# EDDY CURRENT INSPECTION


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## PROBLEM

In modern engineering works, the amount of time and effort devoted to inspection, and where necessary, to rectification is very large indeed. Moreover most of the times the required vital characteristics cannot be measured without inevitably breaking the work piece or making it unfit for use in one way or other.

## OBJECTIVE

To study ‘Eddy Current Inspection’ as a tool for non-destructive testing in production applications.


## ABSTRACT

The eddy-current inspection is based on the principle of electromagnetic induction and is used to identify or differentiate between a wide variety of physical, structural and metallurgical conditions in electrically conductive ferromagnetic and non-ferromagnetic metals and metal parts. Production applications for eddy-current testing include thread checking, crack detection, run out measurement, metallurgical analysis, and weld inspection.

One of the latest developments in eddy-current technology is its combination with contact gauging. With this technology, measurements of a hole can take place as fast as the probe can be inserted into and withdrawn from it.

However, the high sensitivity of the method can be a disadvantage as some non important variations in the material properties may cause signals that mask critical variables or are mistakenly interpreted as defects.

# INTRODUCTION

## What is Eddy Current Testing?

Non-destructive testing (NDT) aims detection and characterization of defects/flaws/discontinuities in a material without impairing the intended use of the material. Eddy Current Testing (ECT) is an electromagnetic NDT technique widely used in nuclear, aerospace, power, petrochemical and other industries to examine metallic plates, sheets, tubes, rods and bars etc. for detection and sizing of cracks, corrosion and other material discontinuities during manufacturing as well as in-service.
This is not a volumetric (radiography and ultrasonic) technique. Like liquid penetrant and magnetic particle techniques, this is a surface technique and can readily detect very shallow surface defects (fatigue cracks, intergranular stress corrosion cracks etc.) and sub-surface defects (inclusions, voids etc.) within a depth of, say 6 mm. Eddy current testing is a simple, high-speed, high-sensitive, versatile and reliable NDT technique and is popularly used in many engineering industries. Theory and principle of eddy current testing, advantages, limitations, applications and standards are covered briefly in this page.

Eddy current inspection systems are used to detect anomalies in metallic components. Manufacturers are interested in whether cracks and flaws are present in a part, whether the part has been correctly heat treated, whether parts have been made from the correct material and whether physical attributes such as thread or splines have been accurately machined. Modern eddy current systems can rapidly detect these conditions and enable assembly line integration.

As most hardness and case depth treatments are invisible to the naked eye, instrument testing becomes critical. Traditional static indentation testing, such as Rockwell and Vickers hardness tests, is time consuming, requires that the surface be perpendicular to the direction of the force applied by the tester and damages the part to some degree. In addition, these tests may be difficult to perform on curved or inside surfaces of complex shapes. Test accuracy also is affected by the surface roughness of the part, which can add surface preparation time to the test.

On the production line, a key is integrating high-speed eddy current inspection into the manufacturing and material handling systems.

## ADVANTAGES AND CAPABILITIES OF EDDY CURRENT TESTING

Advantages and capabilities of eddy current testing include:
· Instantaneous test results
· Rapid test speeds
· Automated, in-line testing
· Accurate measurements
· Wide range of applications

Instantaneous test results coupled with accurate measurements play a significant role in cost-effective testing. Random sampling of parts through destructive analysis is practically eliminated. Eddy current test data can be evaluated, results displayed, and sorting or marking can take place as parts are processed through the testing station, reducing scrap and production costs.

Extremely rapid test speeds are achievable in an automated system. When an automated ball bearing hardness inspection system is in place, for example, every bearing can be tested and sorted without production line slowdown. The eddy current test system with dynamic throughput can evaluate all ball bearings for hardness at test speeds of greater than 10 ball bearings per second. Production rates are often dictated and limited only by the mechanical reaction time of the material handling system.

Eddy current systems today can be installed and operated with minimal impact on existing manpower. The equipment can be operated and maintained by technicians with minimal training. The system can contribute to the final quality obtained in production processes by performing its job and forwarding test results as needed. This can be accomplished by interfacing the eddy current test equipment to a computer for Statistical Process Control (SPC) of test results, data tracking or trending and the monitoring of multiple production lines. [5]

## HISTORY

Eddy current testing has its origins with Michael Faraday's discovery of electromagnetic induction in 1831. In 1879 Hughes recorded changes in the properties of a coil when placed in contact with metals of different conductivity and permeability, but it was not until the second war that these effects were put to practical use in testing materials. Much work was done in the 1950’s and 60's, particularly in the aircraft and nuclear industries, and particularly in France where the nuclear industries are very present.

## WHAT CAN BE DETECTED?

Sensitivity is adjustable to suit individual customer requirements. The system is usually calibrated to meet approved standards such as American Society for Testing and Materials (ASTM) or American Petroleum Institute (API), which relate to the detection of drilled holes or notches of prescribed dimensions. To be detectable, natural defects must produce a disruption of the eddy current flow pattern which is equivalent to or greater than that produced by the calibration Standard. They must also, of course, occur within the field of inspection. They probably will not be visible at the surface. [9]

Typical flaws which show-up, include:
1. *Pin-holes*
2. *Cross cracks*
3. *Seam cracks*
4. *Porosity*
5. *Lack of fusion*
6. *Loss of scarf*
7. *Scarfing chatter*
8. *Impeder loss or inefficiency*
9. *Lamination*
10. *Butt welds*
11. *Hook cracks*
12. *Edge damage*
13. *Burred edges*
14. *Open seams*

Ultimate sensitivity is limited by the tube quality itself. For example, higher sensitivity is generally possible on cold-rolled rather than hot-rolled material.

## WHAT CANNOT BE DETECTED?

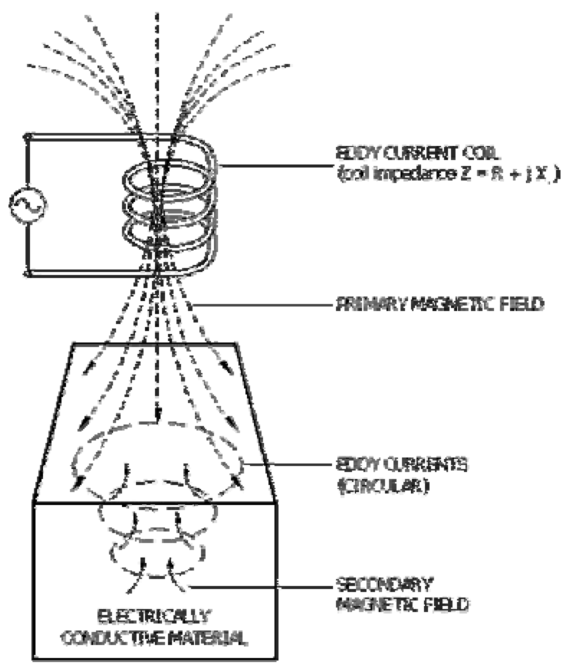
Typical defects that may be missed by eddy current inspection [9]:
1. *Slight undercut or over cut of scarf*
2. *Absolute loss of penetration*
3. *Certain "pasty" welds*
4. *Defects occurring outside the field of inspection*
5. *Brittle welds*
6. *Signals not exceeding calibration levels*
7. *Defects which are created during subsequent processing*

## EDDY CURRENT THEORY

### EDDY CURRENT TESTING PRINCIPLES AND THEORY

Eddy current testing works on the principles of electromagnetic induction (Maxwell's equations, electrical transformers, induction furnace, skin-effect, Ohm's law, Wheatstone bridge etc.). In eddy current (EC) technique, a coil (*also called probe or sensor*) is excited with sinusoidal alternating current (frequency, *f*, ~ 50 Hz-5 MHz) to induce what are called eddy currents (swirling or closed loops of currents that exist only in metallic materials) in an electrically conducting material such as stainless steel, aluminum etc. being tested. The change in coil impedance, Z that arises due to distortion of eddy currents at regions of discontinuities (defects, material property variations, surface characteristics etc,) and associated magnetic flux linkages, is measured and correlated with the cause producing it i.e. discontinuities.

Eddy currents are a problem in electrical engineering systems such as transformers, as they cause severe heating losses. However, they are used to advantage in eddy current non-destructive testing.



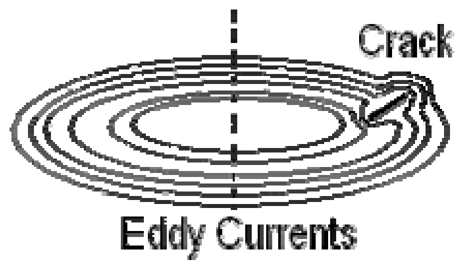

An eddy current coil can be considered to be having resistance and inductance in series in an AC circuit. According to Ohm's law, the circuit impedance Z (Voltage/Current) is a vector quantity with resistance R and inductive reactance $\chi_L$ as the real and imaginary components

$(Z=R+j\chi_L)$.

Briefly in eddy current testing, the following sequential things happen:

1. Eddy current coil generates primary magnetic field (Ampere's Law)
2. Primary magnetic field induces eddy currents in the material (Faraday's Law)
3. Eddy currents generate secondary magnetic field in the opposite direction (Lenz's Law)
4. Coil impedance changes, as a result
5. Impedance change is measured, analyzed and correlated with defect dimensions

The locus of impedance change formed during the movement of an eddy current probe coil over a test material having a defect is called an eddy current signal. The peak-to-peak amplitude of the eddy current signal provides information about the defect severity. The phase angle of the eddy current signal with respect to a known reference (lift-off) provides information about the defect location or depth. Defects that cause maximum perturbation to eddy current flow produce large eddy current response (signal amplitude) and hence detected with high sensitivity (see distortion figure below). Similarly, defects that are parallel to eddy current flow may not produce a significant change in coil impedance and as a result they produce a weak response i.e. detected with poor sensitivity.




## FACTORS AFFECTING EDDY CURRENT RESPONSE [2]

A number of factors, apart from flaws, will affect the eddy current response from a probe. Successful assessment of flaws or any of these factors relies on holding the others constant, or somehow eliminating their effect on the results. It is this elimination of undesired response that forms the basis of much of the technology of Eddy current inspection. The main factors are [2]:

### 1. Material conductivity

The conductivity of a material has a very direct effect on the eddy current flow: the greater the conductivity of a material the greater the flow of eddy currents on the surface.
Conductivity if often measured by an eddy current technique and inferences can then be drawn about the different factors affecting conductivity, such as material composition, heat treatment, work hardening etc.

### 2. Permeability

This may be described as the ease with which a material can be magnetized. For non-ferrous metals such as copper, brass, aluminum etc., and for austenitic stainless steels the
Permeability is the same as that of ‘free space’, i.e. the relative permeability ( $_r$) is one. For ferrous metals however the value of $_r$ may be several hundred, and this has a very significant influence on the eddy current response, in addition it is not uncommon for the permeability to vary greatly within a metal part due to localized stresses, heating effects etc.

### 3. Frequency

Eddy current response is greatly affected by the test frequency chosen, fortunately this is one property one can control.

### 4. Geometry

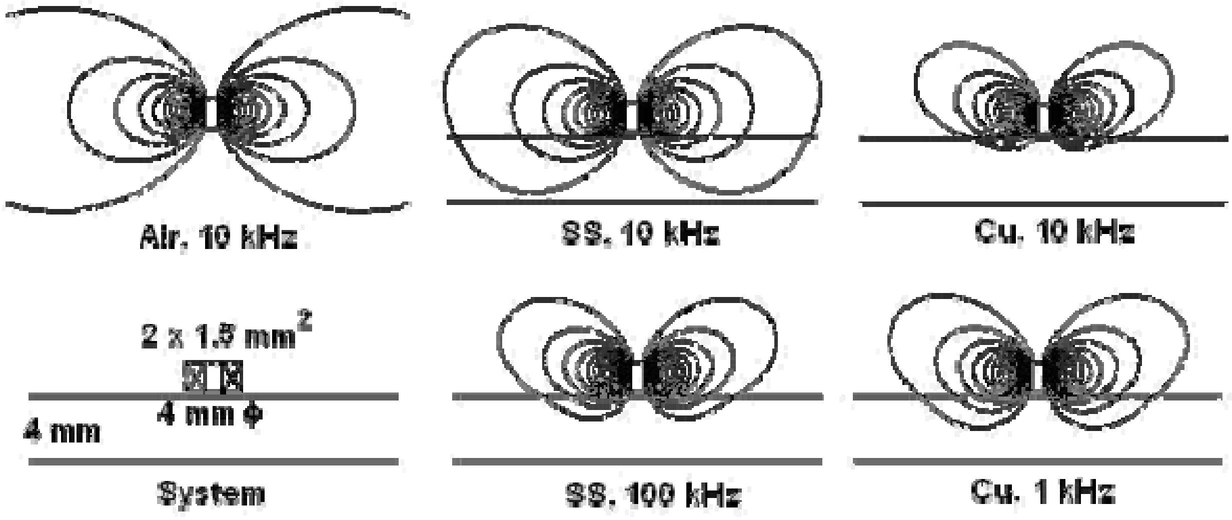
In a real part, for example one which is not flat or of infinite size, Geometrical features such as curvature, edges, grooves etc. will exist and will effect the eddy current response. Test techniques must recognize this, for example in testing an edge for cracks the probe will normally be moved along parallel to the edge so that small changes may be easily seen. Where the material thickness is less than the effective depth of penetration (see below) this will also affect the eddy current response.

### 5. Proximity / Lift-off

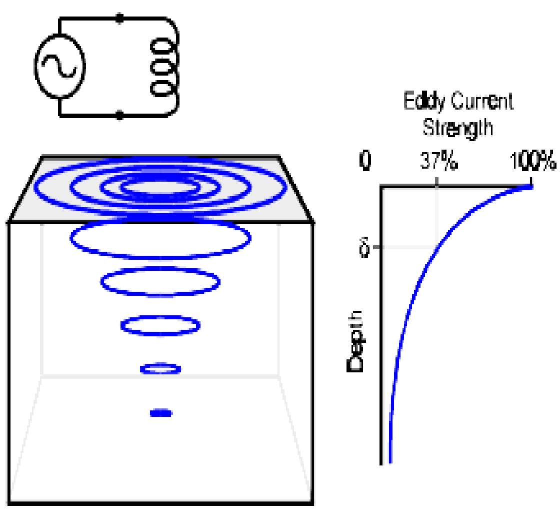
The closer a probe coil is to the surface the greater will be the effect on that coil. This has two main effects:
· The "lift-off" signal as the probe is moved on and off the surface.
· A reduction in sensitivity as the coil to product spacing increases.

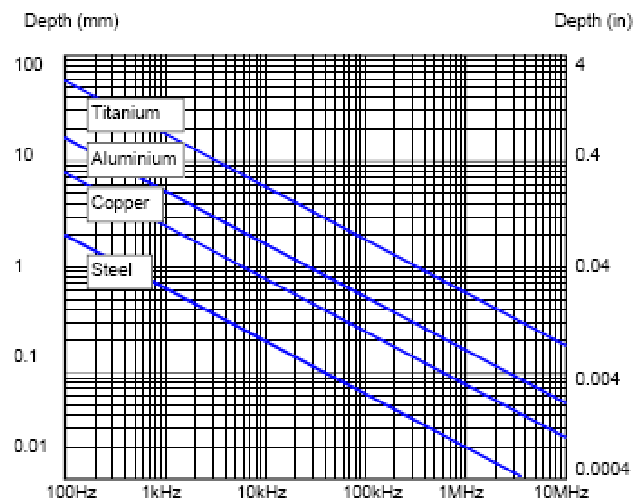
### 6. Skin Effect or Standard depth of penetration

Eddy current density in a material is not uniform in the thickness (depth) direction. It is greatest on the material surface and decreases monotonously with depth (*skin effect*) and the eddy currents lag in phase with depth, allowing employ phase discrimination method to locate, size and differentiate defects and disturbing variables. For a uniform, isotropic and very thick material, SDP is the depth at which the eddy current density is 37% of its surface value. From the SDP equation, one can easily interpret that depth of penetration (delta) decreases with increasing frequency, conductivity, permeability (see flux line contours below). Thus, in order to detect very shallow defects (cracks, flaws) in a material and also to measure thickness of thin sheets, very high frequencies are to be used (see flux line contours below). Similarly, in order to detect sub-surface buried defects and to test highly conductive/ magnetic/ thick materials, low frequencies are to be employed.




*Theoretical isomagnetic flux line contours demonstrating the skin-effect*




The standard depth of penetration is calculated by the following mathematical relation:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

Where, $\delta$=Skin depth or depth of penetration
$f$=Frequency of Current (AC)
$\mu$=Magnetic Permeability of the material
$\sigma$=Electrical Conductivity of the material

**The depth of penetration:**

- Decreases with an increase in frequency
- Decreases with an increase in conductivity
- Decreases with an increase in permeability This is can be very significant penetration into ferrous materials at practical frequencies is very small.

## INSTRUMENT/INSTRUMENTATION FOR EDDY CURRENT TESTING

Usually, current through the eddy current coils is kept constant ~ few hundred mA and changes in the coil impedance that occur due to perturbation of eddy currents at defect regions are measured. Since these impedance changes are very small (< micro-ohms), high precision A.C. bridge (Wheatstone bridge) circuits are employed. The bridge imbalance is correlated with the defect or material characteristic responsible. Thus a typical eddy current test instrument consists of an oscillator (for exciting frequency), constant current supply (step down from 230 V AC), a Wheatstone bridge circuit, amplifier (for amplification), and a CRT screen (to display the impedance changes in a 2-D graph or as a vector). In modern systems, eddy current testing instrument comes in the form a plug-in card and when this hardware is installed in a personal computer, the measurements, adjustments, controls, data storage, analysis and management all are performed by computer software.


***Consider the following example:***
The instrument energizes the driver coils, amplifies and processes the signals from the pick-up coils and shows results on a user-friendly display. Displays usually are shown in an x-y format similar to that of an oscilloscope. This captures both the magnitude and phase information of the signal change sensed by the coil. Earlier instruments using meter-type displays only indicated the magnitude of the response and did not provide traceable data values for test comparison.

Instrument set-up includes setting the drive amplitude and frequencies and receiver gain, filter settings and display controls. Both good and bad parts are analyzed and alarm-box labels are placed around clusters of good data points. If a test sample exceeds the established alarm/accept limits during testing, it is considered to be a reject and triggers the instrument's industrial I/O as programmed. Individual signal conditioning and I/O configurations can be stored and recalled at any time. Increased throughput and performance is achieved by high instrument sampling rates. Data logging allows storing test data as parts are being inspected.

## EDDY CURRENT SENSORS OR PROBES

Design and development of eddy current probes is very important as it is the probe that dictates the probability of detection and the reliability of characterization. In general, defects that cause maximum perturbation of eddy currents are detected with high sensitivity. The shape, cross-section, size and configuration of coils are varied to design an eddy current probe for a specific application. Depending on the geometry of the component three types of eddy current probes viz. surface pancake, encircling and bobbin probes shown in Figure are employed. The three types of probes can be operated in absolute, differential or send-receive modes. [9]

Various types of eddy current sensors or probes available are described below:

### *(1) Surface/Pancake/Flat probes*

Surface probe or Pancake probe, usually a spring mounted flat probe or a pointed pencil type probe, allows determining the exact location of a defect. The probe may be hand held, may be mounted on automated scanners or may even be rotated around to get e.g. a helical scan in tube/rod inspections. Surface probes possess directional properties i.e. regions of high and low sensitivity (Table.2). Usually ferrite cores (absolute cylindrical as well as split-D differential types) and shields are used for enhanced sensitivity and resolution. Besides ferrites, copper coils are used for shielding purpose. Surface probes are extensively used in aircraft inspection for crack detection in fastener holes and for detection of corrosion/exfoliation in hidden layers. When the component geometry is complex, it is not uncommon to use probe guides, shoes, centering-mechanisms to maintain uniform lift-off and detection sensitivity. Surface probes were developed for EC imaging, for measurement of liquid sodium level in steel tanks and also for measurement of thickness of coatings.
These are available in discrete sizes with sensing widths up to 10". Applied to the inspection of skelp at the entry to the forming section to detect and track butt welds to raise scarfing tools and cut-out operations. Also used for the inspection of squares and rectangles after shaping where the heat-affected zone is on the flat.

### *(2) Seam inspection probes*

These are located on the weld platform to test the weld seam only. Fitted with differential detection windings to provide a monitor of weld condition and absolute windings to detect (separately) open seam conditions for corrective action with seam annealing, bright annealing and in-line plating or Coating operations. One size fits all.

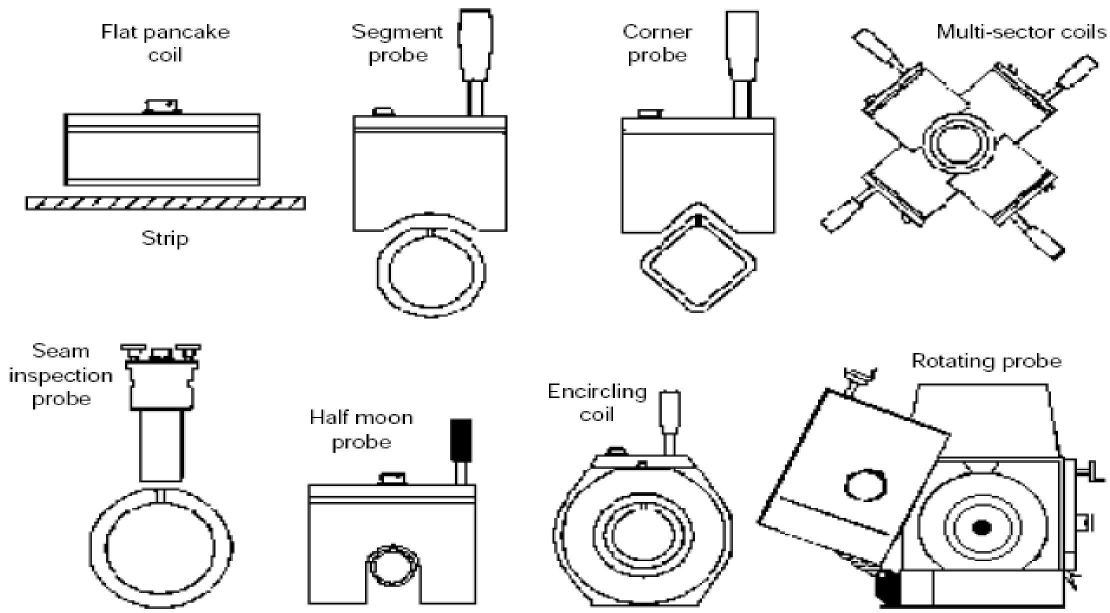



Fig. 4. Classifications of eddy current transducers

### *(3) Segment probes*

Cover a quadrant on round tubes to permit inspection of the heat-affected zone after cooling. Effective arc is around ± 1 ½ " (± 40 mm) either side of top. These are mainly installed at the entry to the sizing section.

### *(4) Half moon probes*

Accommodate weld wander up to 90 degrees either side of TDC for diameters below 3 ½ inch (90 mm). They are needed to be matched to tube sizes in 0.200" (5 mm) increments.

### *(5) Corner probes*

To check shapes where the weld seam has to be formed in or close to the comer.

### *(6) Encircling probes*

Encircling probes are used to inspect rods, tubes and wires. In an encircling probe the coil is in the form of a solenoid into which the component is placed. In this arrangement, the entire outside circumferential surface of the component covered by the coil is scanned at a time, giving high-inspection speeds.
These probes may not detect circumferential defects as the eddy currents flow parallel to them without getting distorted. Popular industrial application of encircling probes is high-speed inspection of tubes from outside during the manufacturing stages. Encircling probes were developed NDE of thin-walled cladding tubes and thick-walled steam generator magnetic tubes.
Full body testing usually applied after sizing. Coils and associated bushings need to be matched to individual tube diameters. Ideal for small diameter mills (refrigeration, heating element, cable sheathing, etc.). Sensitivity falls off as size increases. Tubing needs to be sized to conform to coil aperture. Splits (open seams) may cause damage. Major interference problems from loose I/D scarf. The only realistic mounting location is between the penultimate and final sizing stands, but space is rarely available.

### *(7) Multi-sector coils*

Full body testing achieved by a series of segment probes arranged in a radial pattern around the tube or pipe. Significant advantages over fixed encircling coils particularly for sizes 3” (80 mm) and above.

### *(8) Rotating probes*

Heavy duty assemblies utilizing high speed rotating inspection probes to check for longitudinal surface cracks. They can only be applied after the weld seam has been fully annealed. Prior to annealing, the seam is detected just like a butt weld. Great test that the anneal has normalized the heat-affected zone.

The heart of any current test-system is the probe, which must be designed for the specific application. “The key to the success of any eddy current test system is the design and performance of the probe,” says Martin Bryant of Uson LP (Houston TX). “It is through the probe that the alternating current is applied and the responding signal is measured.” [9]

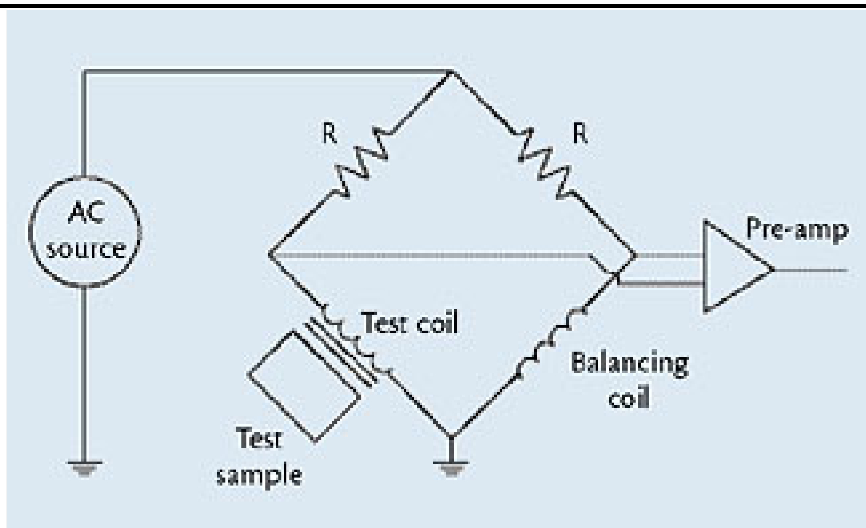
Several other types of probes include [3]:

- **Absolute probes** which normally consist of a single coil and can be used to detect cracks as well as more gradual variations such as variations in metallurgy, heat treatment and shape.
- **Differential probes** which use two balanced coils and respond only to sharp changes such as cracks.

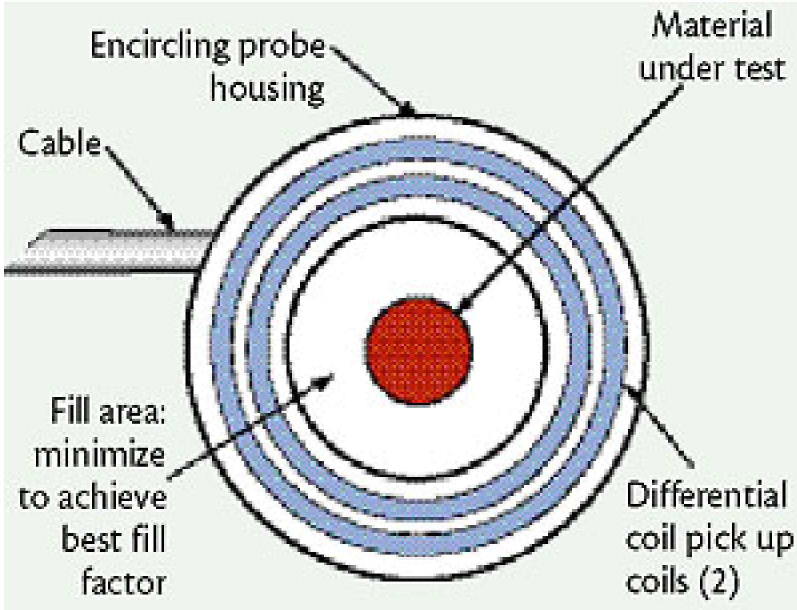
- **Reflection probes** which use separate driver and sensor coils and provide a wider frequency range than other coil arrangements.
- **Shielded probes** which use magnetic shields to focus the magnetic field and provide sensitivity to small cracks with low influence from edges, geometry changes, and other conditions.
- **Unshielded probes** which are less expensive than shielded types and provide a wider scan area but are affected by edges and nearby discontinuities.

**Absolute probes** are typically the least expensive, and they can discern differences in chemistry and hardness as well as thread presence and condition. “But this system detects all four eddy-current parameters from each sample, and consequently the associated part population bell curves are unduly wide,” says William Keely, VP of NDT Technologies Inc. (Holly, MI). As the size of the defect to detected decreases, more good parts must be rejected from the inspected sample population to insure that all bad parts are also rejected.

**Differential probe** systems effectively reject unwanted elements from the eddy-current signature, allowing more sensitivity to geometry differences. “Lot-to-lot variations in base material chemistry, hardness, and temperature are effectively rejected by the system and do not affect the sort,” Keely says. This allows one or two missing threads to be discerned from fully threaded holes.”



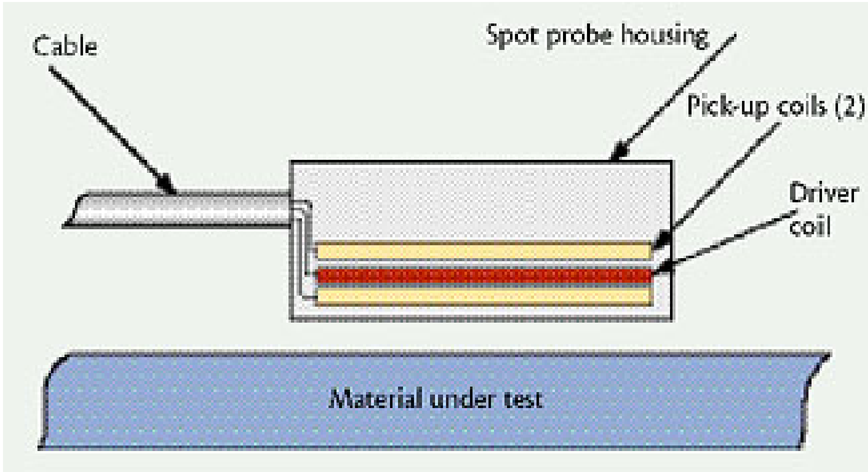

*Differential pair eddy current probe*




*Encircling coil application*

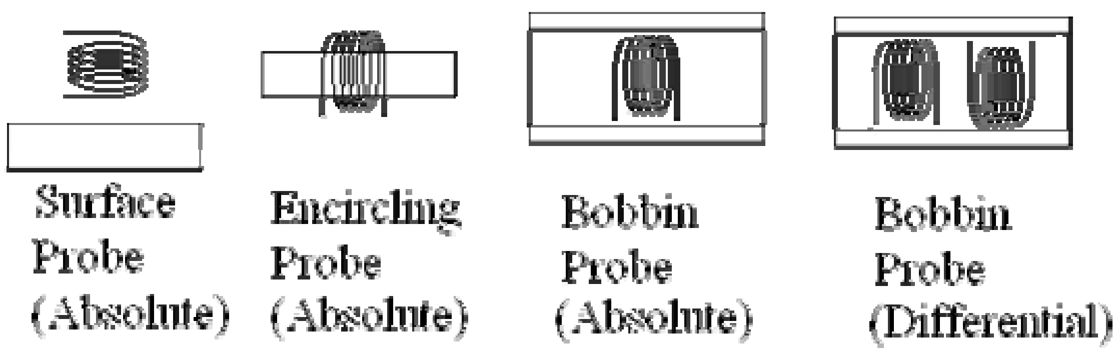
In hardness-testing applications, encircling and pancake coils are most commonly used. Encircling coils are designed to go around a part at a specific location (e.g., an automotive spindle), have a small part pass through the coil (e.g., a ball bearing), or to be inserted into a part (e.g., a cylinder ID). Optimum testing requires getting the coils as close to the part as possible to achieve a good fill factor.

A surface, or spot, probe is used to inspect larger parts, such as an automobile bumper. In this case, lift off and edge effects become critical test criteria. It is important to keep the probe as perpendicular to the part as possible. Testing near the edges of a part requires precise coil positioning.




*Spot-probe application*

A surface, or spot, probe is used to inspect larger parts, such as an automobile bumper. In this case, lift off and edge effects become critical test criteria. It is important to keep the probe as perpendicular to the part as possible. Testing near the edges of a part requires precise coil positioning.




These three types of probes can be operated in absolute or differential (left, last). They can also be operated in send-receive mode (separate coils for sending and receiving [again absolute or differential]). The EC probes consisting of a single sensing coil for excitation and reception are called absolute probes. Such probes are good for detection of cracks (long as well as short) as well as gradual variations. However, absolute probes are sensitive also to lift-off, probe tilt, temperature changes etc. Differential probes have two sensing coils wound in opposite direction and investigating two different regions of the material. They are good for high sensitive detection of small defects and they are reasonably immune to changes in temperature and probe wobble.

| ABSOLUTE VS. DIFFERENTIAL PROBES | | |
|---|---|---|
| **Characteristics** | **Absolute Probe** | **Differential Probe** |
| *Detection response* | Respond to both sudden defects (cracks) and gradual defects (gradual wall thinning) | Respond to only sudden/abrupt defects |
| *Temperature Drift* | Prone to drift | Minimal due to differential nature of two coils (cancel effect) |
| *Lift-off/Wobble* | Highly sensitive | Less sensitive |
| *Signal Interpretation* | Relatively simple | Signal interpretation is difficult |
| *Long defect detection* | Possible | Detects only the defect ends due to differential nature |

| CHARACTERISTICS OF SURFACE AND ENCIRCLING/BOBBIN PROBES | |
|---|---|
| **Surface Probes** | **Encircling/Bobbin Probes** |
| Coil is mounted with axis perpendicular to the component surface | Coils are parallel to the circumference of the component |
| Surface defects are detected with high sensitivity as compared to buried defects | Longitudinal or transverse defects are detected |
| Poor sensitivity for laminar defects | Poor sensitivity for circumferential defects |
| Sensitivity decreases with depth | Sensitivity is zero at the center of rods |
| Popular applications include aircraft inspection for fatigue cracks, corrosion etc. and coating thickness measurement | Popular applications include heat exchanger tube testing, material sorting, dimensional measurements |
| Characteristic parameter, Pc is used for sensor design (scale modeling) | Characteristic frequency f/fg is popular for Thin walls=1, Thick walls=4, cylinders=10. |
| Lift-off distance between the coil and component defines the magnetic coupling and very small lift-off is preferred for better detection sensitivity factor | Fill factor, ratio of square of diameters of coil and component, defines the magnetic coupling and moderate to high fill is preferred |
| Field focusing using ferrite cores and cups, for enhancing sensitivity is possible | Field focusing is difficult and not followed |
| Ferromagnetic material testing difficult in plate geometries | Remote field, saturation, permanent magnet based methods are possible for tubes |

## TIPS FOR SELECTION OF EDDY CURRENT PROBES

| ASPECT | IMPORTANT TIPS | |
|---|---|---|
| Geometry | Surface probes for plates | Encircling probes for tubes, bars |
| Defects | Small diameter probes for shallow & fine defects on smooth surfaces | Large diameter probes for sub-surface defects & rough surfaces |
| Inspection Speed | High Frequency excitation preferred | Array sensors & multiplexing preferred |
| Material | Remote field methods suited for ferromagnetic materials | Multi-frequency, 3-D, low frequency & pulsed excitation methods exist |
| Resolution | Ferrite cup & core design preferred for high resolution | Small sensors in array, magneto-optic imaging, SQUIDs preferred |
| Detection | AC bridge circuits for impedance change | Lock-in amplifiers & GMRs for receiver coil voltage |
| Impedance match | Essential between coil & bridge circuit | Identicality of array sensors must |
| Excitation | One or more frequencies but simultaneous for steady state | Burst excitation in pulsed eddy current for transient situation |
| Environment | Differential coils for temperature compensation and drift | Wear resistant coatings & ceramic insulation for high temperatures. |

## DESIGN OF EDDY CURRENT PROBES

In most EC instruments excitation current is kept constant (in a few tens of mA range) and the inductance may vary by a factor of one thousand. The usual input impedance could range between 20 and 200 ohms. The number of turns and wire gauge (between SWG 30 and SWG 45) are fixed such that the coils fill the available cross sectional space in uniform layers and turns per layer so that inter-winding effects are minimal. In some situations, it may be necessary to use a number of bridge circuits as well as probes operating simultaneously, essentially to cover larger area. For good sensitivity to small defects, small diameter probes are used. Similarly, in order to detect sub-surface and buried defects, large diameter high throughput probes are necessary. As a general rule, the probe diameter should be less than or equal to the expected defect length and also comparable to the thickness of the component. The sensing area of a probe is the physical diameter of the coil plus an extended area governed by magnetic field spread. Hence, it is common to use ferrite cores/shields (high permeability and low conductivity) to contain the lateral extent of magnetic fields without affecting the depth of penetration.

It is essential to operate EC probes below the probe/cable resonance frequency, especially while using long probe cables and at very high frequencies. The probe bodies are usually made of non-conducting plastics. Wear of probes is normally be reduced by giving wear resistant coating to the probe heads or tips. It must be noted here that such coatings add to the built-in lift-off of probes and tend to reduce signal amplitudes. Temperature stability of probes is usually accomplished by using coil holder material with poor heat transfer characteristics. Most common commercial copper wires are used up to about 150 deg. C. For temperatures above this, silver or aluminum wires with ceramic or high temperature silicon insulation or MIC are used. The probe material must be chemically compatible with the component. In brief, probe design is usually done considering the following:

1. Geometry of the component e.g. rod, tube, plate etc.
2. Type of discontinuity expected e.g. fatigue cracks, conductivity variation etc.
3. Likely location of defects e.g. surface, sub surface.
4. Coil impedance and its matching with the bridge circuit of the EC instrument.
5. Frequency range of the probe i.e. for simultaneous multi-frequency excitation.
6. Inspection requirement e.g. detection, evaluation of length, depth etc.
7. Material characteristics e.g. ferromagnetic or non-ferromagnetic.
8. Coil response to a notch, drilled hole or other reference discontinuity.
9. Field distribution in space and eddy current flow distribution in the material.
10. Shape and dimensions of the core, coil/coils and lift-off characteristics.
11. Environmental characteristics such as wear, temperature and chemical attack.

As many factors need to be considered, three different approaches viz. experimental, analytical and numerical are often resorted to for designing eddy current probes.

## Experimental Approach

This approach usually involves trail and error fabrication of probes suiting the geometry. In this approach, the coil dimensions and the test frequency are usually optimized by comparing the detection sensitivity of artificial reference notches as well as natural cracks if available. This approach was used to design encircling EC probes for inspection of stainless steel cladding tubes of Fast Breeder Test Reactor (FBTR) and also to design probes for Cr-Mo steam generator tubes of Prototype Fast Breeder Reactors (PFBR). In another instance, in order to minimize low-sensitivity zones of phased-array eddy current probes for inspection of heat exchanger tubes, tandem probe was developed.

## Analytical Approach

Analytical approaches for probe design involve analyzing the eddy current testing phenomenon and calculating the coil impedance and examining the operating point on the impedance plane as well as the effect of variations in coil radius r, shape, material conductivity, thickness t and test frequency f. Two popular impedance plane diagram based methods are 1) calculation of characteristic parameter, Pc introduced by Deeds and Doods for planar geometries and 2) calculation of characteristic frequency ratio $f/f_g$, where $f_g$ is the characteristic frequency introduced by Förster for tubular geometries. Using these two methods, coils are designed such that the operating point is in the “knee” region on the normalized impedance plane diagrams.

## SEQUENTIAL STEPS IN EDDY CURRENT PROBE DESIGN

1. Decide coil shape and operating mode depending on geometry.
2. Decide frequency using skin-effect relation depending on thickness and detection sensitivity.
3. Decide shielding & core depending on resolution & sensitivity requirements.
4. Optimize coil, shield dimensions, inter-coil spacing following numerical or experimental approach.
5. Carefully fill cross-sectional area with suitable area with suitable gauge wire and number of layers and turns and ensure frequency characteristics and impedance matching.
6. Experimentally establish the detection sensitivity and completely conceal the coils to withstand wear, temperature, irradiation and corrosion.

## RECENT TRENDS IN EDDY CURRENT PROBE DESIGN

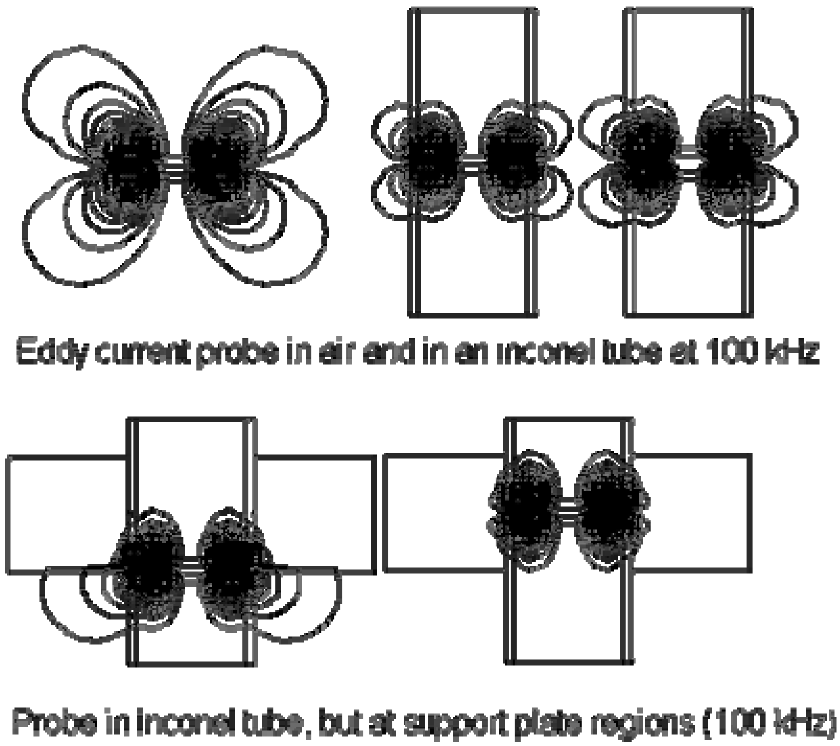
Detection of cracks emanating from edges and corners of components is very important. Often, strong signal from the edges mask the small/weak signal from a potentially harmful crack. Focused surface probes are being explored and likewise appropriate signal processing methods are being incorporated to suppress edge contributions. In the case of heat exchanger tubes, rotating surface probes or array probes with multiplexing are preferred for detection and characterization of defects along the tube circumference (location). For detection of defects at roll joints special array probes are being tried. In order to inspect components with complex geometries, flexible probes are being tried. These probes can be mounted/scanned over a region for inspection purpose and be easily removed. Similarly, for detection of sub-surface and deep-seated defects in multi-layer and other structures eddy current probes are mounted and integrated with Hall probes, SQUIDs, GMR and AMR sensors. The main objective in these strategies is to detect the weak magnetic fields from defects, rather than the traditional impedance changes. When more than one sensor is used and data fusion methods are adopted to combine the sensors data to form a comprehensive global picture of investigated regions. At times, it may be beneficial to combine information of a single sensor, but operating at different frequencies to get enhanced information of defects. Such an approach has been used in an intelligent imaging scheme to obtain accurate and quick 3-dimensional pictures of defects.

Inspection of ferromagnetic tubes is difficult due to high and varying magnetic permeability. For testing such tubes from outside, encircling D.C. saturation coils are used, where as remote field eddy current probes and permanent magnet based probes are used for testing from tube inside. Optimization of frequency and location of receiver coil (usually about 3 to 4 tube diameters away from exciter) in the remote field eddy current testing method is very important. FE model and experimental based approaches have been successfully used for this purpose.

When surface EC probes are scanned in a raster and the impedance data is displayed, Eddy current C-scan images of defects can be formed. EC images provide valuable information of defects. However, these images are blurred due to distributed point spread function of the probe. FE model based approach was used to optimize ferrite-core probes for eddy current imaging. In case of heat exchangers and steam generators, probes have to negotiate U-bend regions and detect defects, if any, in those regions. Design of flexible probes that are insensitive to bend regions is very challenging. For inspection of bend regions in ferromagnetic steam generator tubes, flexible remote field eddy current probe, with WC rings on either sides, was developed and wavelet transform based signal processing method was incorporated to suppress disturbing signals from bend regions.

## EDDY CURRENT TESTING PROCEDURE

Usual EC test procedure involves first calibration. Artificial defects such as saw cuts, flat bottom holes, and electro-discharge machining (EDM) notches are produced in a material with similar chemical composition and geometry as that of the actual component. Well-characterized natural defects such as service induced fatigue cracks and stress corrosion cracks are preferred, if available. The test frequency, instrument gain and other instrument functions are optimized so that all specified artificial defects are detected, e.g. by thresholding of appropriate EC signal parameters such as signal peak-to-peak amplitude and phase angle. With optimized instrument settings, actual testing is carried out and any indication that is greater than the threshold level is recorded defective. For quantification (characterization) master calibration graphs, e.g. between eddy current signal parameters and defect sizes are generated. In the case of heat exchanger tube ECT, calibration graph is between depth of ASME calibration defects (20%, 40%, 60%, 80% and 100% wall loss flat-bottom holes) and the signal phase angle. In order to detect and characterize defects under support plates multi-frequency EC testing which involves mixing of signals from different frequencies is followed and separate calibration graph is generated for quantification of wall loss.




*Magnetic flux line contours of an eddy current probe in air, in an Inconel tube and in the tube surrounded by a carbon steel support plate. Freedom-loving flux lines are constrained by the tube wall and the support plate. This constraint (manifested as distortion / perturbation of eddy currents and associated impedance change) is what is measured to advantage in eddy current testing*

**<u>APPLICATIONS OF EDDY CURRENT TESTING</u>**

## 1. HARDNESS TESTING APPLICATIONS OF EDDY CURRENTS

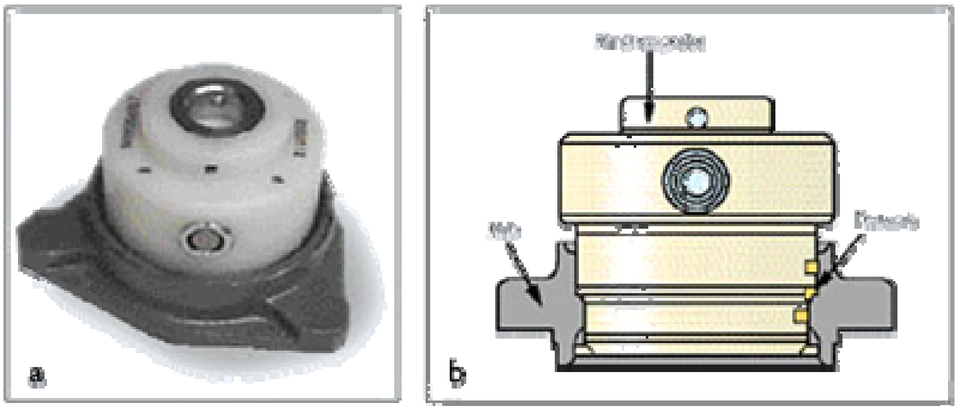
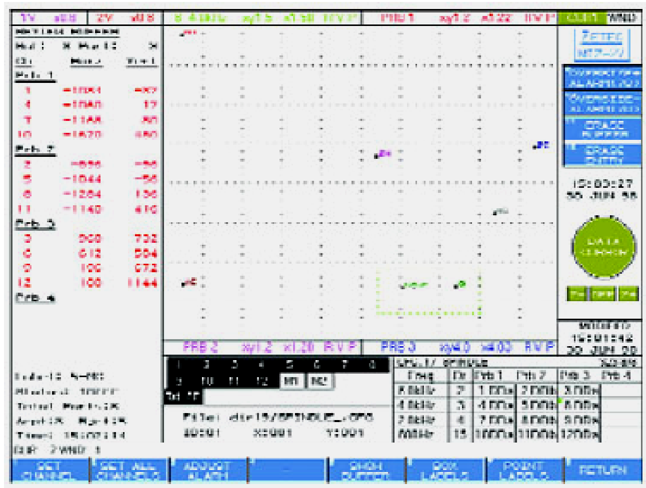



*Fig1. Automotive hub hardness probe: multicoil probe (a) and (b) relative positions of part and probe*

Eddy-current testing lends itself to high-volume manufacturing. Parts tested for proper heat treatment include automotive hubs and spindles, camshafts, gears, roller bearings, ball bearings, etc. Many of these parts are case hardened using induction heating. Induction hardening and tempering processes also are compatible with modern lean manufacturing processes, and, therefore, are easily incorporated into production lines. Eddy-current testing is used to perform 100% in-line hardness and case-depth testing of these parts. Eddy-current testing is a clean process, is operator independent and is able to automatically operate sorters and markers to segregate good and bad components without touching the parts.

The size and geometry of the part dictate how testing is to be accomplished, as they influence eddy-current probe design and in what manner the probe and part interface. The type of testing required also affects probe design and the instrument used for the test.



For medium-size components such as automotive hubs and spindles, custom probes are designed to bring individual coils in proximity to the area under test. Figure 6a shows a multicoil probe designed to test an automotive hub. The coils are positioned to measure the case depth and hardness at very specific locations. Figure (B) shows how the coils are positioned relative to the part. The coils are positioned to test the bearing races where the induction heating has been applied. The stainless steel jacket covering the coils offers protection for use in high-volume production.

All coils are simultaneously driven at multiple different frequencies. This ensures that a set of predetermined unacceptable conditions, such as shallow case depth or misplaced case, delayed quench and short or no heat treatment, is detected. While a single-frequency test may be adequate to identify problems, three or four frequencies typically are more than adequate to identify all required separations. Test frequencies typically range from 100 Hz to 25 kHz. Figure 2 shows the different groupings of heat-treatment conditions. The alarm box was created around the grouping of acceptable (green) responses, rejecting all other conditions.

*Fig 3 Table-top sorting station*

Symmetrical parts such as ball bearings and small gears can be passed through standard-shaped encircling probes. A single-coil, single-frequency tester is suitable for this application. Automation can be achieved by connecting the instrument to a simple sorting chute or to a complex sorting mechanism. This type of test is easily integrated into a production line or performed in a bench-top application (Fig. 3). For extremely large parts such as auto bumpers, spot probes can be used with a portable hand-held probe for spot checks either in the field or on the production line.

Several Eddy Current instrument manufacturers produce instruments to measure this effect, but one example is Technofour Multi Frequency Testing with the competitively priced Multifect instrument that statistically relates the electromagnetic responses from components over a wide range of frequencies, and those components that display even slight changes in properties will easily be detected. Typical hardness detection limits here are about 2 points on the Rockwell C scale at about 60 HRC.

## 2. MATERIAL PROPERTY TESTING

Modern eddy current instruments that use digital electronics to nondestructively test material properties are reliable, repeatable, have high resolution, and are easy to implement and maintain. Properly applied, multi-frequency test protocols extend the scope of the eddy current method, increase test reliability and make the method easy to implement.

Determination of optimum setup and calibration procedure is facilitated by a built-in computer. During calibration, parts known to be metallurgically correct are tested at a multitude of frequencies, producing locus curves for the alloy and structural characteristics of the parts. A minimum of 15 to 20 parts are necessary to provide a sufficiently broad statistical base of allowable production variables. At each test frequency, the scatter of readings is displayed and tolerance zones are created to encompass readings at selected frequencies. Size, shape and position of each tolerance zone is established, calculated and drawn by the computer.

In production use, parts are tested at up to eight selected frequencies. Parts are only accepted if the measured values meet each and every tolerance zone. If the part fails to meet just one criterion, it is rejected. The principal advantage of this method is that a variety of metallurgical anomalies may be detected; hardness variations may be detected at 1 kilohertz (kHz), material mix may better be determined at 12.5 kHz, case depth at 20 hertz (Hz) or decarburization at 63 kHz. Most important, unexpected mixed structures from significant heat-treat process errors are detected and sorted from production. Unwanted mixed structures include retained austenite, untempered martensite, bainite, pearlite and ferrite in their various combinations.

Electronic processing technologies have reduced testing time. Typically, a part can be tested at eight different frequencies in less than 100 milliseconds (0.1 second).

## 3. HEAT TREATMENT INSPECTION

Improperly heat treated components can develop structural problems that dramatically shorten a product's life and may ruin an entire batch of finished product. Any condition listed below can lead to defective or inferior parts. Consideration must be given to the fact that any of these situations, gone undetected, may lead to failures and the potential for liability.

**Possible Heat Treatment Problems are:**

- Failure of induction heating coils
- Mislocated heating coils
- Improper heat treat temperature
- Improper heat treat time
- Improper feed rate
- Improper quenching

Products can be automatically inspected after the rough machining and grinding stages, before adding finish machining costs to the part. Many manufactured parts require heat treating with induction heating processes that allow specific areas to be heated and quenched, see Figure 1. During the process failures can occur. Shallow case depth, misplaced case, delayed quench, short or no heat treatment, structural differences and cracks or flaws can be detected. A differential driver pick-up (hardness) coil configuration contains one higher energy coil which creates the primary eddy current signal and one differential coil pair which is used to detect heat treat anomalies in the test sample. Hardness coils check for these anomalies in very specific areas on the part that are determined critical, see Figure 2.

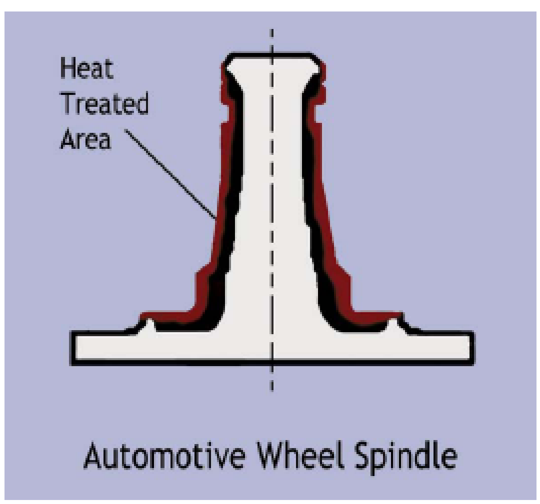



*Fig1. Heat treated Automotive Wheel Spindle*

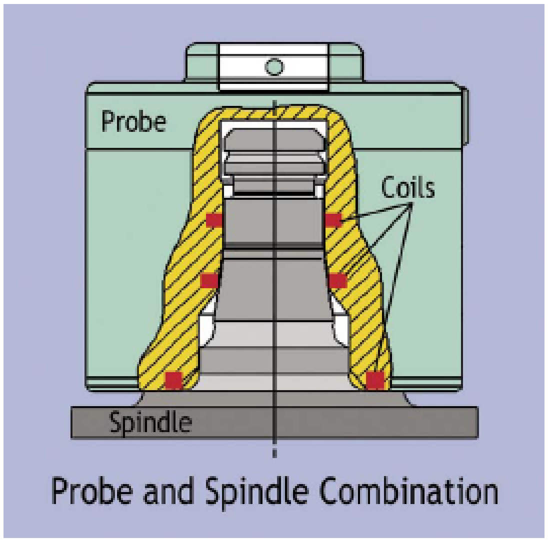


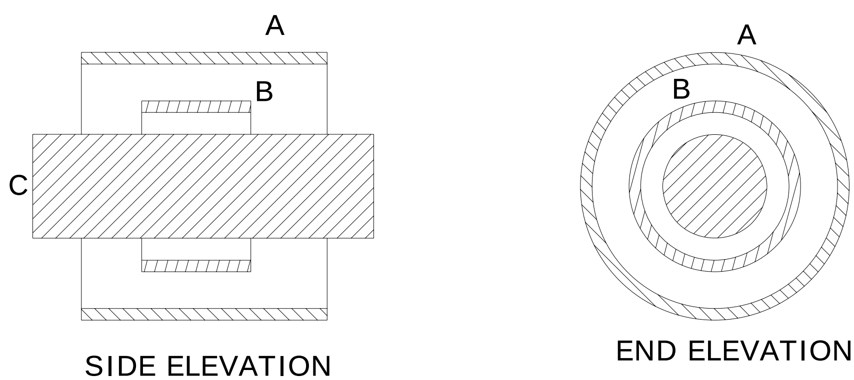

*Fig2. Spindle with hardness probe*

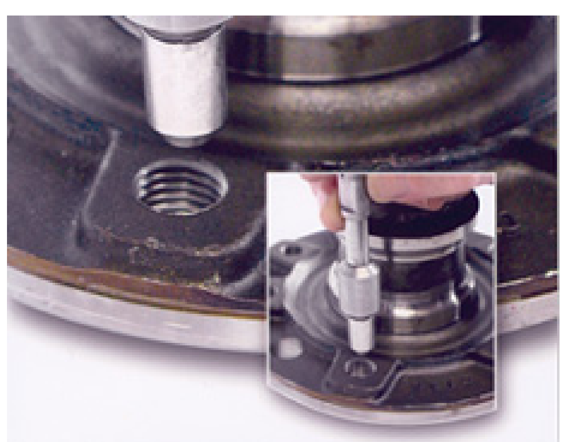
Symmetrical parts such as ball bearings and small gears can be passed through standard-shaped encircling coils. A single-coil, single-frequency tester will work for such an application. Automation can be achieved by connecting the instrument to a simple sorting chute or to a complex sorting mechanism.
Used in small part testing applications, the eddy current system is often integrated in the production line. To test larger or more complex parts, such as auto bumpers, spot probes may be used, either in a bench top application or with a portable hand-held probe for spot checks. It is important to keep the probe as perpendicular to the part as possible. Testing near the edges of a part requires precise coil positioning. Probe fixturing or custom probe design may be necessary for such applications. These inspections can be done on the production line, but can also be performed in the field. [5]

## 4. SCREW THREAD INSPECTION USING EDDY CURRENTS [6]

For the application of the eddy currents to non destructive testing, an alternating current of given frequency is generated in primary or exciting coil A. An alternating magnetic flux is produced and an alternating current of same frequency is generated in the secondary coil B. the coil B may also be called pick up or search coil. With introduction of the specimen C having external screw threads, the alternating flux $N_1$ induces in the latter an eddy current flow which gives rise to an alternating magnetic flux $N_2$ in the opposite direction (Lenz's Law), the current in the secondary coil B is reduced. For the given condition, the reduction in the current should be equal for all identical specimens kept at the same position relative to the coils. Any observed inequality in the reduced current could indicate

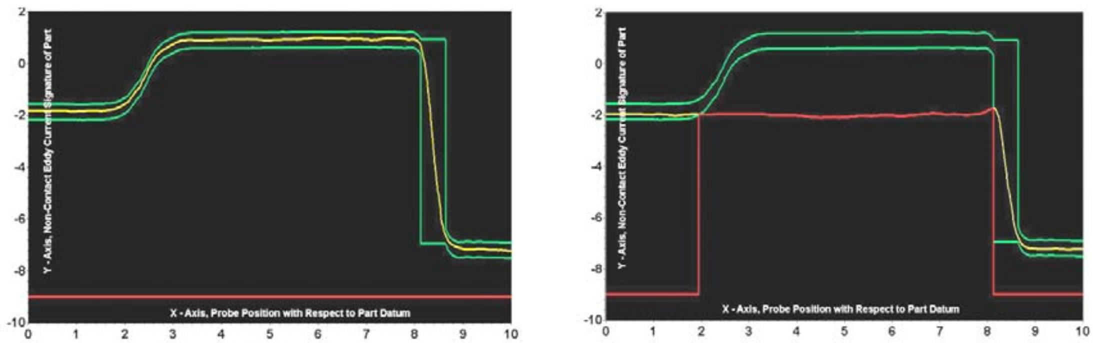
- The presence of a defect,
- A change in dimension, such as pitch, major and minor diameters etc., or
- Variation in electrical conductivity
- In the magnetic permeability of the sample



## Some advancement in Screw Thread Inspection by Eddy-Currents [3]

Detection of both internal and external threads is one of the most common applications for eddy-current testing. The threads detection using eddy current inspection has become sophisticated to the point where not only the presence of threads can be sensed, but also the no. of threads in the hole can be accurately determined and, with properly engineered systems, the portion of the last thread helix that is present in the hole can be determined.




*Eddy current profiles of a correctly threaded transmission part (left) and a part with half threads. Green Limits are ±3$\sigma$ limits, yellow is the good part profile and the red line overlays the yellow line where the part falls outside the control limits.*

## 5. EDDY CURRENT APPLICATION TO DETECT SURFACE FLAWS

Eddy current testing has been used for more than 30 years in testing steam generator tubing and bar, tube and wire stock. More recently, it has been applied to the testing of individual components on production lines. Eddy current offers rapid testing that makes 100% inspection a reality, thus reducing both scrap and warranty costs. Current systems are used to detect anomalies in metallic objects. Manufacturers are interested in whether cracks and flaws are present in a part, whether the part has been correctly heat treated,
Whether parts have been made from the correct material and whether physical attributes such as threads or splines have been accurately machined. Modern eddy current systems can rapidly detect these conditions and enable assembly line integration. [4]

### The instruments

Eddy current testing instruments function by energizing a set of electrical current driver coils and processing the returned signals from the pick-up coils. The instrument amplifies and processes the returned signals and displays the results. Displays and user interfaces for crack and flaw testing differ from those used when eddy current is used for hardness testing. An eddy current coil passing over a flaw creates a Lissajous type pattern while hardness test data tends to be grouped within alarm boxes on the screen. Modern instruments have the ability to drive coils simultaneously at multiple frequencies. This is critical for hardness testing applications where multiple failure conditions may occur.

Instrument setup includes setting the drive amplitude and frequencies, and the receive gain, filter settings and display controls. Both “passed” and “failed” components are analyzed and alarm box labels are arranged around clusters of passing data points. During actual testing, if a test part exceeds the established alarm or acceptance limits, the part is rejected and the instrument’s industrial I/O is triggered. Individual signal conditioning and I/O configurations can be stored and recalled at any time. Increased throughput and performance are achieved by high instrument sampling rates. In addition, with data logging, it is possible to store the test data as inspection occurs.

### Finding flaws

Eddy current technology is most often used in applications where the manufacturer wants to find surface flaws. Typical depth of penetrations for aluminum parts are 6 millimeters while surface inspections of ferromagnetic materials are limited to the surface layers only. To correctly detect cracks and flaws, an eddy current probe must pass over the flaw. This can be accomplished by either moving the probe across the part, or moving the part in relation to the probe. A standard pencil probe, scanned across the top of a cylinder liner, for example, can be automated by either rotating the cylinder liner while keeping the probe fixed, or keeping the cylinder liner fixed and moving the probe around the part. For parts with complex geometries, custom probes are used to reach in critical areas. Inspection of a wheel spindle for cracks and flaws, a common application, can be done using an eight-coil probe. Each of the coils is positioned to inspect a critical area on the spindle. The uppermost coil is used to inspect the underside of the keeper groove near the top of the shaft. Cracks as small as 0.004 by 0.005 inch are the minimum flaw criteria called for. To detect such minute flaws, the wheel spindle is gripped and rotated at 120 rpm during the test. The eddy current probe moves over to the part and the test is run while the part spins. [4]

The actual coils ride in near proximity to the wheel spindle. Wear-resistant ceramic wheels keep the probe correctly positioned with respect to the part. Spindles can be tested at a rate of one every 6 seconds, as compared to more than 3 minutes for each spindle using magnetic particle inspection.

Industrial I/Os on the eddy current test instrument drive programmable logic controllers that route parts out of the assembly line, keeping track of the number of passes and failures.

Eddy current testing lends itself to small components inspection, such as inspecting threaded parts. Thread size and location can be determined by an eddy current's capability to determine the physical attributes of metals. *Photo: Zetec Inc.*

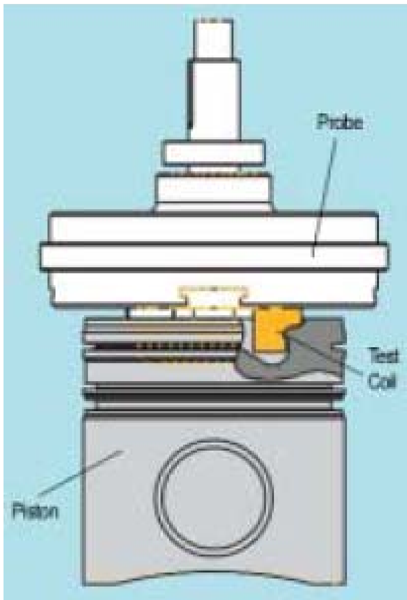
## Passing the 'bar'

The bar, tube and wire industries have been long-time users of eddy current technology for flaw testing. Many of these products are made in a continual feed fabrication process—sometimes at several thousand feet per minute—and tested at the same time. The test system coils are often covered with stainless steel or ceramic probe guides for protection of the electronics. Encircling coils offer the advantage of fast, simple detection but have lower flaw detectability. They detect flaws around the entire area that the coils cover.

For improved flaw detection, rotating probe systems using spot type probes, or array probes that offer alternatives to encircling coils. Flaw detection in ferromagnetic tubes and pipe is made difficult because of the eddy current "noise" caused by the permeability variations within the steel. By introducing a strong magnetic field in the area of inspection, these permeability variations are reduced, increasing the signal-to-noise ratio and allowing for better defect detection.

The most widespread use of an eddy current test is to detect surface flaws in parts. Either the operator moves the probe over the part, or the part is moved across a stationary probe. *Photo: Zetec Inc.*

Correct hardness and case depth treatments are critical to many manufactured components. Incorrectly hardened automotive bearing surface may fail after 5,000 miles instead of 250,000 miles. As most hardness and case depth treatments are invisible to the naked eye, instrument testing becomes critical. Traditional static indentation testing, such as Rockwell and Vickers hardness tests are time consuming, require that the surface be perpendicular to the direction of the force applied by the tester and damage the part to some degree. Eddy current heat treat testing is a relative test. While it will not display an absolute Rockwell hardness number, it will indicate whether a part under test is within a few Rockwell points of the desired hardness. The acceptability of that level of accuracy is manufacturer and design dependent. In many cases, heat treating of bearing races is done by induction heating equipment, in contrast to batch heating in an oven. Induction heating allows bearing races to be hardened while retaining the strength of the underlying metal structure. However, variations within the induction heating process can affect the quality of the heat treating. Conditions such as a misplaced case, shallow case or inadequate quench can occur, all of which need to be identified. Eddy current probes are designed to position test coils over the exact location of the hardened bearing races. Using multiple coils allows several points to be tested simultaneously. These probes can be integrated in production line material handling systems, where testing and positioning time fit in the product cycle time. Stainless steel jackets over the probe protect the coils from wear caused by continuous use. [4]

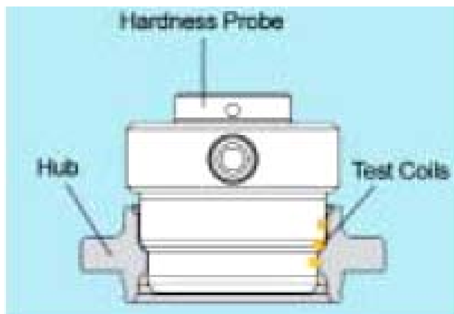



Reaching inside a piston to do inspection using traditional means often requires costly custom probes. In this diagram, a four-coiled eddy current probe is used to detect flaws as small as 1 by 0.3 by 0.1 millimeter. The probe rotates while the piston remains stationary. *Source: Zetec Inc.*

## Sorting and detection

Symmetrical parts, such as ball bearings and small gears, can be passed through standard shaped encircling probes. A single-coil, single-frequency tester will work for such an application. Automation can be achieved by connecting the instrument to a simple sorting chute or to a complex sorting mechanism. Used in small part testing applications, the eddy current system is often integrated in the production line. For larger parts such as auto bumpers, spot probes may be used, either in a bench top application or with a portable handheld probe for spot checks. These applications can be done on the production line, but can also be used in the field. Eddy currents are also sensitive to physical configuration of metals. While this can be a detriment, because of lift-off variations in testing, it

can be used to verify attributes such as thread installation and assembly verification. Probes can be used to detect missing, undersized and oversized threads, as well as double-threaded parts. Probes can also be configured to look for taps that have broken off in threaded holes. The correct broaching of features such as splines can be verified as well. As for the ensuring the correct mechanical assembly of components, eddy current technology is used for verifying
that all ball bearings have been installed in a bearing race. A single coil is held briefly over the race, and a missing ball will trigger a failure. Airbag manufacturers use eddy current technology to verify that a single diffuser has been installed. Conditions such as no diffuser or multiple diffusers are detected, noted and trigger alarms. [4]




The nondestructive nature and speed of eddy current testing lends itself as an alternative to traditional hardness testing in some applications. This diagram show how multiple test coils can be used to do hardness testing. Unlike traditional microindentation technology, the probes do not have to be perpendicular to the surface being tested. *Source: Zetec Inc.*

## 6. SURFACE CRACK DETECTION

This is normally carried out with pencil probes or 'pancake' type probes on ferrous or non-ferrous metals. Frequencies from 100 kHz to a few MHz are commonly used. Depending on surface condition it is usually possible to find cracks 0.1 mm or less in depth. Shielded probes, with their focused field, add the ability to test very close to edges or dissimilar materials such as ferrous fasteners in an aluminum structure.

Differential probes are sometimes used, particularly in automated applications, but care must be taken to ensure that the orientation of flaws is correct for detection.

### Sub-surface crack/corrosion detection

This is primarily used in airframe inspection. By using a low frequency and a suitable probe, eddy currents can penetrate aluminum or similar structures to a depth of 10 mm or so, allowing the detection of second and third layer cracking, which is invisible from the surface, or thinning of any of the different layers making up the structure.

Test frequencies are generally in the range 100 Hz to 10 kHz. Probe size should also be two or more times wider than the depth of penetration required.

### Crack Detection

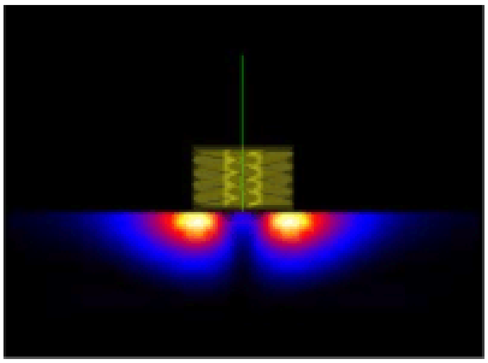
Eddy Current testing relies on the integrity and training of an operator to evaluate the signal changes and to interpret if the surface being interrogated is in accordance with a specification or not.

The detection limits of eddy current testing depend upon the surface condition of the piece being inspected. It is not normally possible to detect defects that are smaller than about three times the surface roughness of the component. This means that if you have a surface roughness of about 0.5mm, you cannot easily detect defects shallower than about 1.5mm deep. The detectable length of defects depends upon the integrity of the scan pattern.

Limits of detection on components with very good surface finish are in the order of 0.05 to 0.1m Eddy current testing can very easily detect cracks at or near the surface. As material thickness, conductivity, or permeability increases significantly, eddy currents often cannot move completely through the test specimen, limiting testing to the outer surface in some cases.

## Surface flaw and crack testing

Use of the eddy current method to detect cracks, pores and other surface flaws in critical automotive components is increasing because it is reliable, repeatable, easily automated and provides cost savings over magnetic particle and other methods. It is particularly applicable to test finished machined parts, although there are many applications on as-formed parts.



Eddy-current instrumentation for crack detection functions differently than eddy current material properties testing. It is best characterized as high-speed, high-precision surface scanning. A probe that sequentially senses small sections of the surface—a 1 millimeter or less diameter area—must be moved over the surface area with high precision to reliably detect small cracks and flaws. High precision means that the probe orientation to, and distance from, the metal surface being tested must be maintained within prescribed tolerances. Also, the rotation rate of the part being tested and the scan rate of the probe must be monitored (error proofed) so to guarantee that the surface area is completely scanned with no skipped areas.

## 7. WELD INSPECTION PROCESS

In most weldments there are acceptable levels for some types of discontinuities in the weld. These normally are classified as either internal inclusions (solid) or porosity (gas bubbles). If a weld has cracks, it almost always is rejected, and the part must be scrapped or repaired. Inspectors decide which types of discontinuities will make a particular product unacceptable to either the manufacturer or the end user.

While straight tubing is quickly inspected by automated methods, complex geometries, such as bends and welds, may require inspection by hand-held probes. These probes are available in a variety of configurations, all intended to give access to tight places, keep lift-off to a minimum, and ensure the maximum response given the expected type of flaw.
One of the more common types of eddy current probes is the pancake coil, used to find cracks on the surface of non ferromagnetic materials such as aluminum or stainless steel (see Figure 1a). The use of pancake coils around a weld zone is limited because of the complex information near the weld zone.
Another option is the plus-point, or cross-point, coil. The coil actually is a differential pair of coils that interrogate the same test area. In general, this probe is insensitive to everything except cracks and other material discontinuities, which allows suppression of localized geometry variations (curved surfaces, corners, weld splatter) and material composition variations (filler metals, heat-affected zone) (see Figure 1b). The coil also is relatively insensitive to permeability changes, so it can be used on both ferromagnetic and non ferromagnetic materials.

This coil most often is used in conjunction with lightweight, portable eddy current test systems. Portable testers can be set up fairly easily with a minimum of training. Since the plus-point coil suppresses unwanted noise while responding to cracks, test result interpretation is fairly straightforward.

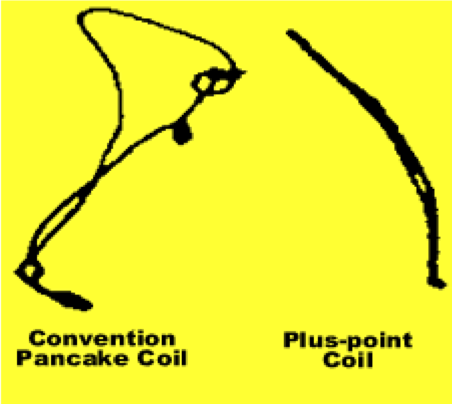



*Fig 1(a) and 1(b)*

## 8. EDDY CURRENT TESTING OF AEROSPACE MATERIALS [8]

The flow of eddy current within the material is disrupted by the presence of discontinuities, such as, cracks, porosity, or inclusions. Discontinuities cause a decrease in the flow of current in the material by increasing the length of the path along which the current must flow as shown in Figure 2. This results in a reduction of current flow which causes a change in the impedance of the test probe coil. There are three major factors that affect ECT.

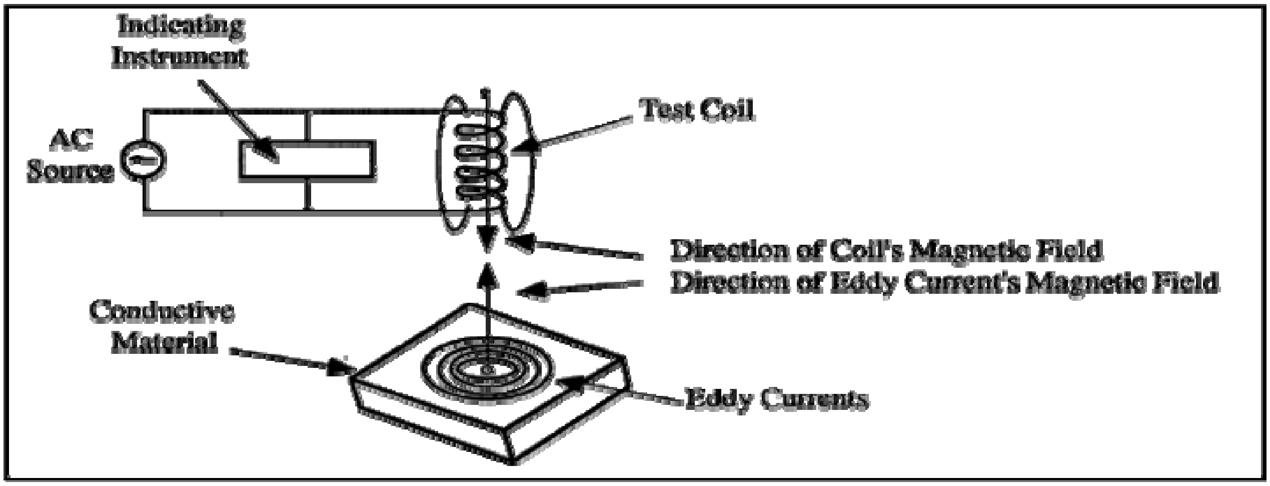



Figure 1. Basic Eddy Current Testing System

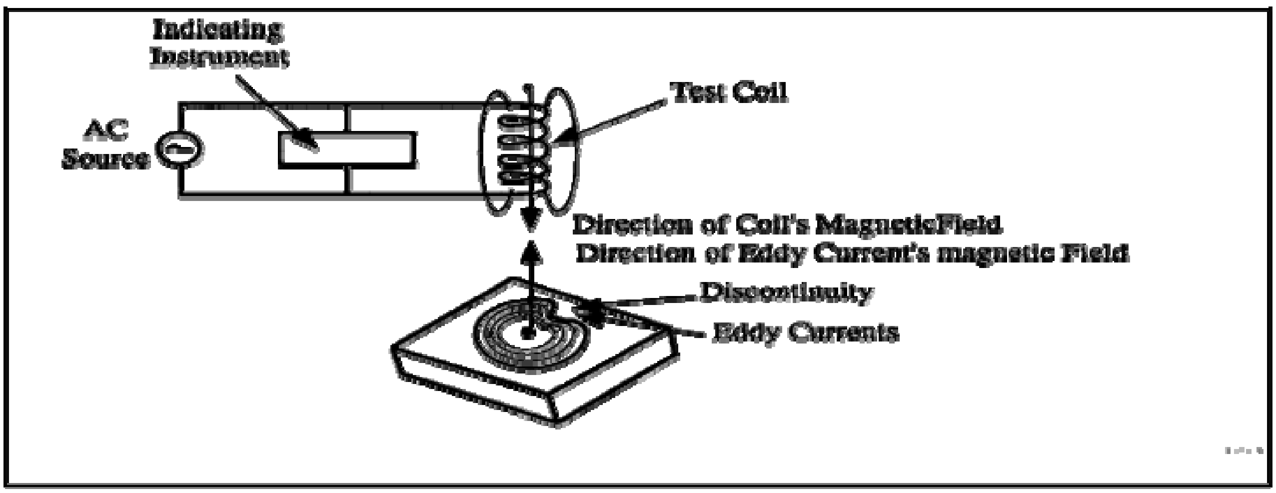



Figure 2. Distortion of Eddy Currents by a Discontinuity

These are material conductivity, geometry, and permeability of the material being tested. In addition, there are contributors that affect the three major factors. These are shown in Table 1.

**Table 1. Factors Affecting Eddy Current Testing**

| Conductivity | Geometry | Permeability |
|---|---|---|
| Alloy<br>Hardness<br>Temperature<br>Residual stresses<br>Coatings | Thickness<br>Discontinuities<br>Coil-to-Material Separation (liftoff) | Ferromagnetic* |

* Material capable of being magnetized

The ECT signal is strongly related to the geometrical shape of the coil, i.e., the size, shape, and positioning of the coil; the relationship between the coil windings and suspected discontinuities; the effect of changes in liftoff or fill factors; the depth of penetration; and the edge effect.

## Distortion of Eddy Currents by a Discontinuity

Identifying the various factors causing impedance changes depends upon the knowledge and skill of the ECT technician. Thus, selecting the appropriate eddy current probe is an important part of eddy current testing.
Various types of test instruments available for ECT are: 1) conductivity testers, 2) crack detectors, 3) resistance and reactance measuring testers, 4) coating thickness testers, and 5) oscilloscopes and output devices such as strip chart recorders, printers, etc. when used as part of a test setup.
A standard test specimen with known flaw sizes must be fabricated for use in adjusting the sensitivity setting of the test instrument for accurate interpretation of the test results. The standard test sample should be sound and of the same alloy, temper, and geometry as the part to be tested. Flaws may be produced in the standard test specimen by drilling, electrical discharge machining, milling, or any other means that will not distort the standard. Any flaw size outside the predetermined acceptable flaw size for the object being tested shall be a noted defect for corrective action or rejection.

**Table 2. Advantages and Limitations of Eddy Current Testing (ECT)**

| Advantages | Limitations |
|---|---|
| 1. High speed testing (can be automated)<br>2. Accurate measuring of conductivity<br>3. Discontinuities at or near surface can be reliably detected<br>4. High-sensitivity to small discontinuities<br>5. Accurate coating thickness measurements<br>6. Direct Go/No Go answers can be quickly obtained.<br>7. No physical contact required<br>8. Low cost<br>9. Portable | 1. Limited penetration into test article<br>2. Several variables simultaneously affect output indication<br>3. Discontinuities are qualitative not quantitative indications<br>4. Material must be conductive<br>5. Requires skill when many variables are involved<br>6. False indications can result from edge effects and parts geometry. |

**Table 3. Typical applications of Eddy Current Testing**

| Material Property Determinations | Thickness Measurements | Flaw detection |
|---|---|---|
| Heat treatment evaluations | Thin sheet metal | Sheet metal |
| Hardness | Foil | Foil |
| Fire damage | Paints | Wire |
| Impurities | Anodic coatings | Bars |
| Chemical compositions | Lacquers | Tubes |
| Corrosion damage | Thin insulation | Bolt holes |
| Conductivity of ionized gas | Rocket motor linings | Fasteners |
| | | Welds |
| | | Ball Bearings |

## 9. TUBE INSPECTION

Tubes may be inspected from the outer diameter (OD), usually at the time of manufacture and from the inner diameter (ID), usually for in-service inspection, particularly for heat exchanger inspection. [7]

### ID heat exchanger tube testing

Heat exchangers used for petrochemical or power generation applications may have many thousands of tubes, each up to 20 m long. Using a differential Internal Diameter (ID or 'bobbin') probe, these tubes can be tested at high speed (up to 1 m/s with computerized data analysis) and by using phase analysis, defects such as pitting can be assessed to an accuracy of about 5% of tube wall thickness. This allows accurate estimation of the remaining life of the tube, allowing operators to decide on appropriate action such as tube plugging, tube replacement or replacement of the complete heat exchanger.

The operating frequency is determined by the tube material and wall thickness, ranging from a few kHz for thick-walled copper tube, up to around 600 kHz for thin-walled titanium. Tubes up to around 50 mm diameter are commonly inspected with this technique. Inspection of ferrous or magnetic stainless steel tubes is not possible using standard eddy current inspection equipment.

Dual or multiple frequency inspections are commonly used for tubing inspection, in particular for suppression of unwanted responses due to tube support plates. By subtracting the result of a lower frequency test (which gives a proportionately greater response from the support) a mixed signal is produced showing little or no support plate indication, thus allowing the assessment of small defects in this area. Further frequencies may be mixed to reduce noise from the internal surface. [1, 7]

### Remote field

Remote field is a branch of eddy current testing that has evolved over the last decade or so. By using specially designed equipment and ID probes it is possible to obtain indications of wall thickness changes on magnetic material.

### In-line inspection of tubing

External eddy current encircling test coils are commonly used for inspecting high quality metal tubing of wall thicknesses less than 6 mm. When the tube is made of a magnetic material there are two main problems:

- Because of the high permeability, there is little or no penetration of the eddy current field into the tube at practical test frequencies.
- Variations in permeability (from many causes) cause eddy current responses which are orders of magnitude greater than those from defects.

These problems can be overcome by magnetizing the tube using a strong DC field. This reduces the effective permeability to a low value, thus increasing the

depth of penetration and masking the permeability variations, hence allowing effective testing. [7]
Ferromagnetic tubing up to around 170 mm diameter is commonly tested using magnetic saturation and encircling coils. Testing may be in-line during manufacture or off line on cut length tube.

When tubes are welded (usually by the ERW method) the weld area is the usual site of defects and as the weld position is well controlled, it is more efficient to inspect the weld area only by means of a sector (or saddle) probe.

## Ferrous weld inspection

The geometry and heat-induced material variations around welds in steel would normally prevent inspection with a conventional eddy current probe, however a special purpose ‘Weld Scan’ probe has been developed which allows inspection of welded steel structures for fatigue-induced cracking. The technique is particularly useful as it may be used in adverse conditions, or even underwater, and will operate through paint and other corrosion-prevention coatings. Cracks around 1 mm deep and 6 mm long can be found in typical welds both in the root area and the cap. [7]

## Dynamic hole inspection

Here, differential probes are used attached to high-speed rotary scanners with test speeds as high as 3000 rev/min then the inner bore of holes may be inspected rapidly and reliably with the eddy current technique. Probes may be as small as 1 mm diameter and test frequencies used follow the same rules as for surface defect detection. The use of high- and low-pass filters (so called band-pass filters) is essential to ensure optimum signal to noise. Target calibration notch is usually a 0.5 mm corner notch at 45º. [7]

# 10. MATERIAL SORTING

## Non-ferrous metal sorting

This is conductivity testing, and for dedicated applications a conductivity meter may be a better choice. From the impedance plane diagram one can observe that the indication from a conductivity change is essentially the same as from a crack, and both meter and impedance plane type crack detectors can be successfully used to sort similar metals using a suitable absolute probe. It should be remembered that:

- widely different metals may be a similar conductivity;
- the allowable values for similar alloys may overlap;
- an alloy of one material can, in vastly different states of heat treatment, have the same electrical conductivity; and
- There is no direct relationship between conductivity and hardness.

However, once these caveats are understood then conductivity measurement can be used as part of a quality control system. Suitable test frequencies used are in the range 10 kHz to 2 MHz, although account should be taken of the material thickness to ensure the depth of penetration is less than one third of the material thickness. [7]

## Ferrous metal sorting

Ferrous material may be sorted using eddy current impedance plane equipment. Unfortunately it is not possible to produce quantitative values due to the reading obtained being related to electrical conductivity, magnetic permeability and the depth of the change in material properties. Frequencies to use are 100 Hz to 10 kHz. The use of two or more frequencies gives additional information about the depth of the material properties such as in induction hardening. [7]

## Coating thickness assessment

In the simple case of a non-conductive coating (for example paint) on a conductive material, then the eddy current lift of signal can be used. The probe type to be used should have an absolute response with reflection spot face probes offering some advantage in temperature stability and frequency range. Higher frequencies are preferred (100 kHz and higher) and for non-ferrous materials it should be checked that the frequency is sufficiently high so as not to be influenced by material thickness (say 10 times that to make the wall thickness equal the effective depth of penetration).

To obtain quantitative readings, a calibration piece with several different thickness of coating in the range of interest is essential, and a calibration curve created. Some instruments have an intrinsic function as part of conductivity measurement for obtaining direct readings. [7]

For the more complex case where the coating is conductive, then the following needs to be taken into account. The two materials must have different conductivities and/or relative permeabilities and the top coating must be non-magnetic. Choose a frequency that will make the effective depth of penetration equal the nominal wall thickness. If the surface coating has higher resistivity than the lower coating, then by using a frequency that is sufficiently low to penetrate the surface coating, results will be similar to that for non-conductive coatings.

## Wall thickness assessment

This is possible in the same way as it is possible to determine non-ferrous conductive coating thickness and the same rules apply about choice of frequency. [7]

## Contact + Eddy Current = Precise Bore Measurement

One of the latest developments in eddy-current technology is a system from NDT Technologies that combines contact gauging and eddy-current testing. The patent-pending Ball Runner system can measure hole diameter, ovality, cylindricity, taper, and surface finish with a single probe. According to the company, measurement takes place as fast as the probe can be inserted into and then withdrawn from the hole.

The Ball Runner probe allows accurate measurement of any ID greater than about 0.2" (5 mm) to within ±5 µm. This is accomplished by inserting the Ball Runner probe into the hole and then withdrawing it while recording the position of the probe with respect to an established part datum. During probe movement, both the "contact" eddy-current signature of the part extracted by the probe and the position of the probe within the hole are inputted to a computer. Software then plots probe position versus part signature, generating a profile that represents the inside diameter of the hole on the computer screen.

The system was developed when NDT Technologies was asked to determine the ID of a center hole in electric motor rotors, which were produced from a stack of laminates arranged so that a center hole in each of the laminates would align to create the center hole in the stack. The customer wanted to measure the hole ID within ±0.00075" (19.5 µm). Several attempts had been made by other companies, using various inspection technologies, with no success.

Print requirements were for the center hole in production parts to be from 0.4970 to 0.4985" (12.62 – 12.66 mm) diameter. Measurement was complicated by the fact that the ends of the stack were staked, thereby decreasing hole size of a few of the outer laminates by about 0.0009" (22.9 µm). This made it difficult to measure the actual ID below the ends of the stack in a production environment.

To provide an absolute gage reference for measurement of the rotor bores, NDT Technologies located two "gage rings" that bracketed the part ID dimensions so that the probe would first pass through them as it entered the part. The ID profile of these gage rings was therefore stored in the computer memory along with the ID profile of the part. Profiles generated by the system show both the two gage ring profiles and the part ID profile.

When NDT Technologies used the system to perform measurements on rotor laminate stacks, technicians discovered that none of the parts tested was within the required tolerance.

## Case Study (A Project)

In this project, an eddy current technique requiring minimal surface preparation was developed to inspect thread roots for surface cracks. Eddy current inspection offers many advantages over traditional surface methods. Minimal surface preparation reduces the overall inspection time thereby reducing inspection cost. Fastener inspection is often performed in radiological controlled areas; therefore, reduced inspection time is also a health benefit. Eddy current methods do not require developers or liquid suspended ferromagnetic particles, thus consumable material use is reduced. For fasteners in radiological controlled areas, reduction in consumable material use reduces the generation of mixed hazardous waste.

Several materials issues were investigated to aid in the development and verification of an eddy current technique. Initially, the thermal behavior and electromagnetic properties of the anti-seize lubricant were investigated to determine the feasibility of an eddy current technique. In addition, electromagnetic properties of common fastener materials such as 4340 steel were also investigated. A system to detect and size circumferential cracks in thread roots was developed and demonstrated on fasteners with service induced flaws. Signal analysis methods were also developed for determining crack length and depth. Capable of detecting and sizing circumferential cracks in thread roots, this eddy current technique provides an alternative to traditional surface methods for examination of fastener thread roots.

### WHY USE EDDY CURRENT?

- It saves time and money to run the equipment.
- It is preventative tool to detect problems before they arrive.
- Controlling and monitoring the corrosion rate, air leaks, inhibitors, water treatment and life expectancy.

Early detection by Eddy Current examination would have prevented the following failures:

Fig. 1 Copper prime tube from evaporator section stress-corrosion crack

Fig. 2 Copper-Nickel skip-fin tube from generator section. Severe tube wear at support sheet

Fig 3 Copper-Nickel prime tube from Hot water, Heat exchanger. O.D. corrosion on water side

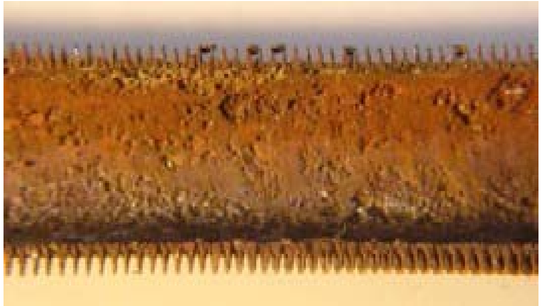


Fig. 4 Copper tru-fin tube from Condenser section. Massive I.D. corrosion

Fig. 5 Copper prime tube from Absorber section. I.D. corrosion due to improper water treatment

Fig. 6 Copper prime tube from Condenser section O.D. corrosion at support sheet due to air leak

## CONCLUSION

Therefore, in this project report, we have seen that Eddy current inspection is nowadays one of the growing and advanced non-destructive testing methods of inspection of defects in the finished components. It is not just for cracks any more. The various fields of application of eddy current inspection include detection and testing of Short Surface & Subsurface OD Cracks and Weld line Defects, ID Defects in Thin Wall Tube, Internal, ID and OD Defects in Heavy Wall Oil Country Goods, Internal Longitudinal and Transverse Flaws, Wall Thickness Measurement, Long Continuous Surface Defects, Ferrous inclusions in nonferrous tube, Alloy and Hardness Detection and in Situ Defect Detection in Heat Exchanger Tubes.

Eddy current theory and principles is based on the principle of electromagnetic induction and following sequential things happen during eddy current testing:

1. Eddy current coil generates primary magnetic field (Ampere's Law)
2. Primary magnetic field induces eddy currents in the material (Faraday's Law)
3. Eddy currents generate secondary magnetic field in the opposite direction (Lenz's Law)
4. Coil impedance changes, as a result
5. Impedance change is measured, analyzed and correlated with defect dimensions

Eddy current also makes use of the various types of sensors/probes, which are considered as the heart of eddy-current test system and designed for the specific applications. The various types of probes are Absolute, differential, reflection and shielded etc. Design and development of eddy current probes is very important as it is the probe that dictates the probability of detection and the reliability of characterization. In general, defects that cause maximum perturbation of eddy currents are detected with high sensitivity. The shape, cross-section, size and configuration of coils are varied to design an eddy current probe for a specific application.

Eddy current instruments can be effectively introduced into production lines to provide semi-automated or fully automated 100% testing. Test decisions are clear cut. The human factor is eliminated. This thus proves to be a very reliable and very effective inspection method of today's competitive manufacturing era.

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