Failure Analysis: Nondestructive Testing Methods

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Many defect-testing techniques exist and it may not be clear why one is used over the other. This article describes nine different testing methods explaining how they are used and what they can detect.

Nondestructive testing (NDT) methods are important tools to help us assure product safety, quality and reliability. Finding defects, whether they are flaws or imperfections, during the manufacturing process or before a product is placed into service will decrease liability, increase productivity, save time and improve the bottom line. These techniques are also the first step in any “postmortem” failure analysis.

The most common types of NDT methods are:

- Visual inspection
- Dye (liquid) penetrant
- Magnetic particle inspection
- Radiographic (X-ray) testing
- Eddy current
- Ultrasonics
- Leak detection
- Acoustic emission
- Infrared thermography

Each method has advantages and limitations (Table 1), and often more than one technique is needed to identify the root cause and quantify the extent of the problem.

We will briefly review each of these methods with respect to how they work, where they are used and what can be found as a result of their use.

**Visual Inspection**

Visual inspection is the most basic and widely used method for the examination of parts. It is used to detect surface abnormalities (cracks and imperfections). Since it can be performed by virtually anyone and is subjective in nature, it is a good idea to develop standards or use comparative aids. It is useful in pinpointing areas that require closer inspection (perhaps by another NDT method) and is the place to start before performing any other type of NDT test.

Always begin by preparing an area where the visual inspection will take place. It should be well lit and allow easy manipulation of the part so that all surfaces can be easily viewed. Start by inspecting all surfaces in the “as received” condition. As the examination proceeds, the surface may need to be cleaned or treated in some manner to highlight a defect in more detail. All observations should be documented and adequate time allowed to do a thorough inspection.

**Infrared Thermal Imaging**

Infrared thermal imaging is a remote and continuous measurement method that can detect temperature differences and is sensitive to surface and material temperature variations. This method is useful for identifying hot spots or areas of high temperature in components that are operating in service.

**Table 1** Comparison of NDT Methods

<table>
<thead>
<tr>
<th>NDT Method</th>
<th>Principle Advantages</th>
<th>Main Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Inspection</td>
<td>• Convenient • Inexpensive • Fast • Requires minimal preparation</td>
<td>• Subjective • Inspector dependent • Surface inspection only • Direct examination method</td>
</tr>
<tr>
<td>Dye Penetrant</td>
<td>• Inexpensive • Can be used on irregular shapes • Minimal equipment required</td>
<td>• Messy • Surface flaw detection only • Requires nonporous surface • Ventilation required</td>
</tr>
<tr>
<td>Radiographic Testing</td>
<td>• Wide material applicability • Requires minimal preparation • Full volumetric examination • Permanent record</td>
<td>• Radiation hazard • Requires two-sided access to sample • High skill level required</td>
</tr>
<tr>
<td>Eddy Current</td>
<td>• Speed • Reliable with modern machines • No human factor • Permanent record • Part contact not necessary</td>
<td>• Difficult to interpret • High mechanical precision required • Flaw orientation critical • Part must be electrically conductive • Surface condition important • Can lack specificity</td>
</tr>
<tr>
<td>Ultrasonics</td>
<td>• Speed • Sensitivity • Portability • Full volumetric information</td>
<td>• Difficult to interpret • Smooth surface required • Flaw orientation important • Complex geometry difficult</td>
</tr>
<tr>
<td>Leak Testing</td>
<td>• Cost • Speed • High sensitivity</td>
<td>• System must be isolated • Closed system required • Cause not identified</td>
</tr>
<tr>
<td>Acoustic Emission</td>
<td>• Remote and continuous • Inaccessible flaws detected • Permanent record</td>
<td>• Contact required • Multiple contact points • Difficult to interpret</td>
</tr>
<tr>
<td>Infrared Thermal Imaging</td>
<td>• Portability • Remote sensing technique • Permanent record • Quantitative or qualitative</td>
<td>• Expensive • Influenced by ambient conditions • Surface &amp; material affect results • Error a function of distance</td>
</tr>
</tbody>
</table>
• Lights – natural, fluorescent, black light, artificial light
• Magnifiers – loops, table lenses, stereo (5X – 50X) microscopes
• Mirrors – flat, convex, concave
• Measurement devices – rulers, tapes, calipers, micrometers
• Probes – fiberscopes, borescopes
• Cameras – video, digital, film

Dye Penetrant
Liquid penetrant testing uses a dye or other light-sensitive fluid (visible or fluorescent) to examine nonporous surfaces for defects (cracks, flaws) that may be invisible to the naked eye. Since dyes flow into these imperfections by capillary action, it is critical that the surfaces (including the crack area) be clean and dry – free of oils and residual cleaning fluids that may interfere with the ability of the dye to wet the surface.

First, the part is sprayed with a liquid, which penetrates any surface-breaking cracks or cavities. Then the liquid is allowed to soak into the surface. After soaking, the excess liquid penetrant is wiped from the surface and a developer is applied. The developer is usually a dry, white powder that draws the penetrant out of any cracks by reverse capillary action to produce a visible mark on the surface. Since these colored indicators are broader than the actual flaw, they are more easily visible. Fluorescent penetrants are normally used with a UV lamp to enhance sensitivity.

This technique is used to detect surface cracks in materials. For example, a bicycle...
component was inspected. The suspect areas were sprayed (Fig. 1) with red penetrant dye and left to soak. The square hole location was visibly cracked, but another region was also suspect. After the dye was cleaned off, the component was sprayed with chalk developer (Fig. 2). The crack running from the square axle drive hole showed a very distinct red line indicating its precise location and extent. The suspect feature showed no red mark and it was concluded that this area was indeed simply a surface scratch. Porosity, leak paths, seams and laps can also be inspected using this technique.

Common problems with this type of testing are the failure to allow adequate time for the dye to form a film over the surface and the failure to remove excess penetrant from the surface.

**Magnetic-Particle Inspection**

Magnetic-particle inspection involves the basic principles of magnetism and can be thought of as a combination of two nondestructive testing methods: magnetic-flux-leakage testing and visual testing.

The first step in a magnetic-particle inspection is to magnetize the component that is to be inspected. If any defects on or near the surface are present, the defects will create a leakage field (Fig. 3). After the component has been magnetized, iron particles either in a dry or wet suspended form are applied to the surface of the magnetized part. The particles will be attracted and cluster at the flux-leakage fields, thus forming a visible indicator that the inspector can detect.

The basic components that make up magnetic-particle equipment are: yokes (either permanent magnets or electromagnets), coils (multi-loop windings) and prods (to pass current directly to the part).

**Radiographic Testing**

This nondestructive method can be used to detect internal defects in a wide variety of components such as castings, forgings or weldments by exposure to X-ray or gamma-ray radiation. Skilled radiographers
Materials Characterization and Testing

can produce high-quality images using X-ray tubes or gamma-ray isotopes such as Iridium 192 and Cobalt 60. Defects are detected by differences in radiation absorption in the material as seen on a “shadow graph” displayed on photographic film or a fluorescent screen.

In radiography, the process to produce an image is quite different from that of photography. The camera is actually a radiation source, while the film is not placed inside the camera but instead is placed on the opposite side of the object being imaged. The radiation is not reflected to the film but rather passes through the object and then strikes the film. The image on the film is dependent upon how much of the radiation makes it through the object and to the film. Differences in the type of material and the amount of material that the X-rays must penetrate are responsible for the details in the image[3].

Cracks can be detected in a radiograph only if the crack is propagating in a direction that produced a change in thickness – parallel to the X-ray beam (Fig. 4). Cracks will appear as jagged and often very faint irregular lines. Cracks can sometimes appear as “tails” on inclusions or porosity.

Eddy Current
Eddy-current testing is an indirect method and involves the principle of electromagnetic induction. Eddy current is simply electric current induced by an alternating magnetic field. Parts to be inspected are placed within or adjacent to an electric coil. A high-frequency electric current is applied, and the primary field around the coil causes eddy currents to flow in the part [1].

Two principle purposes for eddy-current testing are to investigate material properties and to detect surface flaws.

Material-properties testing (Fig. 5) using the eddy-current method involves the relative permeability property of metals (and sometimes conductivity) to verify that a component is the correct alloy and/or that it has achieved the desired properties from heat treatment, including surface hardness, case hardness and case depth. Testing actually verifies correct microstructure because it is the microstructure that determines the relative permeability and conductivity. Mixed structures (Fig. 5A, 5B) from incorrect heat treatments can also be reliably detected and sorted.

Surface-flaw testing (Fig. 6) with eddy-current method utilizes the conductivity property of metals. Surface flaws disturb the flow of electrical currents that have been generated on the surface of the part being tested. Changes in electrical fields associated with the disruptions in the currents are detected by the eddy-current instrumentation to reveal the surface flaw. Crack testing (Fig. 6A, 6B) is typically done on finished parts because of the precision required for high flaw resolution.

Ultrasonic Testing
Ultrasonic Testing (UT) uses high-frequency sound energy to conduct examinations and make measurements. Sound waves are propagated across the part and their behavior (velocity and attenuation) is a function of its properties. As these properties change during a test due to a crack or pore, the recorded signals change.
Through analysis of signals these changing properties can be determined[3]. Because ultrasonic sound travels inefficiently through air, a liquid couplant – a drop of liquid such as glycerin, propylene glycol, water or oil – is placed between the transducer and the part at the point of measurement. UT is used for measuring part thickness, flaw detection and for material analysis.

Ultrasonic thickness gages work by tracking the time it takes for an ultrasonic pulse to reflect off the far side of a sample. Such measurements require access to only one side of the part. There is no need, therefore, to cut parts in order to measure an interior surface.

Using the same sound reflection principles, ultrasonic flaw detectors (Fig. 7, 7A) look for echoes that result from cracks, voids or other discontinuities. An ultrasonic pulse will travel from a pulse/receiver through solid, homogeneous material (such as a gear) until it encounters a boundary (such as a crack). When there is a discontinuity in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into electrical signal by the transducer and is displayed on a screen. From the signal, information about the defect location, size, orientation and other features can be obtained[3]. By viewing the echo pattern from a reference part and then looking for differences in the patterns received from test pieces, a trained operator can easily locate hidden flaws.

Weld inspection is an important application for ultrasonic flaw detectors.

As the physical structure of a material changes, so will the way in which sound waves pass through it. Ultrasonic material analysis generally involves looking at parameters such as sound speed, sound attenuation or scattering and frequency content of echoes. These parameters help to analyze or qualify material properties, including an elastic modulus, density, grain structure, crystal orientation or polymerization patterns. Because sound-transmission properties of different materials vary, ultrasonic material analysis is a comparative process. Generally, a test is set up using reference standards representing the range of conditions to be quantified.

**Fig. 7. Ultrasonic flaw detector**

**Fig. 7A. Ultrasonic detection process**

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**Leak Testing**

Leak testing is the branch of nondestructive testing that is concerned with the escape of liquids, vacuum or gases from sealed components or systems. The three most common reasons for performing a leak test are content loss, contamination and reliability.

In order to effectively leak test an object, a number of questions should be asked, such as: What is the purpose of the test? Is it to locate every leak of a certain size? Is it to measure the total leakage from the test object without regard to leak number or location? After the purpose of the test has been defined, the selection criteria most often utilized is whether the test object is under pressure or vacuum. Many methods are reliable only under one of these conditions.

Another important criterion is the size of the test object. For example, as the size of the object expands, electronic methods for locating leaks in pressurized units become increasingly impractical due to stratifying of the tracer and the slowness with which the detector probe must be moved. By contrast, mass produced, hermetically sealed items that are accessible only on an external surface is where electronic methods excel[3].

There are a great number of leak-testing methods. Each method has its own advantages and disadvantages and has its own optimum sensitivity range. However, not all methods are useful for every application. By applying a number of selection criteria, the choice can often be narrowed to two or three methods with the final choice being determined by special circumstances or cost effectiveness. Some of these methods involve:

- Bubble testing
- Electronic gas detection
- Mass flow
- Mass spectrometer (helium leak detector)
- Pressure differential/decay
- Ultrasonic leak detector

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**Acoustic Emission**

Acoustic emission (AE) is sound waves emitted by microcracks as they are created or move (Fig. 8). The sound waves propagate through the sample and are recorded by an acquisition system that continuously listens to the sample. Processing techniques similar to those used by seismologists are applied in order to determine information concerning the AE abundance, locations and mechanics. This leads to an analysis of the cracks that have created them[7].

Acoustic-emission technology can determine the amount and intensity of fracturing as it is occurring as well as delineate regions of damage. Microcrack distributions, mapped three-dimensionally through time, describe damage accumulation, crack coalescence and macrofracture propagation. In addition, AE mechanisms (fault-plane solutions and moment tensors) can determine microcrack orientations and failure properties (tensile crack growth, frictional sliding, grain crushing).

In combination with ultrasonic testing, damage to parts can be quantified and failure mechanisms understood.

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**Infrared Thermal Imaging**

The basis of infrared thermography is quite
simple. All objects emit heat or infrared (electromagnetic) energy, but only a very small portion of this energy is visible to our eyes – the infrared wavelength is longer than that of visible light but shorter than a radio wave. In order to see the heat being emitted, an infrared camera must be used. The camera detects this invisible thermal energy and converts it to a visible image. Special training is required to properly interpret these images.

Mechanical and electrical systems are two basic sources of infrared energy. All mechanical systems generate thermal energy during normal operation, which allows infrared thermography to evaluate their operating condition. One of the biggest problems in mechanical systems is excessive temperature. This excessive heat can be generated by friction, cooling degradation, material loss, blockages or an excessive amount of friction caused by wear, misalignment, over or under lubrication and misuse. In mechanical applications, thermography is more useful for locating a problem area than for indicating the root cause. Other equipment such as vibration analysis, oil analysis and ultrasound can be employed to further determine where the problem actually lies.

The first step in evaluation is to establish a normal thermal signature. Afterwards, any deviation from this normal signature will then provide evidence of a developing problem. For example, thermography is
ideally suited for locating and measuring the temperature of areas where refractory has failed (Fig. 9)[8]. Infrared thermography and ultrasonic leak detection can often complement each other. For example, a faulty electrical connection will produce detectable ultrasound before it generates enough heat to be detected by thermographic imaging. Likewise, thermography can highlight hot spots that ultrasound equipment may never detect.

Conclusion
Nondestructive testing is an invaluable tool in both preventing failures and analyzing why they occurred. Each method described above has its relative merits and limitations, so the selection of the tool(s) that best suits your particular application is the key to success. IH

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References
2. The Open University (www.open.ac.uk)
3. NDT Resource Center (www.ndt-ed.org)
4. Private Correspondence, Bill Buschur - ibg NDT Systems Corporation (www.ibgndt.com)
6. American Gas and Chemical Company, Ltd. (www.amgas.com)
7. ESG Solutions (www.esg.ca)
8. Academy of Infrared Thermography (www.infraredtraining.net)
9. Private Correspondence, Steven Berg, Berg Engineering & Sales Co., Inc. (www.bergeng.com)

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