This three-dimensional acoustic image shows a sandwich of three ceramic layers bonded by solder layers. The homogeneous ceramic is invisible; irregular red, blue, and yellow features are voids in the solder. Image courtesy Sonoscan Inc.
picture this

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Nondestructive evaluation covers a wide range of activities, including nondestructive testing, nondestructive inspection, and nondestructive examination. These are similar in that they primarily involve examining or measuring a product to evaluate some characteristic or to determine whether the object contains irregularities, discontinuities, or flaws. These terms can be used interchangeably to mean something that is questionable in the part or assembly, but a flaw that has been evaluated as causing the part to be rejected is usually termed a defect.

The selection of a useful characterization method or a combination of methods first necessitates a clear understanding of the problem to be solved. It is then necessary to select those methods that are suitable for further consideration.

This article overviews five of the most widely applied nondestructive test technologies: Eddy Current, Ultrasonic Inspection, Acoustic Emission, Radiographic Inspection, and Microwave Inspection. The information is from the online version of the ASM Handbooks Online, Volume 17, Nondestructive Evaluation and Quality Control. More details and examples of applications are available in that volume.

**EDDY CURRENT**

Eddy current inspection is based on the principles of electromagnetic induction, and is used to identify or differentiate among a wide variety of physical, structural, and metallurgical conditions in electrically conductive ferromagnetic and nonferromagnetic metals and metal parts. Eddy current inspection can:

- Measure or identify electrical conductivity, magnetic permeability, grain size, heat treatment condition, hardness, and physical dimensions.
- Detect seams, laps, cracks, voids, and inclusions.
- Sort dissimilar metals and detect differences in their composition, microstructure, and other properties.
- Measure the thickness of a nonconductive coating on a conductive metal, or the thickness of a nonmagnetic metal coating on a magnetic metal.

Because eddy currents are generated by an electromagnetic induction technique, the method does not require direct electrical contact with the part. The technology is adaptable to high-speed inspection and can inspect an entire production output. However, the method is based on indirect measurement, and the correlation between the instrument readings and the structural characteristics and serviceability of the parts must be carefully and repeatedly established.

Eddy current inspection is extremely versatile, which is both an advantage and a disadvantage.

- The advantage is that the method can be applied to many inspection problems, provided that the physical requirements of the material are compatible with the inspection method.
- The disadvantage is that it is very sensitive to the many properties and characteristics inherent within a material. Some variables in a material that are not important in terms of material or part serviceability may cause instrument signals that mask critical variables, or are mistakenly interpreted to be caused by critical variables.

**Principles of operation**

Eddy current inspection and the induction heating technique for metal heating, induction hardening, and tempering have several similarities. For example, both depend on the principles of electromagnetic induction for inducing eddy currents within a part placed within or adjacent to one or more induction coils. The heating is a result of $I^2R$ losses caused by the flow of eddy currents in the part. Changes in coupling between the induction coils and the part, and changes in electrical characteristics, cause variations in the loading and tuning of the generator.

The induction heating system is operated at high power levels to produce the heating rate. In contrast, the system for eddy current inspection is usually operated at very low power levels to minimize the heating losses and temperature changes. Also, in the eddy current system, electrical-loading changes caused by variations such as those caused by the presence of flaws or dimensional changes, are monitored by electronic circuits.
In both eddy current inspection and induction heating, the selection of operating frequency is largely governed by the skin effect, which causes eddy currents to be concentrated toward the surfaces adjacent to the coils carrying currents that induce them. Skin effect becomes more pronounced with higher frequencies.

The coils for eddy current inspection differ from those for induction heating because of the differences in power level and resolution requirements, which necessitate special inspection coil arrangements to facilitate the monitoring of the electromagnetic field in the vicinity of the part being inspected.

How it works

The part to be inspected is placed within or adjacent to an electric coil in which an alternating current is flowing. As shown in Fig. 1, this alternating current, called the exciting current, causes eddy currents to flow in the part as a result of electromagnetic induction. These currents flow within closed loops in the part, and their magnitude and timing (or phase) depend on:

- The original or primary field that is established by the exciting currents.
- The electrical properties of the part.
- The electromagnetic fields established by currents flowing within the part.

The electromagnetic field in the part and surrounding the part depends on both the exciting current from the coil and the eddy currents. The flow of eddy currents in the part depends on:

- The electrical characteristics of the part.
- The presence or absence of flaws or other discontinuities.
- The total electromagnetic field within the part.

The change in flow of eddy currents caused by the presence of a crack in a pipe is shown in Fig. 2. The pipe travels along the length of the inspection coil as shown in Fig. 2. In section A-A in Fig. 2, no crack is present and the eddy current flow is symmetrical. In section B-B in Fig. 2, where a crack is present, the eddy current flow is impeded and changed in direction, causing significant changes in the associated electromagnetic field. From Fig. 2 it is seen that the electromagnetic field surrounding a part depends partly on the properties and characteristics of the part.

Finally, the condition of the part can be monitored by observing the effect of the resulting field on the electrical characteristics of the exciting coil, such as its electrical impedance, induced voltage, or induced currents. Alternatively, the effect of the electromagnetic field can be monitored by observing the induced voltage in one or more other coils placed within the field near the part being monitored.

Each and all of these changes can have an effect on the exciting coil or other coils. The effects most often measured are the electrical impedance of the coil, or the induced voltage of either the exciting coil or other adjacent coil.

Ultrasonic Inspection

Ultrasonic inspection is a nondestructive method in which beams of high-frequency sound waves are introduced into materials for the detection of surface and subsurface flaws in the material. The sound waves travel through the material with some attendant loss of energy (attenuation) and are reflected at interfaces. The reflected beam is displayed and then analyzed to define the presence and location of flaws or discontinuities.

The degree of reflection depends largely on the physical state of the materials forming the interface, and to a lesser extent on the specific physical properties of the material. For example, sound waves are almost completely reflected at metal/gas interfaces. They are partially reflected at metal/liquid or metal/solid interfaces, with the specific percentage of reflected energy depending mainly on the ratios of certain properties of the material on opposing sides of the interface.

Cracks, laminations, shrinkage cavities, bursts, flakes, pores, disbonds, and other discontinuities that produce reflective interfaces can be easily detected. Inclusions and other inhomogeneities can also be detected by partial reflection or scattering of the ultrasonic waves, or by producing some other detectable effect on the ultrasonic waves.

The primary reason for ultrasonic inspection of metals is detection of discontinuities, such as internal flaws in metals and alloys. Bonds produced by welding, brazing, soldering, and adhesives can also be ultrasonically inspected. In-line techniques have been developed for monitoring and classifying material as acceptable, salvageable, or scrap, and for process control.

How flaws are detected

Most ultrasonic inspection instruments detect flaws by monitoring one or more of the following:

- Reflection of sound from interfaces consisting of material boundaries or discontinuities within the material.
- Time of transit of a sound wave through the test piece from the entrance point at the transducer to the exit point at the transducer.
- Attenuation of sound waves by absorption and scattering within the test piece.
- Features in the spectral response for either a transmitted or a reflected signal.

Most ultrasonic inspection is done at frequencies between 0.1 and 25 MHz, well above the range of human hearing, which is about 20 Hz to 20 kHz. The amplitudes of vibrations in metal parts impose stresses well below the elastic limit, thus preventing permanent effects.

Ultrasonic inspection is one of the most widely used methods of nondestructive inspection. Its primary application in the inspection of metals is the detection and characterization of internal flaws; it is also used to detect surface flaws, to define bond characteristics, to measure the thickness and extent of corrosion, and (much less frequently) to determine physical properties, structure, grain size, and elastic constants.

Basic inspection methods

The two major methods of ultrasonic inspection are the transmission method and the pulse-echo method. The primary diff-
The difference between these two methods is that the transmission method involves only the measurement of signal attenuation, while the pulse-echo method can be used to measure both transit time and signal attenuation.

- **The pulse-echo method** involves the detection of echoes produced when an ultrasonic pulse is reflected from a discontinuity or an interface. This method is used in flaw location and thickness measurements. Flaw depth is determined from the time-of-flight between the initial pulse and the echo produced by a flaw. Depth might also be determined by the relative transit time between the echo produced by a flaw and the echo from the back surface. Flaw sizes are estimated by comparing the signal amplitudes of reflected sound from an interface (either within the test piece or at the back surface) with the amplitude of sound reflected from a reference reflector of known size, or from the back surface of a test piece having no flaws.

- **The transmission method**, which may include either reflection or through-transmission, involves only the measurement of signal attenuation. In the pulse-echo method, it is necessary that an internal flaw reflect at least part of the sound energy onto a receiving transducer. However, echoes from flaws are not essential to their detection. The simple fact that the amplitude of the back reflection is lower than that from an identical part known to be free of flaws implies that the test piece contains one or more flaws. The technique of detecting the presence of flaws by sound attenuation is used in transmission methods as well as in the pulse-echo method. The main disadvantage of attenuation methods is that flaw depth cannot be measured.

- **The frequency modulation (FM) method**, which was the precursor of the pulse-echo method, is another flaw detection technique. In the FM method, the ultrasonic pulses are transmitted in wave packets whose frequency varies linearly with time. The frequency variation is repeated in successive wave packets so that a plot of frequency versus time has a sawtooth pattern. There is a time delay between successive packets. Returning echoes are displayed on the readout device only if they have certain characteristics as determined by the electronic cir-

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lectric transducer. As the stress in the material is raised, many of the processes that have been observed with AE inspection are the radiations out into the structure and excites a sensitive piezoelectric transducer. Sudden movement at the source produces a stress wave, which movements of small numbers of dislocations in stressed metals.

• Spectral analysis, which can be used in the through transmission or pulse-echo methods, involves determination of the frequency spectrum of an ultrasonic wave after it has propagated through a test piece. The frequency spectrum can be determined either by transmitting a pulse and using a fast Fourier transform to obtain the frequency spectrum of the received signal; or by sweeping the transmission frequency in real time and acquiring the response at each frequency.

• Spectral analysis is also suitable for measuring the thickness of thin-wall specimens. A short pulse of ultrasound is a form of coherent radiation; in a thin-wall specimen that produces front and back wall echoes, the two reflected pulses show phase differences and can interfere coherently. If the pulse contains a wide band of frequencies, interference maxima and minima can be seen at particular frequencies, and these can be related to the specimen thickness.

**ACOUSTIC EMISSION**

Acoustic emissions are stress waves produced by sudden movement in stressed materials. The classic sources of acoustic emissions are crack growth and plastic deformation. The largest-scale acoustic emissions are seismic events, while the smallest-scale processes that have been observed with AE inspection are the movements of small numbers of dislocations in stressed metals.

The process of generation and detection is illustrated in Fig. 3. Sudden movement at the source produces a stress wave, which radiates out into the structure and excites a sensitive piezoelectric transducer. As the stress in the material is raised, many of these emissions are generated. The signals from one or more sensors are amplified and measured to produce data for display and interpretation.

The source of the acoustic emission energy is the elastic stress field in the material. Without stress, there is no emission. Therefore, an acoustic emission (AE) inspection is usually carried out during a controlled loading of the structure. This can be a proof load before service, a controlled variation of load while the structure is in service, a fatigue test, a creep test, or a complex loading program. Often, a structure is going to be loaded anyway, and AE inspection gives valuable additional information about performance under load. Other times, AE inspection is selected for reasons of economy or safety, and a special loading procedure is arranged to meet the needs of the AE test.

In the laboratory, AE inspection is a powerful aid to materials testing and the study of deformation and fracture. It gives an immediate indication of the response and behavior of a material under stress, intimately connected with strength, damage, and failure. Because the AE response of a material depends on its microstructure and deformation mode, materials differ widely in their AE response. Britteness and heterogeneity are two major factors conducive to high emissivity. Ductile deformation mechanisms, such as microvoid coalescence in soft steels, are associated with low emissivity.

In production testing, AE inspection is used for checking and controlling welds, brazed joints, thermocompression bonding, and forming operations such as shaft straightening and punch press operations. In general, AE inspection can be considered whenever the process stresses the material and produces permanent deformation.

Acoustic emission equipment is highly sensitive to any kind of movement in its operating frequency range (typically 20 to 1200 kHz). The equipment can detect not only crack growth and material deformation, but also such processes as solidification, friction, impact, flow, and phase transformations.

**RADIOGRAPHIC INSPECTION**

Radiology is the general term given to material inspection methods that are based on the differential absorption of penetrating radiation, either electromagnetic radiation of very short wavelength, or particulate radiation. Different amounts of penetrating radiation may be absorbed by different sections of a part because of differences in density, variations in thickness, or variations in composition. These variations in the absorption of the penetrating radiation can be monitored by detecting the unabsorbed radiation that passes through the testpiece.

The term radiography often refers to the specific radiological method that produces a permanent image on film. In a broad sense, however, radiography can also refer to other radiological techniques that can produce two-dimensional, plane-view images from the unabsorbed radiation.

The principal advantage of real-time radiography over film radiography is the opportunity to manipulate the test piece during radiographic inspection. This capability allows the in-
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spection of internal mechanisms and enhances the detection of cracks and planar defects by manipulating the part to achieve the proper orientation for flaw detection.

Moreover, part manipulation in real-time radiography simplifies three-dimensional (stereo) dynamic imaging and the determination of flaw location and size. In film radiography, the position of a flaw within the volume of a part cannot be determined exactly with a single radiograph; depth parallel to the radiation beam is not recorded. Consequently, other film techniques, such as stereoradiography, triangulation, or simply making two or more film exposures (with the radiation beam directed at the part from a different angle for each exposure), must be used to locate flaws more exactly.

Computed tomography (CT) involves the generation of cross-sectional views instead of a planar projection. The CT image is comparable to that acquired by making a radiograph of a physically sectioned thin planar slab from an object. This cross-sectional image is not obscured by overlying and underlying structures, and is highly sensitive to small differences in relative density. Moreover, CT images are easier to interpret than radiographs.

**MICROWAVES**

Microwaves (or radar waves) are a form of electromagnetic radiation located in the electromagnetic spectrum at the frequencies listed in the table below. The microwave frequency region is between 300 MHz and 325 GHz. This frequency range corresponds to wavelengths in free space between 1000 cm and 1 mm.

The interaction of microwave electromagnetic energy with a material involves the effect of the material on the electric and magnetic fields that constitute the electromagnetic wave; that is, the interaction of the electric and magnetic fields with the conductivity, permittivity, and permeability of the material.

Microwaves behave much like light waves in that they travel in straight lines until they are reflected, refracted, diffracted, or scattered. Because microwaves have wavelengths that are 10^4 to 10^5 times longer than those of light waves, microwaves penetrate deeply into materials, with the depth of penetration dependent on the conductivity, permittivity, and permeability of the materials.

Microwaves are also reflected from any internal boundaries, and they interact with the molecules that constitute the material. For example, it was found that the best source for the thickness and voids in radomes was the microwaves generated within the radomes. Both continuous and pulsed incident waves were used in these tests, and either reflected or transmitted waves were measured.

**Advantages of microwaves**
- Broadband frequency response of the coupling antennas.
- Efficient coupling through air from the antennas to the material.
- Microwaves readily propagate through air, so successive reflections are not obscured by the first one.
- Information concerning the amplitude and phase of propagating microwaves is easily found.
- No physical contact is required.
- The surface can be scanned in strips by moving the surface or by scanning the surface with antennas.
- No material changes caused.
- The complete system can be made from solid-state components, making it small, rugged, and reliable.

**Limitations of microwaves**
- In some cases limited by inability to penetrate deeply into conductors or metals.
- Another limitation of the lower-frequency microwaves is their comparatively low power for resolving localized flaws. If the receiving antenna is of practical size, a flaw whose effective dimension is significantly smaller than the wavelength of the microwaves cannot be completely resolved.
- The shortest wavelengths for which practical microwave apparatus exists are of the order of 1 mm. However, the development of microwave sources with wavelengths of 0.1 mm are proceeding rapidly.

**Divisions of radiation, frequencies, wavelengths, and photon energies of the electromagnetic spectrum**

<table>
<thead>
<tr>
<th>Division of radiation</th>
<th>Frequency, Hz</th>
<th>Wavelength, m</th>
<th>Photon energy, J</th>
<th>eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio waves (FM and TV)</td>
<td>3 x 10^8</td>
<td>1</td>
<td>1.6 x 10^-25</td>
<td>10^-6</td>
</tr>
<tr>
<td>Microwaves</td>
<td>3 x 10^8</td>
<td>10^-1</td>
<td>1.6 x 10^-24</td>
<td>10^-5</td>
</tr>
<tr>
<td></td>
<td>3 x 10^10</td>
<td>10^-2</td>
<td>1.6 x 10^-23</td>
<td>10^-4</td>
</tr>
<tr>
<td></td>
<td>3 x 10^11</td>
<td>10^-3</td>
<td>1.6 x 10^-22</td>
<td>10^-3</td>
</tr>
<tr>
<td>Infrared</td>
<td>3 x 10^12</td>
<td>10^-4</td>
<td>1.6 x 10^-21</td>
<td>10^-2</td>
</tr>
<tr>
<td></td>
<td>3 x 10^13</td>
<td>10^-5</td>
<td>1.6 x 10^-20</td>
<td>10^-1</td>
</tr>
<tr>
<td>Visible light</td>
<td>3 x 10^14</td>
<td>10^-6</td>
<td>1.6 x 10^-19</td>
<td>1</td>
</tr>
<tr>
<td>Ultraviolet light</td>
<td>3 x 10^15</td>
<td>10^-7</td>
<td>1.6 x 10^-18</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3 x 10^16</td>
<td>10^-8</td>
<td>1.6 x 10^-17</td>
<td>10^2</td>
</tr>
<tr>
<td>X-rays and γ-rays</td>
<td>3 x 10^17</td>
<td>10^-9</td>
<td>1.6 x 10^-16</td>
<td>10^3</td>
</tr>
<tr>
<td></td>
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<td>1.6 x 10^-15</td>
<td>10^4</td>
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<td></td>
<td>3 x 10^21</td>
<td>10^-13</td>
<td>1.6 x 10^-12</td>
<td>10^7</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>3 x 10^22</td>
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<td>1.6 x 10^-11</td>
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