This IBM z10 microprocessor chip is the type of product that must be inspected via nondestructive testing methods. Image courtesy IBM.

COMPARISON OF NDT METHODS
MAGNETIC PARTICLE INSPECTION
SCANNING AUGER MICROPROBE
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Overview of Nondestructive Testing

Nondestructive Testing (NDT) and inspection techniques for detecting and evaluating flaws (irregularities or discontinuities) or leaks in engineering systems are reviewed in this article.

Of the many different NDT techniques, liquid penetrant and magnetic particle testing account for about half of all nondestructive tests. Ultrasonic and X-ray methods account for about another third, eddy current testing about 10%, and all other methods for only about 2%. Table 1 is a simplified breakdown of the complexity and relative requirements of the five most frequently used NDT techniques. Table 2 compares common NDT methods.

**Table 1 — Relative cost and other characteristics of various NDT methods**

<table>
<thead>
<tr>
<th>Important considerations</th>
<th>Ultrasonics</th>
<th>X-ray</th>
<th>Eddy current</th>
<th>Magnetic particle</th>
<th>Liquid penetrant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost</td>
<td>Medium to high</td>
<td>High</td>
<td>Low to medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Consumable cost</td>
<td>Very low</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Time of results</td>
<td>Immediate</td>
<td>Delayed</td>
<td>Immediate</td>
<td>Short delay</td>
<td>Short delay</td>
</tr>
<tr>
<td>Effect of geometry</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Not too important</td>
<td>Not too important</td>
</tr>
<tr>
<td>Access problems</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
</tr>
<tr>
<td>Type of defect</td>
<td>Internal</td>
<td>Most</td>
<td>External</td>
<td>External</td>
<td>Surface breaking</td>
</tr>
<tr>
<td>Relative sensitivity</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Formal record</td>
<td>Expensive</td>
<td>Standard</td>
<td>Expensive</td>
<td>Unusual</td>
<td>Unusual</td>
</tr>
<tr>
<td>Operator skill</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Operator training</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
</tr>
<tr>
<td>Training needs</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Portability of equipment</td>
<td>High</td>
<td>Low</td>
<td>High to medium</td>
<td>High to medium</td>
<td>High</td>
</tr>
<tr>
<td>Dependent on material composition</td>
<td>Very</td>
<td>Quite</td>
<td>Very</td>
<td>Magnetic only</td>
<td>Little</td>
</tr>
<tr>
<td>Ability to automate</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>Capabilities</td>
<td>Thickness gaging; some composition testing</td>
<td>Thickness gaging</td>
<td>Thickness gaging; grade sorting</td>
<td>Defects only</td>
<td>Defects only</td>
</tr>
</tbody>
</table>

**Table 2 — Comparison of various NDT methods**

<table>
<thead>
<tr>
<th>Method</th>
<th>Characteristics detected</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Example of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonics</td>
<td>Changes in acoustic impedance caused by cracks, nonbonds, inclusions, or interfaces</td>
<td>Can penetrate thick materials; excellent for crack detection; can be automated</td>
<td>Normally requires coupling to material either by contact to surface or immersion in a fluid such as water. Surface needs to be smooth.</td>
<td>Adhesive assemblies for bond integrity; laminations; hydrogen cracking</td>
</tr>
<tr>
<td>Radiography</td>
<td>Changes in density from voids, inclusions, material variations; placement of internal parts</td>
<td>Can be used to inspect wide range of materials and thicknesses; versatile; film provides record of inspection</td>
<td>Radiation safety requires precautions; expensive; detection of cracks can be difficult unless perpendicular to x-ray film.</td>
<td>Pipeline welds for penetration, inclusions, and voids; internal defects in castings</td>
</tr>
<tr>
<td>Visual optical</td>
<td>Surface characteristics such as finish, scratches, cracks, or color; strain in transparent materials; corrosion</td>
<td>Often convenient; can be automated</td>
<td>Can be applied only to surfaces, through surface openings, or to transparent material</td>
<td>Paper, wood, or metal for surface finish and uniformity</td>
</tr>
<tr>
<td>Eddy current</td>
<td>Changes in electrical conductivity caused by material variations, cracks, voids, or inclusions</td>
<td>Readily automated; moderate cost</td>
<td>Limited to electrically conducting materials; limited penetration depth</td>
<td>Heat exchanger tubes for wall thinning and cracks</td>
</tr>
<tr>
<td>Liquid penetrant</td>
<td>Surface openings due to cracks, porosity, seams, or folds</td>
<td>Inexpensive, easy to use, readily portable, sensitive to small surface flaws</td>
<td>Flaw must be open to surface. Not useful on porous materials or rough surfaces</td>
<td>Turbine blades for surface cracks or porosity; grinding cracks</td>
</tr>
<tr>
<td>Magnetic particles</td>
<td>Leakage magnetic flux caused by surface or near-surface cracks, voids, inclusions, or material or geometry changes</td>
<td>Inexpensive or moderate cost, sensitive both to surface and near- surface flaws</td>
<td>Limited to ferromagnetic material; surface preparation and post-inspection demagnetization may be required</td>
<td>Railroad wheels for cracks; large castings</td>
</tr>
</tbody>
</table>
Magnetic Particle Inspection

Magnetic particle inspection locates surface and subsurface discontinuities in ferromagnetic materials.

Magnetic-particle inspection is based on the fact that when a ferromagnetic material is magnetized, discontinuities that lie in a direction generally transverse to the direction of the magnetic field cause a leakage field to form at and above the surface. The presence of the leakage field, and therefore the presence of the discontinuity, is detected by finely divided ferromagnetic particles applied over the surface. Some of the particles are gathered and held by the leakage field.

The magnetically held particles form an outline of the discontinuity and generally indicate its location, size, shape, and extent. Magnetic particles are applied over a surface either as dry particles, or as wet particles in a liquid carrier such as water or oil.

The magnetic-particle method is a sensitive means to locate small, shallow surface cracks. Those large enough to be seen by the naked eye can produce an indication, but very wide cracks do not produce a particle pattern if the surface opening is too wide for the particles to bridge.

Discontinuities that do not actually break through the surface also are indicated in many instances within certain limitations. Fine, sharp discontinuities close to the surface (a long stringer of nonmetallic inclusions, for example) can produce an indication. However, indications of deeper discontinuities are less distinct.

Magnetic limitations

The operator must be aware of certain limitations of magnetic-particle inspection. For example, thin coatings of paint and nonmagnetic coverings, such as plating, adversely affect sensitivity. Other limitations:

- Workpiece material must be ferromagnetic.
- The direction of the magnetic field must intercept the principal plane of the discontinuity at right angles for best results. This could require two or more sequential inspections with different magnetizations.
- Demagnetization following inspection often is necessary.
- Postcleaning to remove remnants of magnetic particles and carrying solutions on the surface could be required after testing and demagnetization.
- Inspection of very large parts could require very large current.
- Local heating and burning of finished parts and surfaces at the points of electrical contact is possible if care is not taken.
- Experience and skill are required to interpret the significance of magnetic-particle indications.

Magnetic fields

- **Horseshoe magnet:**
  When a magnetic material is placed across the poles of a horseshoe magnet having square ends (forming a closed or ring like assembly), the magnetic lines of force flow from the north pole through the magnetic material to the south pole (see Fig. 1a). Magnetic lines of force flow preferentially through magnetic material rather than through nonmagnetic material or air. The magnetic lines of force are enclosed within the ringlike assembly because no external poles exist, and iron filings or magnetic particles dusted over the assembly are not attracted to the magnet even though lines of magnetic force are flowing through it.

  If one end of the magnet is not square, leaving an air gap between the magnet end and the magnetic material, the poles still attract magnetic materials. Magnetic particles cling to the poles and bridge the gap between them, as shown in Fig. 1b. A radial crack in a round magnetized piece creates north and south magnetic poles at the edges of the crack. Magnetic particles are attracted to the poles created by such a crack, forming an indication of the discontinuity.

  The magnetic fields at cracks and other physical and magnetic discontinuities in the surface are called leakage fields. The strength of a leakage field determines the number of magnetic particles that will gather to form indications; strong indications are formed at strong fields, and vice versa. The density of the magnetic field determines its strength and is partly governed by the shape, size, and material of the part being inspected.

- **Bar magnet:** A straight piece of magnetized material (bar magnet) has a pole at each end. Magnetic lines of force flow through the bar from the south pole to the north pole. Because the magnetic lines of force within the bar magnet run the length of the bar, it is said to be longitudinally magnetized or to contain a longitudinal field.

  If a bar magnet is broken into two pieces, a leakage field with

---

Fig. 1—(a) Horseshoe magnet with a bar of magnetic material across poles forms a closed, ringlike assembly, which will not attract magnetic particles. (b) Ringlike magnet assembly with an air gap, to which magnetic particles are attracted.
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north and south poles is created between the pieces, as shown in Fig. 2a. The field exists even if the fracture surfaces are brought together (see Fig. 2b). If the magnet is cracked but not broken completely into two pieces, a similar result occurs. A north and a south pole form at opposite edges of the crack, just as though the break were complete (see Fig. 2c). It is this field that attracts the iron particles that outline the crack. The strength of the poles is different from that of the completely broken pieces; it is a function of the crack depth and the width of the air gap at the surface.

- **Circular magnetic field:** Electric current passing through any straight conductor such as a wire or bar creates a circular magnetic field around the conductor. The passage of current through a ferromagnetic conductor induces a magnetic field in both the conductor and surrounding space. A part magnetized in this manner is said to have a circular field or to be circularly magnetized, as shown in Fig. 3a.

- **Longitudinal magnetization:** Electric current also can create a longitudinal magnetic field in magnetic materials. When current is passed through a coil of one or more turns, a magnetic field is established lengthwise, or longitudinally, within the coil, as shown in Fig. 3b. The nature and direction of the field around the conductor that forms the turns of the coil produce longitudinal magnetization.

**Magnetic flux direction**

To form an indication, the magnetic field must approach a discontinuity at a sufficiently large angle to cause the magnetic lines of force to leave the part and return after bridging the discontinuity. An intersection approaching 90 degrees produces the best results. For this reason, discontinuity direction, size, and shape are important. The direction of the magnetic field, and the strength of the field in the area of the discontinuity also are important for optimum results.

Figure 4a illustrates a condition in which the current is passed through the part, causing formation of a circular field. Under normal circumstances, there would be no indication of the presence of a discontinuity such as one designated “A” in Fig. 4a because it is regular in shape and lies in a direction parallel to that of the magnetic field.

A discontinuity having an irregular shape and predominantly parallel to the magnetic field, “B,” has a good chance to form a weak indication. Where the predominant direction of the discontinuity is at a 45 degree angle to the magnetic field, such as at “C,” “D,” and “E,” the conditions are more favorable for detection regardless of the shape of the discontinuity. Discontinuities whose predominant directions, regardless of shape, are at a 90 degree angle to the magnetic field (“F,” “G,” and “H”) produce the most pronounced indications.

Figure 4b shows a bar that has been longitudinally magnetized. Discontinuities “I,” “M,” and “N,” which are at about 45 degrees to the magnetic field, would produce detectable indications, as they would in a circular field. Discontinuities “J” and “K” would display pronounced indications, but discontinuities “P,” “Q,” and “R” would probably not be detected.

### Magnetization methods

In magnetic-particle inspection, the magnetic particles can be applied to the part while the magnetizing current is flowing, a technique known as the “continuous method.” When the magnetic particles are applied after the current has ceased to flow, depending largely on the magnetization retention (residual magnetism), it is called the “residual method.”

If residual magnetism does not provide a leakage field strong enough to produce readable indications when magnetic particles are applied to the surface, the part must be continuously magnetized during application of particles. Consequently, the residual method can be used only on materials that retain sufficient magnetism, usually harder materials. The continuous method is the only method used on low-carbon steels and iron, which retain little residual magnetism, having little or no retentivity.

**For more information:** This information is from the ASM Handbooks Online, Volume 17, Nondestructive Evaluation and Quality Control → Magnetic Particle Inspection.
Auger electron spectroscopy involves precise measurements of the number of emitted secondary electrons as a function of kinetic energy.

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Albuquerque, New Mexico

The scanning Auger microprobe (SAM) is basically a scanning electron microscope (SEM) with two additional features:

- An Auger electron detector replaces the X-ray detector. The Auger detector measures the energies of Auger electrons emitted from the sample. These characteristic energies enable identification of the elements in the first few atomic layers of the surface. The concentrations of each element can also be determined from the number of electrons detected at each characteristic energy. All elements except hydrogen and helium can be identified and analyzed in this way.
- An in situ ion milling capability provides for gradual removal of surface layers, thereby permitting depth profiling of elemental compositions within about one micron of the surface.

Typical capabilities

These capabilities make the SAM well suited for the following types of applications:

- Identification and mapping of light elements (atomic numbers 3 to 9) that are difficult to detect via SEM or electron probe microanalysis (EPMA).
- Elemental characterization of surface contaminants.
- Depth profiling of elemental compositions within about one micron of the surface. This is especially applicable for microelectronics.
- Secondary electron imaging of surface topography: 10 nm (same as SEM).
- Auger electron characterization of elemental chemistry: 10 to 20 nm; sampling depth is about one millimeter.
- Threshold sensitivity: 0.5%.
- Precision of quantitative analyses: 10% relative or 0.5% absolute, whichever is greater.

Limitations

- Cannot detect hydrogen or helium.
- Quantitative analyses are typically lower in quality than those of EPMA.
- Samples up to 2.5 cm diameter and 0.5 cm thick can be accommodated by most SAMs; larger samples can be accommodated by instruments designed for this purpose.
- Provisions must be made for charge to bleed off. Ideal samples are electrically conductive and must be free of fingerprints, oils, and other high vapor pressure materials.
- Flat samples are preferred, but rough samples can also be accommodated.

Operating principles

As noted above, the scanning Auger microprobe is essentially an SEM to which an Auger electron detector and an ion miller have been added, Fig. 1. An electron beam is produced and focused to a small spot on the sample surface. This spot can be rastered across an operator-defined area of the surface or stopped and moved to a particular location of interest. The beam penetrates the sample and interacts with the atoms in the first 1 micron, exciting atoms and producing secondary electrons, exactly as in the scanning electron microscope. A secondary electron detector provides the capability to image the surface and locate areas of particular interest, as in a scanning electron microscope. However, the primary tool for chemical analysis is the Auger electron detector.

Auger electrons are produced whenever incident radiation—photons, electrons, ions, or neutral atoms—interacts with an atom with an energy exceeding that necessary to remove an inner-shell electron (K, L, M, . . .) from the atom. This interaction, or scattering process, leaves the atom in an excited state with a core hole, that is, a missing inner-shell electron. These excited atoms are unstable, and de-excitation occurs immediately, resulting in the emission of an X-ray or an electron termed an Auger electron. Figure 2 illustrates this process with incident X-rays. When the X-ray is absorbed by an inner-shell electron, the electron is emitted from the atom and is termed a photoelectron. The resulting atom with a K electron missing is unstable, and de-excitation occurs immediately, resulting in emission of an X-ray or Auger electron.

An Auger electron is an electron from one of the outer shells.
that is ejected from the atom with kinetic energy equal to the energy released by the relaxation event, minus the energy required to remove the Auger electron from its orbit (Fig. 2). Because both energies associated with the relaxation events and the binding energies of the outer shell electrons provide characteristic “fingerprints” for each element, so do their differences, the energies of Auger electrons. Hence, the energies of Auger electrons can also be detected and used to identify which elements are in the portion of the sample being excited by the incident electron beam. These characteristic Auger electrons typically have energies of tens to thousands of electron volts.

The tendency for excited atoms to relax by Auger electron production versus X-ray photon emission increases with decreasing atomic number. Elements with atomic numbers less than 7 produce few characteristic X-rays but many Auger electrons (except for hydrogen and helium). As a result, SAM is commonly used for microstructural detection and quantification of such elements.

Higher atomic number elements, however, produce more X-rays, so these elements are typically detected and quantified using SEM or EPMA. Although for analysis of the first few atomic layers, SAM provides elemental analyses corresponding to this very near surface region.

Although Auger electrons are generated throughout the beam-sample interaction...
volume, most of these dissipate some or all of their characteristic energies by interacting with the electrons belonging to other atoms in the sample. The only Auger electrons that escape the sample with their original characteristic energies are those generated within a few atom layers of the sample’s surface. If the energies of all emitted electrons are detected and analyzed, then a graph similar to Fig. 3 is obtained. The lowest energy range is dominated by secondary electrons, the highest energy range is dominated by backscattered electrons, and the mid-energy range is dominated by Auger electrons, nearly all of which have had their characteristic energies reduced by interactions with the sample. But if Fig. 3 is examined closely, small signals can be found at particular energies. These represent the characteristic energies of the “undisturbed” Auger electrons that were generated by atoms at the surface or within a few atomic distances below the surface.

Energy measurement
The energies of the emitted electrons are usually measured by a cylindrical “mirror” that has a variable negative potential applied to it, as shown in Fig. 1. As electrons enter the inlet aperture and pass though the analyzer chamber, the negative bias on the wall of the chamber repels them and causes them to travel in curved paths. The curvature of this path varies inversely with the kinetic energy of each electron; the paths of electrons with low kinetic energy are more easily deflected than those paths of electrons with high kinetic energy. This information provides a means of measuring the energy distribution of the electrons emitted from the sample. An electron detector is mounted near the exit aperture of the cylindrical mirror, and the negative bias applied to the mirror is gradually increased. The numbers of electrons entering the detector is counted as a function of mirror bias. This information enables the energy distribution of the electrons to be plotted.

The portion of the signal corresponding to the “undisturbed” Auger electrons is very small compared with the signal resulting from backscattered and Auger electrons whose energies have been reduced by interactions within the sample. This situation is typically overcome by differentiating the signal and plotting $dN/dE$ versus $E$, as shown in Fig. 3. Because the Auger electrons typically originate in the outer electron shells, their energies are somewhat affected by bonding between atoms. These small energy shifts, which can frequently be discriminated by the energy analyzer, provide the ability to determine some information about the elements to which the atoms of interest are bonded.

Scanning Auger microprobe results are often presented as secondary electron images with accompanying Auger electron spectra identifying the elements present in particular features of interest. Low atomic number elements that cannot be detected by SEM and EPMA are readily detected in Auger spectra. Figure 4 provides an example of the use of Auger electrons to detect low atomic number elements with high spatial resolution.

Alternatively, the detector can be set to the energy associated with a particular element or compound of interest and the electron beam rastered over the surface, resulting in a map indicating the areas of high concentration of this material (Fig. 5).

For more information: This article is from the online Desk Edition of the ASM Metals Handbook → Surface Analysis → Scanning Auger Microprobe (SAM).

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