apparently superior toughness under impact of hot-pressed silicon nitride was obtained when an accident caused the temperature to rise to 1600°C and then fall to 315°C within seconds. The metal combustor basket in the test rig had failed and pieces of the basket impacted the silicon nitride and silicon carbide stator vanes being tested. Afterward, it was found that the silicon nitride vanes had survived intact, whereas the silicon carbide vanes (already cracked due to thermal shock) were destroyed.

The ARPA ceramic turbine program has contributed to a revival of interest in ceramics as structural materials. A consortium of (mainly) Department of Defense agencies is now working on turbines for remotely piloted aircraft. A program similar to the ARPA project is under way in Germany. It would thus seem that interest among all parts of the research community is sufficient to make ceramics succeed if it is at all possible.—Arthur L. Robinson