PERSPECTIVES: MATERIALS SCIENCE

Controlling Cracks in Ceramics

William J. Clegg

From bricks to dental implants to protective tiles on the space shuttle, ceramics are prized for their resistance to heat, corrosion, and wear. But ceramics also break easily, and the maximum stress they can withstand varies unpredictably from component to component. Efforts to control their brittleness and reduce the variability in their strength are now paying off. The most promising new approaches use layered materials, which control cracks by deflection, microcracking, or internal stresses.

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Ceramics break easily because dislocations do not move as rapidly in these materials as they do in metals. This limits the amount of energy that can be dissipated ahead of a growing crack by plastic flow, resulting in brittle failure. Efforts to influence the dislocation speed by doping have produced only minimal improvements (*1*). The strength, that is, the stress that is required to break a ceramic component, is determined by the size of the largest flaw in the material (*2*).

Flaws in ceramics develop during their fabrication and while they are in use. Ceramic components are generally made from ceramic powders that are heated to form a continuous, polycrystalline material; this process is referred to as sintering. However, agglomerates of primary particles (*3*) give rise to flaws in the powder compact that cannot be removed by sintering. In addition, new flaws can develop once the component is in service because of either particle impacts or corrosion.

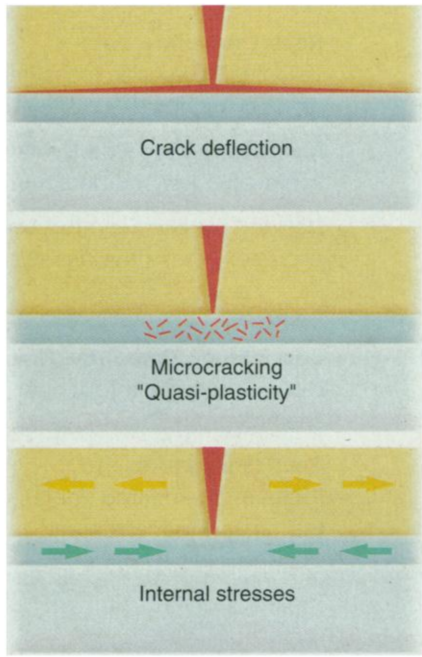
In a typical ceramic such as alumina, flaws about 50 μm in size will result in a strength of about 400 megapascals; for comparison, the ideal shear strength of flawless alumina would be 40 gigapascals. These flaws are too small to be detected unless they are close to the sample surface. The inevitable variability in their size causes a scatter in the strength of individual components. The ceramics designer is thus faced with a component whose strength he does not know; worse, there is no guaranteed lower limit. Currently, he copes with this by measuring the spread in strengths in a batch of samples and estimating the probability of failure at a given stress. The smaller the scatter in the strengths of his samples, the more reliably he can estimate the maximum stress the component can sustain.

The greatest improvements in ceramic strengths have come from modifying the fracture behavior such that the final failure stress is not so strongly dependent on the size of the flaw. This can be done by incorporating strong, thin fibers into the material, where the fracture energy of the fiber-matrix interface is somewhat lower than that of the matrix (*4*). When cracks begin to grow in the matrix, they cannot penetrate into the fibers. The overall strength of the component is then given by the strength of the fibers, rather than the size of the largest flaw (*5*). However, some technical problems still exist with this approach, and the enormous costs associated with both the fibers themselves and the special processing methods required have prevented the widespread application of these materials.

Microstructures containing shorter fibers can be more easily made, most successfully by inducing the growth of elongated crystals within a ceramic (*6*). In materials of this type, such as silicon nitride, relatively small cracks (less than 100 μm or so in size) are stopped by fibers extending across the crack; this reduces the strength variability with flaw size compared with simple ceramics such as alumina. However, above a certain crack length the crack surfaces are too far apart to be held together by the fibers. At this point, the scatter in the strength is the same as in the basic material, although the resistance to the growth of cracks (the material's toughness) is improved.

For these materials to become useful, their toughness must be increased such that they can tolerate flaws of a size that can be easily detected, as in metals. Alternatively, the material must be protected against the growth of the largest flaws. This can be done very simply by making layered ceramics with crack-deflecting interfaces (*7*). In these materials, any crack that starts to grow is deflected at the first interface it meets (see the top panel in the figure); no further cracking will occur until the stresses in the next layer are equal to the failure stress of that layer. The growth of the crack is thus not stopped; it is only deflected along a path of weakness. Such structures have proved particularly effective in withstanding thermal shock, a common application for ceramic materials, but the improvement in resistance to cracking is obtained at the expense of allowing some delamination.

In an effort to prevent delamination, layered structures made up of outer layers of isotropically grown silicon nitride grains and inner layers of elongated silicon nitride grains have been made. It has been shown that cracks in the outer layers do not penetrate into the inner layer of elongated grains. Rather, extensive microcracking occurs in the inner layer, and the larger cracks are arrested (see the middle panel in the figure) (*8*). Such materials are extremely useful in applications requiring wear resistance, where the crack-driving forces are small compared with situations such as thermal shock.



Controlling brittle failure. Different approaches are used to control cracking in layered ceramic structures. Depending on the composition and structure of the different layers, cracks can be deflected at the interface (**top**), arrested by microcracking (**middle**), or inhibited as a result of internal stresses (**bottom**).

If layers of different materials are used, residual stresses develop upon cooling from the sintering temperature at which the materials are produced. If the residual stresses are caused by differences in thermal expansion coefficients between the layers, those with the greater expansion coefficients will be in tension, whereas those with the smaller expansion coefficients will be in compression. The compressive stress inhibits the growth of flaws in the layers that are in compression (see the bottom panel in the figure). This basic idea has been known for more than 100 years and is still widely used in the manufacture of glass. Refinements of

The author is in the Department of Materials, Pembroke Street, Cambridge, CB2 3QZ, UK. E-mail: wjc1000@cus.cam.ac.uk

this principle can be used to give crack arrest in glass under certain conditions (*9*). It has also been used in ceramic layered structures, where it reduces the scatter in the strengths of different samples (*10*).

Recently, it has been suggested that this effect might give rise to a threshold stress for a flaw starting in the tensile layer, resulting in its arrest in the compressive layer (*11*). This effect may become extremely useful, as it appears relatively straightforward to achieve useful threshold strengths of a few hundred megapascals. However, it is essential that this minimum stress does not depend on the direction in which the crack penetrates the interlayer. In their model, Rao and co-workers (*11*) assume that the crack will grow directly across the laminae. In contrast, their experiments show that failure occurs by deflection of this crack at the interface, followed by reinitiation of cracking at a higher stress from a flaw within the next layer. This could be resolved by measuring how the laminate strength changes when flaws are introduced into neighboring tensile layers, reducing their strength below the proposed threshold.

Layered structures such as those discussed above clearly offer the key to greater reliability in ceramics. They are easier and cheaper to make than fiber composites, and a wider range of materials can be used as the requirements for interfaces are less restrictive. New applications may result, particularly as more complex structures are tailored to specific applications.

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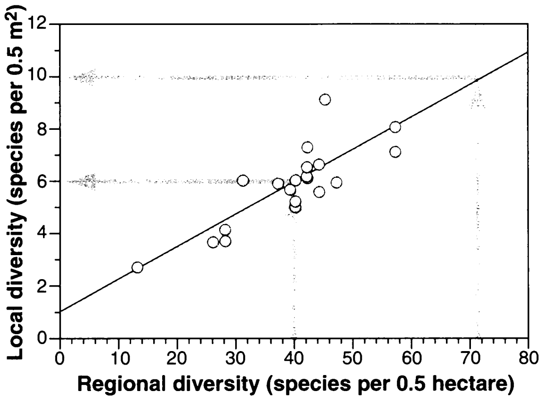
PERSPECTIVES: ECOLOGY

Diversity and Production in European Grasslands

David Tilman

The hypothesis that biodiversity influences the productivity (that is, the rate of biomass production) and stability of ecosystems has recently resurfaced (*1–3*), but it remains contentious (*4–6*). It is unclear whether the purported effect of species diversity on ecosystem productivity is actually the hidden signature of a few important species or whether it implies that species composition is less important than previously thought. Indeed, how can species diversity influence the functioning of an ecosystem, and do such processes operate in nature? Interest in these questions is particularly pertinent given the unprecedented extinction of many species and the reduction in diversity of myriad ecosystems wrought by human actions. On page 1123 of this issue, Hector and 33 European collaborators (*7*) report findings from a unique trans-European study of the effects of plant diversity on grassland productivity that provide answers to some of these questions.

Two mechanisms emerge as potential explanations for the effects of species diversity on productivity. The first, the sampling effect model, is based on the greater probability (given random species selection) that a species will be present when diversity is higher. If those species that are more productive in monoculture (that is, when growing on their own) are also better competitors than less productive species, then plots that are very diverse are likely to be more productive on average simply because of a greater chance of containing such competitive species (*5, 8*). A signature of the sampling effect is that no higher diversity plot should be more productive than the most productive species growing in monoculture. An alternative mechanism is based on niche complementarity (*8, 9*). These models predict that differences among species in resource or environmental requirements would allow some combinations of species to more completely capture and use resources and thus have greater productivity than any individual species in monoculture, a phenomenon called overyielding (*10*).



Variety spices up ecosystems. The productivity of an ecosystem depends on its local diversity (that is, the number of species it contains). Local species diversity in an ecosystem depends on regional diversity. Thus, the maintenance of an ecosystem requires that regional diversity be preserved. Data obtained in 1997 in 100 plots (each 0.5 m^2) within 20 grassland fields sampled at Cedar Creek Natural History Area of Minnesota predict that an average local diversity of Y plant species requires an average regional diversity of $(Y - 1.1)/0.124$. (Regression analysis: $r = 0.82$, $n = 20$, $P < 0.001$). For example, a region must contain 40 species for a local site to contain 6 species.

Several recent papers have explored these mechanisms with the use of theory, laboratory experiments, and a few field studies (*11*). To these can now be added the trans-European study of Hector *et al.*—the first large-scale, multinational field experiment of its kind in ecology (*7*). The investigators report results from its first 2 years. By experimentally controlling grassland diversity, they observed that loss of diversity led to significant decreases in productivity, similar to the findings of other field experiments. Most importantly, and quite surprisingly, across eight different European sites ranging from Sweden in the north, to Portugal and Ireland in the west, to Greece in the south and east, there seemed to be a "single general relationship between species richness and diversity across all sites" (*7*). Such broad inference is rare indeed in ecology. This landmark study demonstrates the power of multisite experiments and, perhaps, the power of a diverse team of scientists. Such experiments are critically important for addressing the effects of human domination on ecosystems and the benefits that ecosystems provide to society. The European Commission's funding of this project may herald the European Union's expanding interest in environmental science.

The author is in the Department of Ecology, 100 Ecology Building, University of Minnesota, 1987 Upper Buford Circle, St. Paul, MN 55108, USA. E-mail: tilman@lter.umn.edu.

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William J. Clegg
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