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New Alcoa Professor Tries to Resist Cracking

Fred Lange, professor of materials and of chemical engineering, chairs the top-flight Materials Department.

Both of UCSB's Nobel Prize-winners this year, one in Physics and one in Chemistry, hold appointments in the department. UCSB's most-publicized new hire, gallium-nitride master Shuji Nakamura, is a member of the department. Feature stories on Nakamura's choice of UCSB have appeared, for instance, in the Sunday Los Angeles Times, Scientific American, Nature, Science, and Time.

Lange may preside over UCSB's glamour department, but his own expertise focuses on a class of materials that despite broad commercial application is not often touted in the headlines of the glitzy new high-tech press such as Red Herring and Wired. Lange, newly named to the Alcoa Chair, is an expert on ceramics.

With Aristotelian precision, the no-nonsense Lange begins discussing his research with a definition: "Ceramics are inorganic materials, made up of tiny crystals all bonded together across boundaries that separate the crystals. Each crystal is called 'a grain.'"

He goes on to give a common example of such a "polycrystalline" material -- the sodium lamp tube. "The translucent tube is made out of aluminum oxide powder," he explains, "because of the need to withstand higher temperatures than glass. The tube contains a drop of sodium, which vaporizes when an arc is struck between two electrodes. Other lighting methods produce a broad spectrum, but sodium emits only at an orange-yellow wavelength. Not everybody," Lange adds almost regretfully, "likes that color."

The energy-efficient sodium lamp has been around for 40 years, almost as long as the 61-year-old Lange has been specializing in ceramics. Over that time he has seen the field evolve from trial-and-error-based technique towards a basic science understanding. Lange, elected a member of the National Academy of Engineering, has been one of the principal movers of the field in that direction.

Yes, he admits, his wife MaryAnn collects a kind of Depression-era tableware by Hall, but cups and plates and pottery have little to do with the stuff on which Lange works. The windowsill of his corner office in Engineering II sports examples of modern ceramic technology such as valves and bearings.

He picks up a conical-shaped valve. It looks like it could be made out of metal, but hefting it in hand reveals the difference. The silicon-nitride valve designed for a racing car is lightweight, but still too expensive because of the proof-testing that would be used for even a Mercedes passenger vehicle.

Next he beckons to a tube. "See the little white dots in this tube. Those are imperfections. This tube was made by Westinghouse when I used to work there. In the early days we consistently got little white dots in these ceramic tubes for sodium lamps. They scatter light, so all of the light does not get out, and the tube heats up."

Such imperfections or heterogeneities, whether air pockets (voids) or contaminants, differ in density from the principal material of the ceramic. They also provide the key to the material's failure. As Lange puts it, "The heterogeneities concentrate stress and thereby initiate failure."

One of the main foci of Lange's research career has been the quest to increase the reliability of ceramic components by removing heterogeneities. It has been a surprisingly difficult problem. He outlines the three ways evolved in the field to attack the problem.

Proof-testing for reliability

The first and by far simplest is proof-testing. Before use in a real racing car, each ceramic valve is tested in an engine. If the valve fails, it is thrown away. Such a trial-and-error approach is too costly for any but the most "precious" use.

The second way is to remove the heterogeneities from the material before it is formed into a shape.

Colloidal processing

Modern ceramics begin with a powder that is added to a liquid, usually water, to form a "slurry." The grains of the mixture attract one another because electrons fluctuating around the nucleus of an atom set up a dipole, and dipoles attract each other. Noted and formalized in the 1930s, this relationship is called Van der Waals attraction. Shrouding the particles with something that produces a repulsive force overrides the Van der Waals attraction. And if the shroud is very thin, the particles via Van der Waals attraction will come together at first and become repulsive only at very short distance.

Each of these three particle relationships defines a potential (i.e., "pair potential") between particles: (1) fully attractive, (2) fully dispersed, and (3) somewhere in between. This latter short-range repulsion can be understood in terms of an equilibrium separation distance between the particles' forces of attraction and repulsion.

The shroud provides the key to control, and that is the focus of much of Lange's research.

At the outset of processing, the particles added to water to form the slurry are shrouded so that they are repulsive and pass easily through a filter that then excludes all contaminants larger than the filter mesh. As Lange explains, "We have to completely shield the Van der Waals potential to put the slurry through a filter because a paste of attracting particles won't pass readily through a filter. Now, we know that if no further contaminants are added, flaws will not occur bigger than a given size. The size of the largest flaw will define the lowest strength.

"Next, we've got to increase the relative density of the powder to make the material malleable, so we have to remove some liquid. To do this we employ pressure filtration by pushing the slurry through another finer filter that enables only the liquid to pass."

The trick is to produce just the right short-distance repulsive force via the shroud so that after de-watering the consolidated powder has a clay-like consistency that enables it to be shaped. In other words, according to Lange, "By manipulating the pair potentials we can make a body that can be formed into a shape with a defined threshold strength below which it will not fail."

The consequence is that Lange's research group can make advanced powders that normally do not behave like clay into bodies that do. Lange and his research collaborators have, moreover, formulated a mathematical description whereby the pair potentials can be manipulated. These results will be published in Advanced Materials.

In addition to proof-testing and colloidal processing, the third way to increase the reliability of ceramic components focuses on preventing large cracks from causing failure until a special stress is achieved, called the "threshold" strength.

Laminates and fracture mechanics

Ceramics exhibit two types of flaws: those due to heterogeneities in the powder and those due to surface imperfections induced after an engineering component is made. "If you scratch a window with a diamond ring," explains Lange, "that glass will be weaker than it had been before the scratching. "In some systems we can minimize the effect of surface flaws by putting the surface under compression. Basically, we are squeezing the surfaces of the crack together. Therefore, the stress you need to apply to cause a crack to open up and cause failure is much larger than if there were no compression on the surface. This is done all the time, for instance, in the making of safety glass."

There are other methods of inducing surface compression for ceramics than that used for safety glass, which utilizes compressive stresses produced during the quenching of the heated glass.

A layer of material can be put, for instance, on the surface of a ceramic, and the combination heated. The material on the surface can be selected so that during cooling it does not contract as much as the material within, so that the contracting insides force the surface into compression.

Lange's group devised a way of making ceramics such that not only the surface is in compression, but also layers within the body. These laminates stop internal as well as surface flaws. Lange teamed up with Robert McMeeking, who chairs the UCSB Department of Mechanical and Environmental Engineering, and an associate professor in that department, Glenn Beltz.

The two experts in fracture mechanics showed that the stress threshold of such a laminate is controlled by the magnitude of compressive stresses and the distance between the layers under compression. Basically, the shorter the distance is between layers, the smaller the crack, and the higher the threshold strength. The Lange laminates and their fracture mechanics are the subject of an article that appeared in the Oct. 1, 1999 issue of Science.

"The problem," said Lange, "is that the laminates work in only two dimensions. Now, we are devising ways of forming compressive layers in the third dimension with layers that curve around one another."

In addition to being lightweight, ceramics withstand very high temperatures, which makes this class of material suitable not only for engine components but also reactor vessels. The materials also wear well. One type of rollerblade uses silicon-nitride bearings.

Where does Lange rank in the constellation of ceramic stars? A fellow of the American Ceramic Society, he is the recipient of its Kraner Award, John Jeppson Award, Sosman Memorial Lectureship, and Richard M. Fulrath Award (conferred jointly with the Japan Ceramic Society). The International Academy of Ceramics has elected him a member, and the Ceramic Association of New Jersey gave him the distinguished Malcolm G. McLaren Award.

Note: Professor Lange may be reached at 805-893-8248.

Images

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