

# New Directions in Eddy Current Sensing

Nondestructive testing needs an effective, inexpensive way of detecting deeply buried or small cracks at the edges of metallic parts and structures. One solution comes in the form of solid-state magnetic sensors based on giant magneto-resistance (GMR) and spin-dependent tunneling (SDT) effects integrated in eddy current probes.

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**E**ddy current testing is an effective way of detecting fatigue cracks and corrosion in conductive materials. The cost of using the technology is low, and the devices can monitor subsurface defects and defects under insulating coatings without touching the surface of the specimen. Although this technique is applicable for many tasks, the aircraft and nuclear power industries are the primary users of eddy current probes for in-service inspection.

Because safety-critical systems depend on early detection of fatigue cracks to avoid major failures, there's an increasing need for eddy current probes that can reliably detect very small defects. Also there are increasing demands for probes that can detect deeply buried defects to avoid disassembling structures.

## **Enhancing Eddy Current Probes**

Eddy current testing probes combine an excitation coil that induces eddy currents in a specimen and a detection element that identifies the perturbation of the currents caused by cracks or other defects. The detection elements can be coils, superconducting quantum interference detectors, or solid-state magnetic sensors (e.g., Hall effect, magneto-resistive, and spin-dependent-tunneling sensors). The use of low-field, solid-state magnetic sensors represents a significant advance over more traditional inductive probes in use today. Two key attributes will open opportunities for increased use of eddy current probes: constant sensitivity over a wide range of frequencies and development of smaller sensors.

Probes that detect eddy current fields using inductive coils have less sensitivity at low frequencies. Unfortunately, this is where the device would have to operate to detect deep flaws. Small sensing coils, which are required to detect small defects, also have low sensitivity. In contrast, small, high-sensitivity thin film sensors can locally measure a magnetic field over an area comparable to the size of the sensor itself (tens of micrometers).

A limitation of conventional eddy current probes is the difficulty of detecting small cracks originating at the edges of a specimen. This defect is the most common type encountered in practice. An example is the cracks that appear around the fastener or rivet holes in aircraft multilayered structures. Most inductive coil probes are sensitive to both the edge and the cracks initiating from or near the edge. The edge creates a large signal that obscures the small signal from the crack. GMR and SDT magnetic sensors can be oriented to eliminate the edge signal. With this orientation, the presence of the edge enhances the signal from the crack.

To achieve high resolution for detecting small surface and near-surface defects, you have to reduce the dimensions of the excitation coil. The minimum length of a detectable crack is roughly equal to the mean radius of the coil. Sensor developers have successfully developed and tested probes incorporating small, flat, pancake-type coils or planar excitation coils deposited on the sensor substrate.

Developers fabricated the first fully integrated eddy current probes using planar technology to precisely position and align the excitation coil with respect to the sensor. This makes large-quantity, high-reproducible probe production economically viable. The technology makes it possible to produce integrated arrays of eddy current probes for fast inspection and—in some applications—to eliminate the need to mechanically scan the probe during inspection.

Exploiting their sensitivity to surface irregularities, high-resolution GMR- and SDT-based eddy current probes have found new applications in imaging metallic profiles. Coin imaging based on the sensing of eddy current perturbations represents just one potential method for detecting counterfeit coins (see Photo 1). Unlike the optical method, the eddy current measurement gives information not only on the actual profile but also on the material.



Photo 1. This image is produced not by light but by scanning it with an eddy current probe containing an SDT sensor. The pixel resolution is 0.1 mm on both axes. When you monitor the perturbations in eddy currents caused by surface irregularities, the probe behaves as a differential proximity sensor. By measuring the magnitude of the signal, you can obtain information about the coin material.

### **GMR and SDT Technologies**

Recent developments in thin film magnetic technology have resulted in films exhibiting a large change in resistance with magnetic field [1]. This phenomenon is called giant magneto-resistance to distinguish it from conventional anisotropic magneto-resistance (AMR). Whereas AMR resistors exhibit a change of resistance of <3%, various GMR materials achieve about a 10%–20% change in resistance.

GMR films have two or more magnetic layers separated by a nonmagnetic conductive layer. Because of spin-dependent scattering of conduction electrons, the resistance is maximum when the magnetic moments of the layers are anti-parallel and minimum when they're parallel.

SDT structures are a recent addition to the materials exhibiting a large change in resistance. In these structures, an insulating layer separates two magnetic layers. Quantum tunneling through the insulator allows conduction. The angle between the magnetization vectors in the two magnetic layers modulates the magnitude of the tunneling current between the two layers.

Researchers have observed changes of resistance of 10%–40% in SDT structures. The field required for maximum change in resistance depends on the composition of the magnetic layers and the method of achieving antiparallel alignment. Values of the saturating field range from 1.25 to 125 Oe. At the low end, this offers the possibility of extremely sensitive magnetic sensors.

Researchers are adapting SDT materials to create highly sensitive magnetic field sensors for use in low-field applications that presently require fluxgate magnetometers [2]. These sensors are very small (SOIC-8 package), require little power, and are easily combined with other electronics. The insulating, tunneling layer provides high-resistance sensors suitable for battery operation. Developers can fabricate extremely small SDT devices (several tens of micrometers on a side) with high resistance using photolithography, allowing dense packing of magnetic sensors in small areas.

### **Eddy Current Probe Configuration**

The main components of an eddy current probe for nondestructive testing are a pancake-type coil and a Wheatstone bridge of GMR or SDT sensors (see Figure 1).

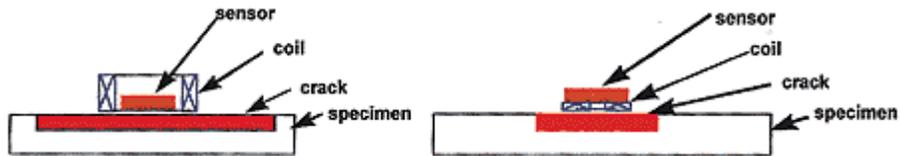


Figure 1. An eddy current probe consists of an excitation coil and a sensor. The size of the coil is a function of the size of the defect being analyzed.

When measuring the sensing axis, you must keep the GMR or SDT probe coplanar with the surface of the specimen. The excitation field on the coil axis, being perpendicular to the sensing axis of the GMR or SDT film, has no effect on the sensor. In this way, the detected field, which is the result of the perturbation of the eddy current flow paths caused by the crack, is separated from the excitation field.

Eddy currents induced in the surface of a defect-free specimen are circular because of the circular symmetry of the field produced by the coil. The tangential component of the field created by the eddy currents is zero at the location of the sensor. In the presence of defects, the eddy currents are no longer symmetrical, and the probe provides a measure of the perturbed eddy currents caused by the underlying flaws.

Figure 2 illustrates the perturbation of the eddy currents by a flaw. The size of the coil is related to the resolution necessary to detect the defects. For large defects and for deep defects, large coils surrounding the sensor are required. Smaller coils located close to the specimen are necessary to resolve small defects.

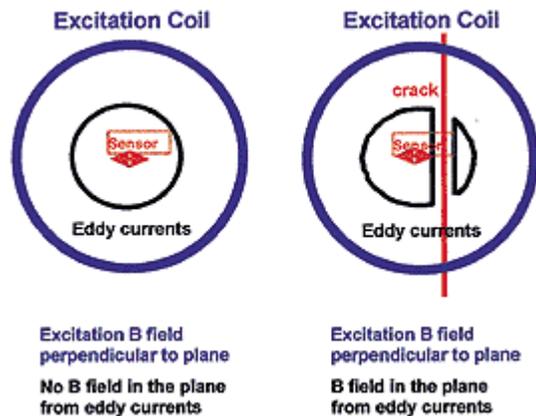


Figure 2. Magnetic fields from the excitation coils create circular eddy currents in the conducting surface below the coils. These eddy currents form along the sensitive axis of the sensor, which is parallel to the conducting surface. A crack or defect alters the eddy current paths, resulting in magnetic fields parallel to the conducting surface and along the sensitive axis of the sensor.

Eddy currents shield the interior of the conducting material with the skin depth related to the conductivity and the frequency. By changing the frequency, you can probe differing depths of the material. GMR or SDT sensors (with their wide frequency response, from DC to the megahertz range) are well suited to this application. The small size of the sensing element increases the resolution of defect location while the detector is raster-scanned over the surface. More rapid scans can be performed using an array of detectors.

Sensor designers built optimized eddy current probe prototypes to detect and map different types of defects encountered in practice. They evaluated probe performance on calibrated slots of different lengths, widths, and heights machined into the top surface, bottom surface, or edges of a specimen. The designers also obtained results on a specimen that contained real cracks artificially grown around a hole. Finally, they demonstrated magnetic profile imaging by scanning a penny using a high-resolution probe.

### Surface Cracks

Eddy current probes were tested on surface cracks longer than the excitation coil diameter. The quality of the maps produced when scanning this type of defect depend on the relative orientation of the sensitive axis of the SDT or GMR sensing elements with respect to the crack orientation. Figure 3A shows the output of the sensor when it was raster-scanned over a crack 15 mm long and 2 mm deep, with the sensitive axis perpendicular to the crack direction. The asymmetry in the magnetic field

is detected as peaks between two shoulders on either side of the crack. The distance between shoulders is approximately equal to the length of the crack. When the sensing axis was parallel to the crack, two peaks, corresponding to the tips of the cracks, were detected (see Figure 3B).

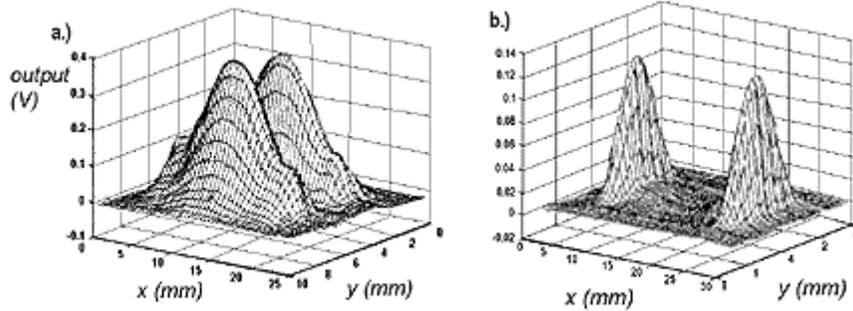


Figure 3. When the eddy current probe passes over a crack with its sensitive axis perpendicular to the crack, an output appears at either side of the crack (A). When the probe passes over the crack with its sensitive axis parallel to the crack, the peaks appear at the end of the crack (B).

Short surface cracks can also be reliably detected using small excitation coils. So far, surface cracks <1 mm long have been measured with the SDT-based, eddy current probes.

### Edge Cracks

The unidirectional sensitivity of GMR and SDT sensors enables the detection of cracks at and perpendicular to the edge of a specimen [3]. This discrimination is possible because the sensitive axis of the sensor can be oriented parallel to the edge. Consequently, the output signal of the sensor is caused only by the crack.

A practical example is the detection of cracks initiating at the edge of a rivet hole. The specimen contains two surface cracks, one 2.65 mm long and the other 2.75 mm, occurring on either side of a 6.4 mm diameter hole on a 3 mm thick aluminum plate. The thin cracks can't be observed visually. A magnified picture of one of the cracks taken with a microscope is shown in Photo 2.

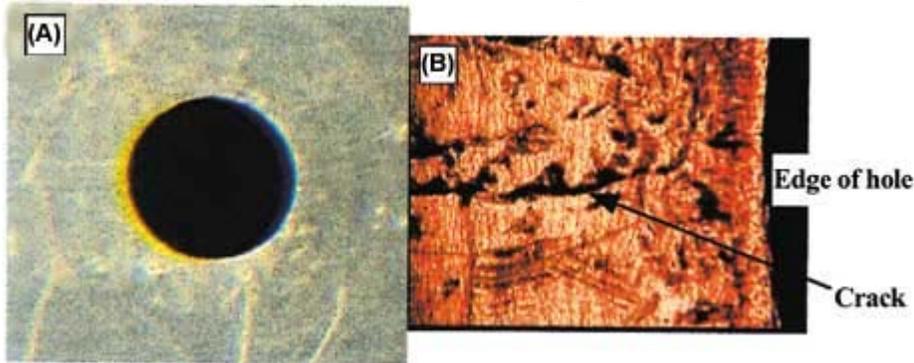


Photo 2. The small microscopic cracks around a 6 mm rivet hole cannot be seen by the naked eye (A). The cracks can be viewed only through a microscope (B).

The test was performed by radial scanning the SDT probe over a ring containing the hole. The sensitive axis was maintained in the circumferential direction to detect radial cracks.

A 3D map indicating the output voltage of the probe as a function of the X,Y position above the plate is shown in Figure 4.

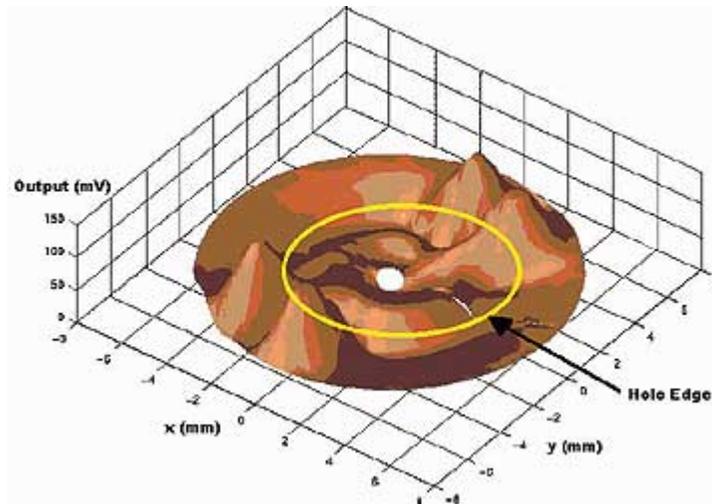


Figure 4. The image above shows a microscopic crack visible to an SDT eddy current sensor.

The map indicates two pairs of peaks, which correspond to the presence of two cracks. The cracks can be precisely located between the pairs of peaks.

### Deeply Buried Edge Cracks

SDT sensors are particularly attractive for nondestructive evaluation, low-frequency applications, such as the detection of deeply buried flaws. In contrast, inductive probes have poor sensitivity at low frequencies because they are sensitive to the time derivative of the magnetic field rather than to the magnitude of the magnetic field created by the flaw.

To detect deep cracks, you have to use large diameter excitation coils to increase the penetration of the eddy currents in the material under test. SDT-based probes were used to detect edge cracks at the bottom of both a single plate and a stack of aluminum plates. An edge crack 3 mm long and 3 mm high was detected 18 mm below the surface, and one 15 mm long and 3 mm high was detected at 23 mm at the bottom of a two-layer aluminum structure.

Figure 5 shows the results of a single scan along the edge and across the buried crack in both magnitude and phase representation. This shows the potential of using SDT eddy current probes.

### What Next?

As sensor development progresses, the next challenge will be to design, develop, and produce marketable eddy current probes for surface and deep crack applications. Probe arrays for rapid data acquisition and patterned arrays to conform to specific specimen geometries will also be developed.

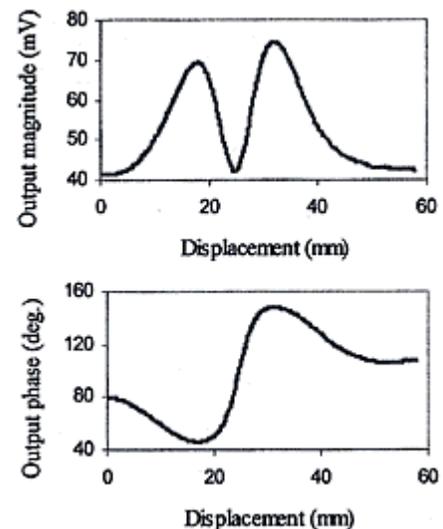


Figure 5. The signature of a 15 mm long edge crack 9 mm below the surface is easily seen both in the magnitude and phase of the output of an SDT eddy current probe.

## References

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## Authors' Note

This article presents results of a collaborative development among the University of North Carolina–Charlotte, NVE Corp., and Albany Instruments to develop eddy current probes based on the recently developed GMR and SDT sensors. The Air Force, NASA, and NSF have sponsored this work.

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