PERSPECTIVES: MATERIALS SCIENCE

Toughened Ceramics

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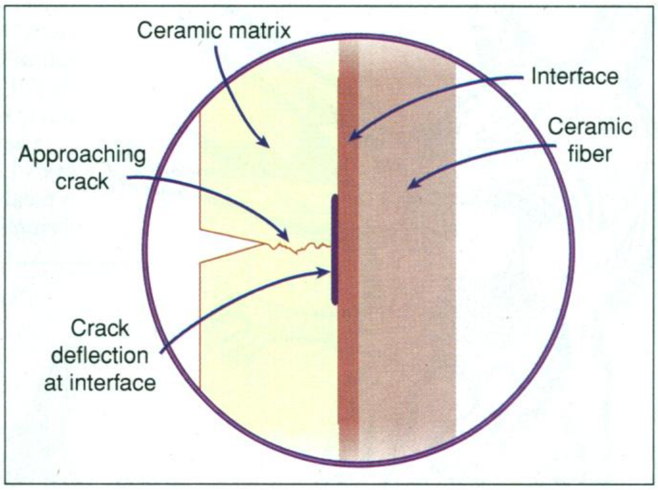
Because of their durability, ceramic materials are traditionally chosen for commonplace applications such as dinnerware, architectural glass, automotive windshields, kitchen and bathroom tile, and substrates for electronic packaging. Most of these ceramic materials are based on oxide compositions, and in fact there is a large manufacturing base specifically devoted to the cost-effective production of these traditional ceramics. Currently, nonoxide ceramic materials, based primarily on silicon carbide and silicon nitride compositions, are being investigated for aerospace and industrial applications where there is a need for combined high-temperature capability, moderate strength, good wear resistance, and high thermal conductivity. As reported on page 1295 of this issue, Ishikawa *et al.* (*1*) have started to address one of the most serious limitations of ceramic materials: low fracture resistance.

The relatively low fracture toughness of monolithic ceramic materials, which leads to very low damage tolerance and essentially brittle fracture behavior, has long been a major concern. One approach that has been used to alleviate this problem is the incorporation of long ceramic fibers within a matrix of silicon carbide as a means of reinforcing the silicon carbide, creating a composite of two or more dissimilar materials. This is similar in concept to the reinforcement of a plastic matrix with glass fibers in Fiberglas. Ideally, as cracks form in the silicon carbide matrix and approach the fibers, they will be deflected at the interface between the fiber and the matrix, thereby halting their propagation (see figure). The critical feature controlling the toughness and long-term durability of the composite is the nature of the fiber-matrix interface. The development of an ideal interface continues to be the subject of intense research.

Another approach toward improving the toughness of ceramics involves the creation of a textured internal structure within the ceramic material itself, similar in some respects to the fibrous structure of wood. The silicon carbide material described by Ishikawa *et al.* (*1*) is an example of such an approach. This concept is fundamentally different from that described previously, in that it is extremely difficult to distinguish separate "fiber" and "matrix" phases in the traditional composite sense. The toughness of the material in this case derives from the tremendous amount of interfacial surface area created within the internal structure through the close packing of the individual silicon carbide filaments. This attempt to mimic nature in some sense may be a more fundamentally stable approach toward creating toughened ceramic materials. Ishikawa *et al.* have created a silicon carbide–based ceramic material that is strong and tough up to temperatures exceeding 1400°C, while also demonstrating high-temperature thermal conductivity substantially higher than other toughened silicon carbide ceramics.



Fracture stopper. Cracks that initiate in the brittle ceramic matrix encounter the interface material separating the fiber from the matrix. In a tough ceramic composite, the matrix crack is deflected at the interface and ceases to propagate, allowing the composite to continue functioning in a structural sense.

The toughened silicon carbide ceramic materials being developed are candidates for such demanding applications as gas turbine engine hot section components, where their high-temperature capability, high thermal conductivity, and low density make them very attractive for replacement of heavy metal superalloy components. For land-based turbines used for power generation, the possibility of running at higher gas temperatures offers the potential for improved efficiency and reduced emission of combustion by-products such as nitrous oxides that can be harmful to the environment. For aerospace gas turbine engines, the opportunity to realize these same benefits as well as to substantially reduce the weight of the engine makes these toughened silicon carbide materials doubly attractive. Commercial and industrial applications that can benefit from the high-temperature capability and hot corrosion resistance of toughened silicon carbide ceramics are also being investigated. Examples of such applications include hot gas candle filters for coal-burning power generation systems, reverberatory screens for porous radiant burners, and immersion heater tubes for molten aluminum furnaces (*2*). These commercial and industrial applications have been the focus of a 10-year initiative to increase the application of continuous fiber reinforced ceramic composites begun in 1992 by the Office of Industrial Technologies, U.S. Department of Energy.

However, there are several issues that need to be addressed before widespread use of these toughened silicon carbide materials can be realized. One of these is the high cost of manufacturing. The factors affecting this high cost are many but are primarily due to the limited number of applications as well as the large fraction of the manufacturing process that requires substantial human labor in the form of setup by hand. As the market develops the need for a larger number of applications requiring the unique properties of these materials and as more automated processes are incorporated into the manufacturing process, the cost should drop considerably. Another serious issue is the lack of a validated design system that can be used in the design of toughened silicon carbide ceramic composites that exhibit an extreme degree of reliability. Also, the experience base in the design and use of these materials is still in a very early stage. Until more success stories are realized, the implementation of toughened silicon carbide ceramic components in real applications will be a slow process.

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References

1. T. Ishikawa *et al.*, *Science* **282**, 1295 (1998).
2. V. P. McConnell, *High-Performance Composites* (March-April, 1996), p. 27.