unique composite, fabricated using both vapor-liquid-solid and vapor-solid silicon carbide whiskers, exhibits a 100% increase in room temperature strength and a 30% increase in fracture toughness. The elevated temperature strength of this composite is 300% greater than that of nonreinforced molybdenum disilicide.

These unique alloys are already finding several applications in the energy technology field. In fact, use of whisker-toughened alumina for machine cutting tools has already gained widespread industrial acceptance and should dominate the market in the near future. Sales of industry products, including cutting tools, gears, wear parts, and other items, is estimated at $25 million for 1995.

Ceramic Surface Modifications

Ceramic materials fail catastrophically because of the growth and propagation of defects, particularly cracks initiated at free surfaces. Surface modification techniques can reduce the size and number of defects and provide a secondary phase in the ceramic matrix that can absorb the crack propagation energy.

DOE-funded research has established that ion and laser surface modifications are capable of arresting surface-initiated crack propagation, thereby significantly increasing the strength and reliability of ceramics. An increase of about 40% in the fracture toughness of silicon carbide was achieved by laser treatment of nickel deposited on the ceramic surface. Implanting partially stabilized zirconia with aluminum ions, followed by annealing, results in a 70% increase in fracture toughness and a 30% increase in microhardness. The development of tougher ceramic materials using these surface modification techniques may permit the substitution of ceramics for metals in many end-use applications at elevated temperatures, at high-stress levels, and in oxidizing environments.

Ceramic Joining

The potential for structural ceramics in advanced energy-conservation applications has not been realized because little research has been conducted on the joining of ceramics. In 1982, DOE decided to fill this gap by initiating long-term, applied R&D in the area of ceramic attachments for high-temperature applications. Subsequent research defined the current limits of room-temperature strengths of brazed ceramic/ceramic joints.

Brazes were developed for silicon carbide and alumina with acceptable room-temperature strengths and toughness. The brazes will allow ceramic components to be used economically in large operational systems such as high-temperature heat engines and heat exchangers or in any other application requiring resistance to high temperatures, stresses, or oxidizing atmospheres. This project was transferred to other DOE programs for subsequent applications development.

In a complementary effort, highly refined, finite-element mathematical models were developed to obtain an understanding of stresses and fracture mechanisms in ceramic/metal joints. These models were validated experimentally for rectangular and cylindrical joint geometries, and a three-point flexure test geometry was developed to experimentally validate adhesion models for zirconia/nodular cast-iron braze joints. This research was transferred to the DOE Ceramic Technology for Advanced Heat Engines Project for further applications development.

Magnetic Resonance Imaging for Advanced Ceramics

Processing of the high-performance, high-temperature structural ceramics planned for use in advanced heat engines requires a much greater level of understanding than has been achieved to date. Part of processing science is the development of practical, nondestructive evaluation methods to identify problems at the earliest possible stages. One such method with the potential to affect processing science is magnetic resonance imaging, a chemically sensitive, noncontacting, nondestructive technique.

DOE funded a project to study the potential of this imaging technique to directly map the distribution of organic binders and plasticizers used in injection molding processes and of porosity after the binder/plasticizer has been removed (i.e., dewaxed). Because the polymeric organic binder/plasticizer used contains a high concentration of protons, it was an excellent candidate for magnetic resonance imaging. It was shown that this technique can be used to directly image distributions of organic binders/plasticizers as used in injection molding and in image-porosity distribution if a carefully selected filler fluid is used with a proper infiltration procedure. Follow-on work with the technique is currently under way by the DOE Ceramic Technology for Advanced Heat Engines Project.