Making Nondestructive Evaluation a Science

Structural materials are rejected if a single flaw can be found; but the goal is to make accept/reject decisions quantitatively

Nondestructive evaluation is the process of determining, without damaging them, whether the materials in products ranging from microelectronics circuits to nuclear reactors contain defects that would prevent their use. Ideally, the inspector would have an instrument that would read out the appropriate message, "This part is (is not) acceptable," during testing. Achieving this capability for structural materials requires that there be a technology to quantitatively characterize flaws by their size, shape, and orientation and that criteria be established to transform this information into a decision to accept or reject. Unfortunately, there is no such instrument now. Present-day nondestructive techniques, which are more art than science, are usually limited to giving qualitative information only—that is, they can indicate the presence of defects but cannot characterize them in detail. Moreover, it is unlikely that this situation will change anytime in the next few years. On the encouraging side, however, researchers are reporting considerable progress.

Proponents of improving nondestructive evaluation point to several contributions improved inspection techniques could make in an era of increasingly scarce but expensive resources. The ability to design structures that perform close to the limits of the materials from which they are made would allow considerable savings in raw materials and in the energy to convert these to finished products. Vehicles from automobiles to airplanes designed in this way would be lighter and would require less energy to operate. And in these litigious times, manufacturers and operators are increasingly liable for the safety of their products.

One example of the economic incentive to improve nondestructive evaluation is the nuclear power plant. Such plants need to comply with a lengthy set of rules, one of which is a mandatory requirement for periodic inspections. According to Gary Dau of the Electric Power Research Institute (EPRI), the research arm of the nation's electric utilities, improved inspection procedures could produce savings amounting to $21 million for each day that the approximately 70 nuclear power plants now operating reduce their unscheduled plant shutdowns.

But, points out Donald Thompson of Rockwell International's Science Center in Thousand Oaks, California, improvement does not imply finding smaller and smaller flaws more and more reliably, if the criterion for rejecting a part is simply that it contains detectable imperfections. Increasing the sensitivity of inspection techniques would just mean that more and more parts, many of which would have performed satisfactorily during their service lives, would be rejected and a needless cost would be incurred.

Engineers have a distinct advantage over those wrestling with safety standards for toxic chemicals and radiation because there is a "threshold" below which flaws are benign. The idea of a threshold comes from the metallurgical discipline of fracture mechanics, which got its start in 1920 when the late British engineer A. A. Griffith derived an equation which said that only above a certain critical size do cracks immediately cause a material to fracture. The critical size depends on the stress, the properties and environment of the material, and the geometry of the crack. Brittle materials, such as ceramics, have critical crack lengths ten or more times smaller than ductile metals, for example.

More recent work by metallurgists, following Griffith's lead, has shown that subcritical cracks, those shorter than the critical size, can grow, although only very slowly. Moreover, not all cracks in a material exist from the start. Some may form during the service life as a result of stress concentrations due to poor design or to other imperfections, such as inclusions of foreign particles whose elastic moduli or thermal expansion coefficients differ from that of the host material. By now, fracture mechanics models have been developed such that engineers can calculate the expected lifetime of a structure under a known stress load and with a known flaw distribution.

The availability of such failure prediction models means that it is possible, says Mike Buckley of the Defense Department's Advanced Research Projects Agency (DARPA), to allow structures to be built from materials known to contain flaws, provided that fracture mechanics analysis shows them to be benign. Harry Berger of the National Bureau of Standards (NBS) remembers just such an instance during the construction of the Alaska pipeline. X-ray inspections of pipe welds showed that many of them were below standard. The Alyeska Pipeline Service Company, builders of the pipeline, petitioned the Department of Transportation in 1976 for a waiver on the basis of a fracture mechanics analysis that showed the welds to be strong enough. An investigation by an NBS team supported the Alyeska claim in principle, although questions were raised as to how well engineers could determine defect sizes (depth is the hardest dimension to measure) from radiographs.

A big hang-up in nondestructive evaluation is still this lack of an ability to measure the seriousness of a defect, because the failure prediction models require numerical values of defect parameters. Consider a large program called Retirement for Cause run by the Air Force Materials Laboratory (AFML) at Wright-Patterson Air Force Base near Dayton, Ohio. The effort focuses on turbine disks, which are the structures to which the turbine blades in jet engines are attached. At present, all such disks are automatically retired after a specified number of hours of operation because engineers have statistical models that tell them that some disks will begin to fail at this time, even though designed for average lifetimes four or five times as long. Since no one knows which ones will fail, all are retired, an expensive proposition because, according to Buckley, disks can cost $20,000 each.

The new AFML program is in part aimed at extending the service life through the use of several nondestructive evaluation techniques to inspect the disks periodically. Although considerable effort is going into automating the techniques to avoid the variabili-

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ty between human inspectors and to speed up the inspection process, the Retirement for Cause program, says Joseph Moyzis of AFML, is still largely using qualitative nondestructive evaluation. A disk will be retired if any defects are found when the instruments are set to a predetermined sensitivity. If successful, the new inspection system will mark a major advance over current practice, but it will not be until the fall of 1981 that a final system will be chosen. How much farther away is the engineers' dream of quantitative nondestructive evaluation?

About 5 years ago, a group led by Donald Thompson at the Science Center, under the sponsorship of DARPA and AFML, mounted a long-term attack on quantitative nondestructive evaluation. One of the ideas behind this program was to provide a critical mass of funding that would permit the generation of a then-lacking body of information about the fundamentals of detecting flaws in a way that researchers working on individual contracts or grants would be unlikely to accomplish. Most of the research so far has been concentrated on the use of ultrasonics as the means of detecting flaws. One reason for the focus on ultrasonics, according to a second Thompson at the Science Center, Bruce Thompson, is the well-known ability of ultrasonic waves to retain a wealth of information about a flaw even after traveling the sometime long distances between it and the sensor detecting the waves.

There are several problems with making ultrasonics quantitative. In the simplest mode of operation, a piezoelectric or other transducer converts an electrical signal into a pulse of ultrasonic (elastic) waves that propagate through the sample. When the pulse meets a section of material in which the velocity of sound is different, part of it is reflected, and this portion can be detected by the same transducer that originated the pulse. In current practice, the size of the reflected pulse is assumed to correspond to the size of the inhomogeneity, which could be, for example, a crack.

But, says Berger, researchers at NBS several years ago found that calibrating this technique is not so easy. A standard calibration method uses a set of metal blocks, costing up to $1700, that are supposed to provide a series of known reflection amplitudes. Yet, when several sets of aluminum reference blocks were tested, NBS investigators found that the measured signals typically varied by 40 percent because of variations in the blocks. Now, an NBS calibration service can reduce this variation to a more tolerable 6 percent or less.

Even with a workable standard, however, the simple pulse echo technique cannot be quantitative. For example, a large crack aligned parallel to the direction of propagation gives a smaller signal than a small crack perpendicular to pulse direction. All in all, that a quantitative ultrasonic technique would require much more information than just the amplitude of a single reflected pulse seems to be a generally accepted conclusion.

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An obvious way to obtain more information is to use a set of sensors (or to scan with a single sensor) to record the pattern of scattered ultrasonic waves, as is done in ultrasonic imaging in medicine. Bruce Thompson points out that there is an additional complication because elastic waves in a solid have three possible polarizations; they are not simple longitudinal compression waves of the type that occur in gases and liquids.

One of the accomplishments of the Science Center program of which Donald Thompson is proudest is the recruiting of top-notch academic scientists from several disciplines to make fundamental contributions to the solution of this problem. Moreover, even researchers not directly involved in the program have been drawn into working on the theory of scattering of elastic waves by defects in solids, including Bernard Budianski, a mathematician from Harvard University, James Rice, an engineer from Brown University, and Walter Kohn and Robb Thomson, physicists from the University of California at San Diego and from NBS, respectively.

(What Dau at EPRI says has been an eye-opening experience for him may reflect only a difference between long-term basic research and the more applied variety. EPRI has had an extensive nondestructive evaluation program that, in accord with the institute's mandate, is directed toward solving specific problems for utilities. Dau says that in very few instances have researchers approached his office with unsolicited proposals, despite the availability of research money. He has had to seek out potential contractors to work on EPRI-originated ideas.)

To validate the results of theory, experiments using samples with known flaws in them were necessary. Since the types of defects that the theories can handle are rather artificial, a way had to be found to create these imperfections; for example, how does one put a void in the center of a block of metal? A solution that was developed earlier by Donald Kettering of Grumman Aerospace Corp. and expanded upon by Neil Paton of the Science Center makes use of the aerospace technique of diffusion bonding. At high temperature and pressure, two pieces of metal will grow together, and the boundary between will disappear. Thus, a sphere, for example, could be created by machining hemispheres into the surfaces of two metal slabs and then joining them by diffusion bonding.

Experiments by Bernard Tittmann of the Science Center and Laszlo Adler of the University of Tennessee on the angular distribution of scattering in titanium alloy samples containing spheroidal inclusions or voids have indeed shown that the theories are appropriate. More recent theoretical and experimental work has shifted toward more realistically shaped flaws. (The business of duplicating imperfections seems to be thriving. EPRI is, for example, spending more than $500,000 per year learning how to make realistic cracks in reactor components so that new nondestructive techniques will be able to prove themselves in near real-world situations.)

The real problem in inspection, however, is to deduce the properties of a defect from the scattering pattern. This problem—the so-called inverse problem—is also much more difficult than calculating the scattering pattern from a defect, in part because the inverse problem need not have a unique solution. Most of the current theoretical work is devoted to inversion with the earlier results being used as a guide.

Imaging is the most natural form of inversion because it provides the inspector with a visual picture of the flaws. Moreover, imaging can be done by lenses that focus ultrasonic rays, just as in optics, thus obviating the need for theorists to solve a complex mathematical problem.

One instance of such ultrasonic imaging is that done in Gordon Kino's laboratory at Stanford. The laboratory is a good model, according to some observers, for nondestructive evaluation research because Kino has assembled an interdisciplinary collection of scientists from the electrical engineering and materials science and engineering departments. The laboratory also receives support from several sources, including the Science Center and EPRI.

Among its other projects, Kino's group is working on a computer-controlled, electronically scanning, ultrasonic imaging system. There are two linear arrays of transducers, one for "illuminating" the sample and one for recording the reflected ultrasonic waves. The system operates on a principle similar to that used in some modern radars called a phased array. By electronically controlling the phases of the waves emitted by each transducer in the source array, it is possible both to focus the incident ultrasonic beam to a particular point in the sample and to scan the point of focus across the sample. Similarly, the receiving array can focus and scan with the same phase adjustment technique. To make a picture of the entire sample, the two linear arrays are mechanically scanned in the direction perpendicular to the arrays. An early version of the system, in which only a single transducer was mechanically scanned in both directions over the surface of planar aluminum samples containing holes or notches and put under tensile stress in a testing machine, enabled researchers at Stanford to determine the stress distributions around these imperfections.

Often, the most useful information is not a picture of the defects in a part but only characteristic features of flaws. In other words, a picture may contain more information than the inspector needs and may, in fact, require extra computation to plow through the extraneous information to find the relevant parameters. Moreover, says Bruce Thompson, from the point of view of automating nondestructive evaluation, pictures are not as useful as a set of numbers that characterize the defect and that can be plugged into a computer program that evaluates the severity of the flaw. For this reason, a hefty part of the Science Center's inversion research is oriented toward nonimaging procedures.

Inversion procedures fall into three classes defined by the ratio of the wavelength of the ultrasonic waves to the size of the flaw. When the wavelength is small, either imaging or another inversion technique can be used. When the wavelength is comparable to the size of the defect, available mathematical approaches are deficient and recourse is made to empirical methods. One of these, which has been developed by Adaptronics, Inc., in McLean, Virginia, makes use of a concept called an adaptive learning network. The adaptive learning network, says Tony Mucciardi of Adaptronics, allows a computer both to construct a model representation of the defect (size and orientation) and to determine the parameters of the model from experimental scattering data; however, not surprisingly the more information the computer has stored in it about the expected defects from the start, the better the results.

One of the bigger surprises has come from work in the wavelength region where one would intuitively expect the least amount of information to be available, where the wavelength is longer than the flaw size. Taking their cue from extensive calculations by James Krumhansl of Cornell University, Budianski and Rice showed that there is a correlation between the long-wavelength scattering properties and the failure-inducing properties of defects. In essence, a long-wavelength (low frequency) elastic wave looks something like a static load to the region of a material containing a defect, and therefore the scattering and failure are controlled by the same parameters, according to John Richardson of the Science Center. However, it has not been shown that it is always possible to extract the failure-determining parameter from long-wavelength scattering. Recently, Richardson has shown that it is possible to find the shape and orientation of ellipsoidal imperfections from experimental data giving the angular distribution of long-wavelength scattering.

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A perennial problem is finding a way to convert discoveries into technology for use in the field. To help facilitate this process, an ultrasonic testbed is being assembled at the Science Center. (Testbeds are not a new idea; several others will soon be in existence at EPRI, Battelle Pacific Northwest Laboratories, and elsewhere.) A microcomputer will control a scanning mechanism that has 6 degrees of freedom. Overall control and data processing will be taken over by a minicomputer that will tell the microcomputer where to position the scanner, will gather data from the sensors, and will execute the signal processing algorithms.

Having a quantitative measurement capability in hand, how would one use it? Tony Evans of the University of California at Berkeley has been collaborating with Kino's group at Stanford on a project that illustrates one approach. The researchers created surface cracks of varying sizes in a set of ten glass disks by means of an indenting tool of the type used to make hardness measurements. A variation of long-wavelength ultrasonic scattering in which a special transducer launched surface acoustic waves on the glass enabled the investigators to detect the cracks, the smallest of which was 100 micrometers deep. From these measurements, a materials parameter required for a fracture mechanics analysis could be extracted, and predictions were made of the stress at which the samples would rupture. When the researchers compared predicted fracture stresses to those actually obtained by breaking the samples, they found that the two sets of values agreed within 10 percent.

This disagreement was due to limitations of the theory. In every case, however, there will be uncertainty traceable to errors in the measurement and to statistical variations in the fracture strength due to small differences in the properties of the samples, such as other defects. By doing enough measurements, it would eventually be possible to generate a probability curve that would allow an inspector to determine the likelihood that an inspected part would or would not fail under a given load when defects of a given size are indicated. A complete program would require this procedure for each of the half dozen or more defect types that can cause fracture, for each kind of material to be inspected, and for each inspection technique, according to Evans.

Researchers emphasize that there can never be a 100 percent certain answer to the question: Will a part last the designed service life or not? Thus, in view of an inevitable uncertainty, some of the decision-making must be based on nonquantitative values, such as how badly we want to avoid DC-10 crashes. For components not critical to safety, it may simply be a matter of balancing the costs of failures caused by acceptance of defective parts with the costs of rejecting parts that would have served. In either case quantitative nondestructive evaluation has the aim of reducing the uncertainty to a minimum by providing as quantitative a basis as possible for making cost/risk trade-offs.

—Arthur L. Robinson