Lab Notes

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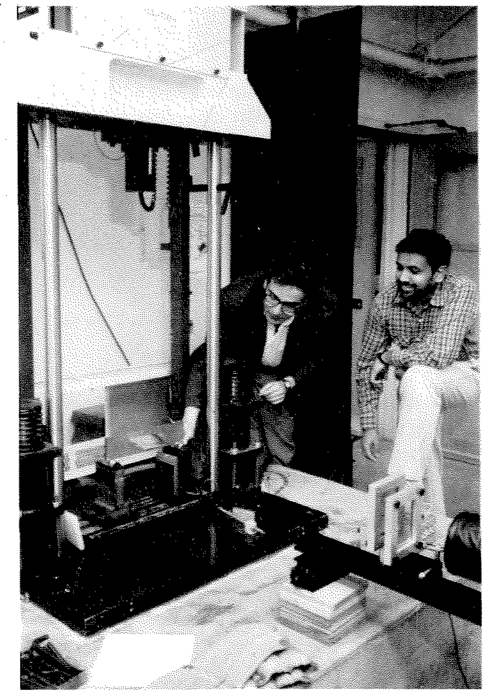


Above: Rosakis sets up a steel specimen as Tippur looks on. A 1,000-pound weight plunging from a height of two stories will crack the specimen at a precut notch. The diffraction gratings and part of the high-speed camera are visible to the lower right.

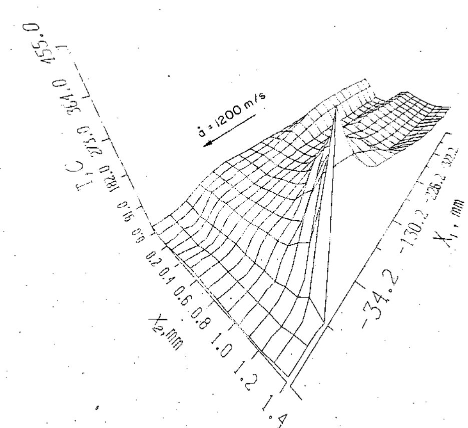
Faster than a Speeding Fracture

When the wing tears off of a jetliner, or an overloaded steel cable snaps, the crack moves through the metal faster than a mile a second. Scientists studying fracture behavior would love to watch a crack as it travels, but have been stymied by its speed. But now Ares Rosakis, associate professor of aeronautics and applied mechanics, and his colleagues have developed two techniques fast enough to catch a crack in the act.

One method measures transient temperature changes in the crack tip's vicinity. Thermocouples, the standard temperature sensors, can't respond fast enough to register these transients. Thermocouples also measure temperature over too large an area—they measure heat through physical contact and obscure any fine detail by reporting one average value for the entire contact region.

Rosakis and Alan Zehnder (now an assistant professor at Cornell) built a remote-temperature sensor based on cesium-antimonide infrared detectors, originally developed for use in heat-seeking missiles, that have a response time on the order of half a microsecond (millionth of a second). A linear array of eight detectors is focused on a narrow strip of the specimen's surface—about 0.16 mm wide by 1.5 mm long—perpendicular to, and in the projected path of, the crack. Each detector provides a continuous temperature readout for a specimen area 0.16 mm square as the crack tip approaches, passes by, and recedes. "Ideally, we'd like to have a square array of perhaps 1,000 by 1,000 of these detectors, so that we could get a series of complete pictures of the whole area," says Rosakis, "but unfortunately just the eight of them cost \$40,000." So, instead, the group uses time as a proxy for distance. Electrically conductive paint is silk-screened onto the back of the specimen in a pattern of parallel lines 3 mm apart. Each line breaks in turn as the crack passes beneath it, tracking the crack's progress. Plotting the temperature readings in their correct positions relative to the crack tip gives a composite picture of the temperature all around the crack.

When a crack shoulders its way between atoms, rupturing the bonds



Below: A 3-D plot of temperature (vertical axis) relative to the crack tip. The crack runs down the X_1 axis, moving out of the page at 1200 m/s. The spike marks the crack tip, and the spreading wave behind it defines the zone of changed yield stress.

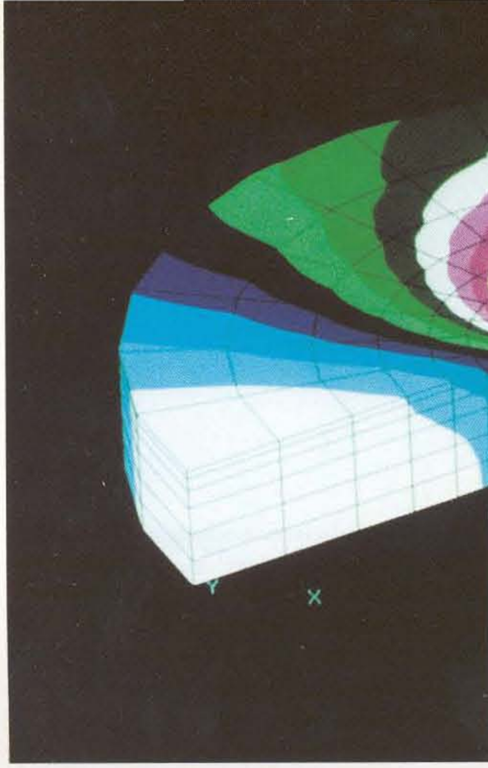
between them, heat is released. Theorists knew this, but assumed that any effect on the bulk of the material would be negligible. Rosakis has found, however, that in a half-millimeter-wide zone running one millimeter ahead of the crack tip, the temperature shoots up to about 500° C in two microseconds, and it stays that hot for about 150 microseconds. "This is actually enough heat to change the local yield stress—the stress needed to break the material," he says. "So this research tells us we need to modify our theories to incorporate the heat effect, because it's important."

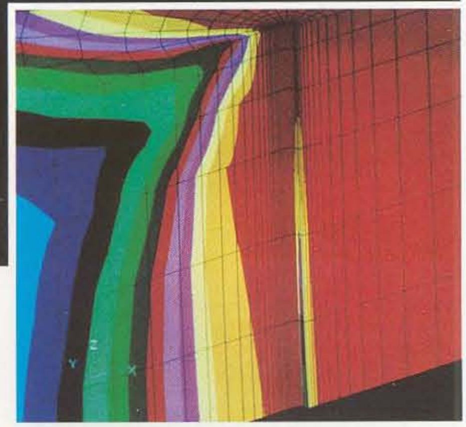
The second method, called coherent-gradient sensing, uses high-speed photography to record the stresses around the crack's path. Previous techniques have usually been limited to a single snapshot of the crack in progress, or only gave data about one point instead of the entire region surrounding the crack. Multiple images of a crack and its environment could be made, but only if the stressed material was transparent, like Plexiglas—a class of materials of limited use to structural engineers.

The new method photographs the stresses in an opaque plate such as a metal or ceramic at the rate of two million frames per second—fast enough to follow a crack as it crosses the plate. The method uses a laser, firing high-intensity pulses 20 billionths of a second long, as the flashbulb. Each pulse illuminates the area the crack will traverse. The plate has been polished until it's optically flat—any two points a centimeter apart on its surface differ in elevation by less than one wavelength of the laser light. The stresses responsible for the crack make the plate deform before it breaks, causing different regions of its surface to reflect the laser light slightly out of phase. The reflected light creates interference patterns upon passing through a set of diffraction gratings placed in front of the specimen. The diffracted light enters a drum-shaped camera, where a whirling mirror slings the patterns onto the photographic film lining the drum. The researchers analyze the interference patterns to track how much each point on the specimen's surface moves from its initial position, which in turn reveals the stresses at that point. The succession of patterns thus records the stress at every point on the surface throughout the cracking process. The method was developed by Rosakis and postdocs Hareesh Tippur and Sridhar Krishnaswamy (now a postdoc at UC San Diego).

"Previous methods for opaque materials weren't compatible with high-speed photography," Rosakis notes. "The gratings were actually glued onto the specimen, and they scattered a lot of the light. You need very intense light to expose the film at the speeds necessary to follow the crack in motion, and those methods just didn't reflect enough light back to the camera. They were essentially static techniques. This is the first method that gives full-field information on the crack environment in real time."

The research group has developed numerical models based on these experiments. These models, which run on supercomputers at Caltech's Jet Propulsion Laboratory and at the supercomputing center in San Diego, will help scientists refine theories on how cracks grow. "Fatigue cracks always exist," says Rosakis. "They cannot be prevented. And sometimes they start propagating. So the practical question is, how does one design structures so that cracks arrest themselves before there is a catastrophic failure? Our models can help engineers answer that question."□—*DS*





Above: A supercomputer model of the stresses around the crack, which is moving from left to right across the face of the model. Blue is the lowest stress, red the highest. The inset shows that bonds breaking at the crack tip relieve stress in the immediate area. Below: A typical interference pattern. The crack is moving up the middle of the photo.