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Surface Characterization of Stainless Steel Part by Eddy Current

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September 2003

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Introduction

The Pacific Northwest National Laboratory (PNNL) has nearly a 40 year history of research and development in the field of nondestructive evaluation (NDE). One area of NDE expertise at PNNL is electromagnetic testing, which includes the field of eddy current testing (ET) [1-7].

ET is widely used across many industries for inspection of parts and materials. One benefit is that ET can typically be performed at high speeds, and as a result has found many applications in process monitoring and production lines. Another important benefit is that ET can be a non-contact measurement, and does not require the sensor to be in direct contact with the part being evaluated.

ET has been used in the nuclear, aerospace, and automotive industries for many years. ET technology lends itself well to the detection of near-surface or surface breaking defects such as surface scratches.

This paper provides an overview of theory regarding the usage of ET, selected application studies performed by PNNL, a safety analysis, and a write up pertaining to the operations of ET to detect surface scratches with a depth on the order of 25 µm.

Electromagnetic Theory/Principals of Operation

Eddy current evaluation examines material and object properties by employing an alternating electromagnetic current induced into a conductive material. A coupled system forms when the ET probe is brought into close proximity with a conductive material. The probe current generates a magnetic field that induces electrical eddy currents in the part to be evaluated. The eddy currents generate another magnetic field that affects the electrical properties of the probe. Part properties in the vicinity of the probe; therefore, affect the real time properties of the probe. (Additional detail of the fundamentals of electromagnetism and eddy currents are provided in references [8-10].)

Eddy current depth of penetration is dependent on frequency. Generally, a lower frequency will penetrate deeper into the part than a higher frequency, and the induced current density dissipates as 1/e, or 37%, of its surface value [8]. This is called “skin effect” and is given by the formula:

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

Where: S = the standard depth of penetration

π = 3.14159

σ = the conductivity of the material
f = the frequency in hertz
μ = the relative magnetic permeability; and
μ_0 = the permeability of free space.

For detecting and sizing defects near the surface, such as scratches, a frequency would be selected that would provide adequate sensitivity near the surface, yet able to penetrate deep enough to reliably size the defect.

The complex impedance plane of a probe is monitored, where one axis represents a real component of the signal, and another axis represents the imaginary component of the signal. Using vector mathematics, the magnitude of the impedance can be broken down into the real component (resistance) and imaginary component (inductive reactance) for analysis by using a phase angle. Detection and sizing of defects is made possible by observing signal magnitude and phase angle changes.

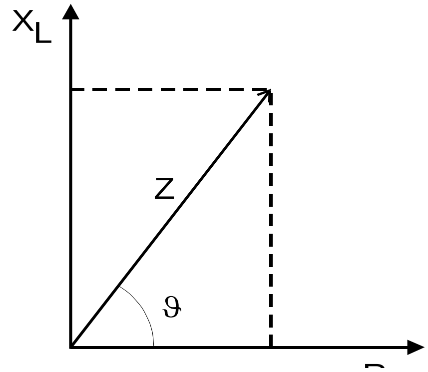


Figure 1. Complex impedance plane data point represented by either Real and Imaginary coordinate values or Magnitude and Phase Angle.

Selected EM Applications and Studies Performed by PNNL

<u>Custom Coil Design and Fabrication:</u>
PNNL is continually improving the state-of-the-art in probe design and electronics because many of PNNL's first of a kind applications require hardware that are not commercially available. Advancing the technology and developing unique solutions to challenging applications require Laboratory Staff to maintain a probe design and fabrication capability. Coils made at PNNL are typically one-of-a-kind designs, or short run development probes used in proof-of-principal testing, and can vary in size from large, 55-gallon drum encircling coils to miniature (sub-millimeter) coils that will nearly fit on the head of a pin.

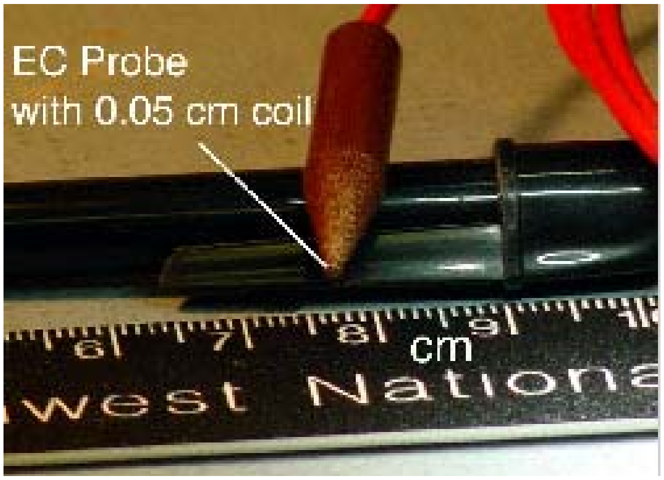


Figure 2. Custom ET probe fabricated by PNNL [0.5-mm (0.020-in.) diameter] to examine finely threaded parts such as gear teeth and bolts.

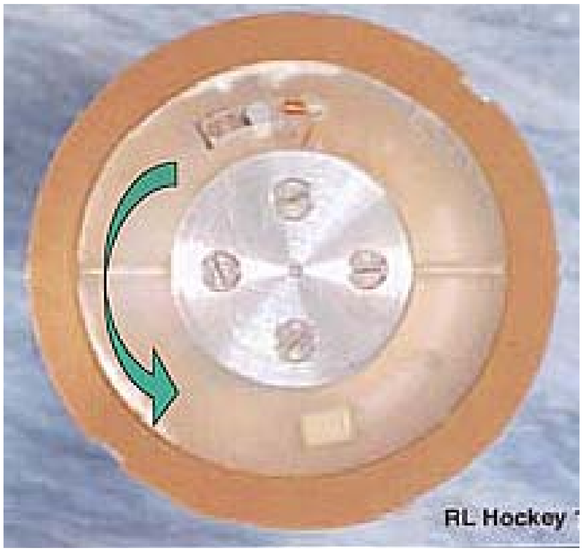


Figure 3. Custom ET probe fabricated by PNNL to examine under fastener heads of aerospace structures for deeply buried flaws. (The probe head rotated at a rate of 10,000 revolutions per minute.)

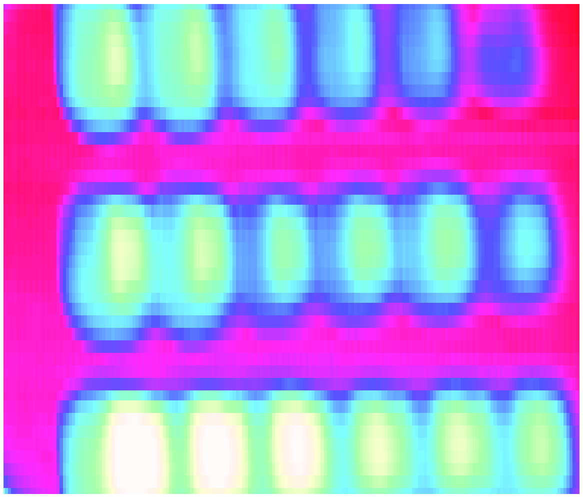
Figure 4. Cartridge Case Measurement Ejection System (CCMES) delivered to US Army.

Cartridge Case Measurement Ejection System (CCMES): An automated, on-line inspection system using combined optical and eddy current testing was built for detection of flaws in brass cartridge cases. The eddy current spindle rapidly and reliably inspected 100% of the product at an inspection rate of 1,200 cartridge cases per minute. This system was taken from concept to field deployment, including

- Development of the inspection technology and selection of eddy current probes
- Custom electronics,
- hardened inspection modules for measuring five key parameters
- Design of the integrated parts handling and control system
- Plant deployment to the on-line production process

This system has been in place for over 15 years and has an excellent track record. This successful deployment demonstrates PNNL's ability to form multidisciplinary teams necessary to develop a concept into a practical and robust solution.

ET Imaging of Scratches on a Stainless Steel Surface: An ET study was performed to evaluate the detection of scratches on a stainless steel surface. The sample was a polished stainless steel disk with three sets of simulated scratches fabricated onto the surface. Set 1 consisted of narrow scribe marks with a depth range from 35 to 80 µm. Set 2 consisted of 1.0-mm wide indications with a depth range of 15 to 65 µm. Set 3 consisted of 2.0-mm wide indications with a depth range of 25 to 80 µm. A non-contact scan was implemented by a 0.05-mm (0.02-in.) gap between the probe and the part surface to eliminate the possibility of surface damage by probe contact.

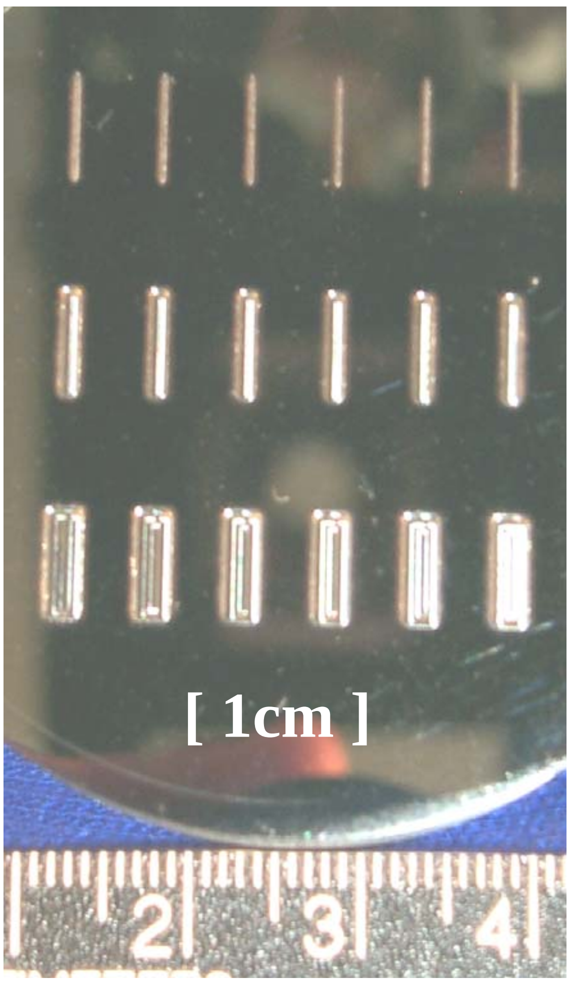


Set 1 - Narrow Indications
(New Tungsten Carbide Scribe Used as Tool):
Depths of 82, 75, 65, 54, 40, 37 µm

Set 2 - 1-mm (0.040-in.) Wide Indications
(End Mill Tool):
Depths of 67, 57, 44, 29, 21, 14 µm

Set 3 - 2-mm (0.080-in.) Wide Indications
(End Mill Tool):
Depths of 81, 68, 56, 39, 33, 23 µm

(A) Eddy Current Image of Reference Scratches.



(B) Photograph of Polished 304 Stainless Steel Sample with Reference Scratch Set.

Figure 5. An ET image of a scratch pattern placed onto the surface of a polished 304L stainless steel sample. (A depth range of 15 to 80 µm was optically measured for the scratch pattern).

Ferromagnetic Resonance (FMR) System: A Ferromagnetic Resonance (FMR) eddy current system was developed to increase detection sensitivity several orders of magnitude to small-scale defects within 100-µm of the surface of a metallic object. A 0.5-mm (0.020-in.) diameter Yttrium Iron Garnet (YIG) sphere was placed inside a 0.8-mm (0.030-in.) diameter loop to create electrical resonance at 900 MHz. A YIG sphere was selected because of its ferromagnetic properties and small size. This design greatly increased the signal-to-noise ratio and permitted an eddy current like evaluation to be performed at a much higher frequency than had been done historically. The interaction between the probe and material is essentially the same as eddy current evaluation; however, the probe and associated system electronics are significantly different.

Tritium Target Qualification Project (TTQP): The TTQP needed a reliable inspection method to evaluate the integrity of nuclear-grade parts that were subjected to coating and plating processes. Eddy current techniques satisfied stringent measurement requirements and were used to measure the integrity of aluminide-coating and nickel-plating parameters.

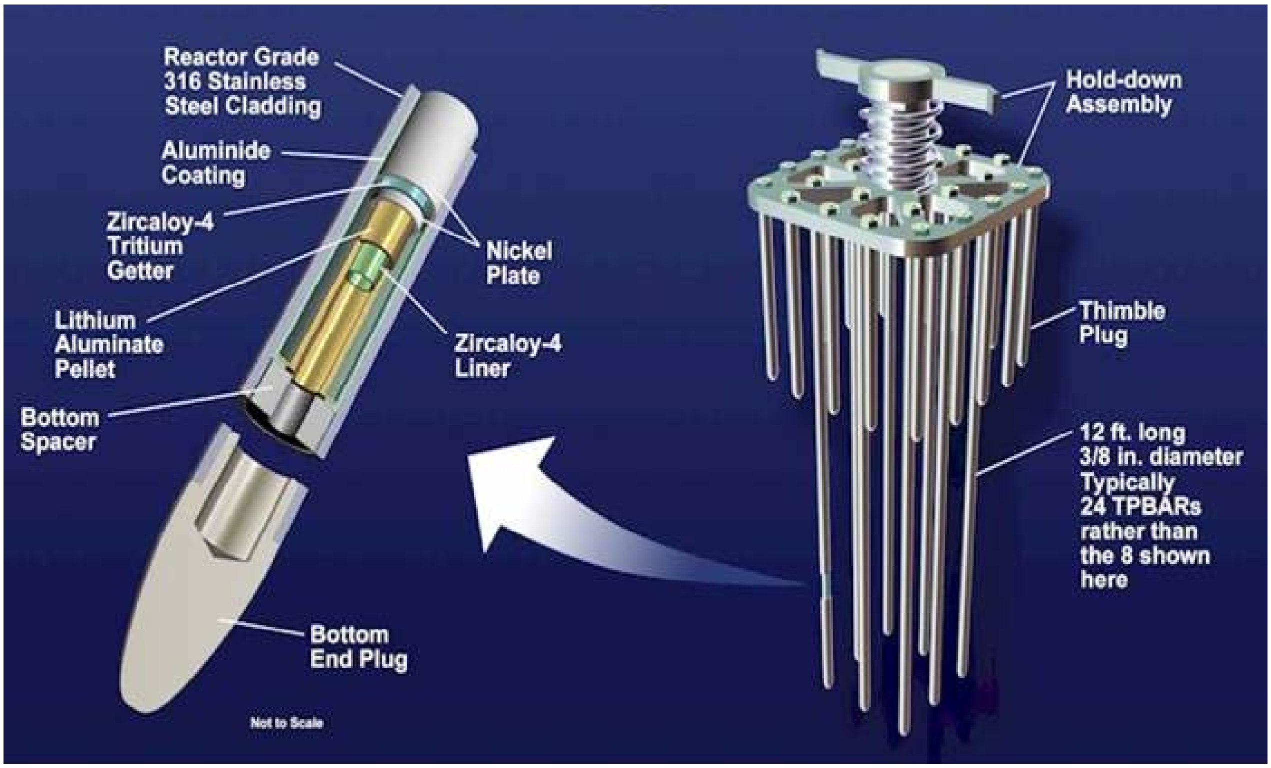
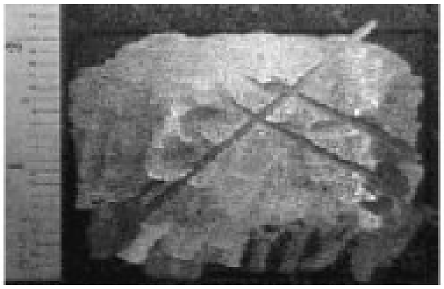
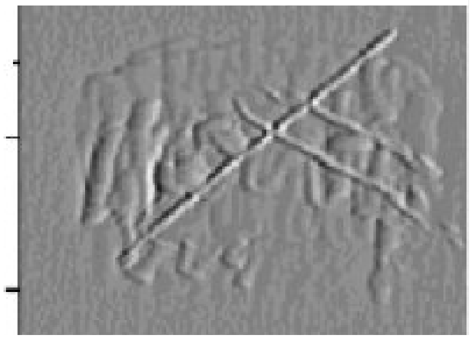


Figure 6. A tritium-producing burnable absorber rod for a commercial light water reactor.

Additionally, a short-tube inspection system was built that integrated eddy current technology with other inspection methods (air gaging and laser gaging). Based on the positive results of the single-tube coating scanner, another coating inspection system was built that performed eddy current inspections on four tubes simultaneously. Custom software was developed for these systems, and it provided a user-friendly analysis and a visual display for defect detection. Additionally, the eddy current data was presented in a three-dimensional image for advanced analysis.



(A) Photograph of Eroded Surface.



(B) MFL Image Acquired from Opposite Smooth Side of Plate.

Figure 7. Magnetic Flux Leakage (MFL) image of inner eroded surface with probe access to outside surface. Note marked correlation between optical and MFL images.

Flaw Detection in Magnetic Materials: Magnetic materials pose unique inspection challenges using electromagnetic methods, in part because their magnetic permeability can vary to a great extent, and therefore, distort the results of the inspection.

Staff at PNNL have developed a Magnetic Flux Leakage (MFL) method to detect defects in magnetic materials. Remarkably, this technology was proven to image defects on the inside surface when the probe was placed on the outside surface of the test piece. This technology was successfully demonstrated to image corrosion inside sealed waste storage drums.

Proliferation Detection Technologies: An electromagnetic sensing system was developed to non-invasively obtain a model signature of a metal object placed within a closed container. Large custom encircling coils were made to generate low frequency electromagnetic fields that penetrated the container and interacted with an object inside. The sensor impedance measurements clearly distinguished between various possible metal objects placed within containers.

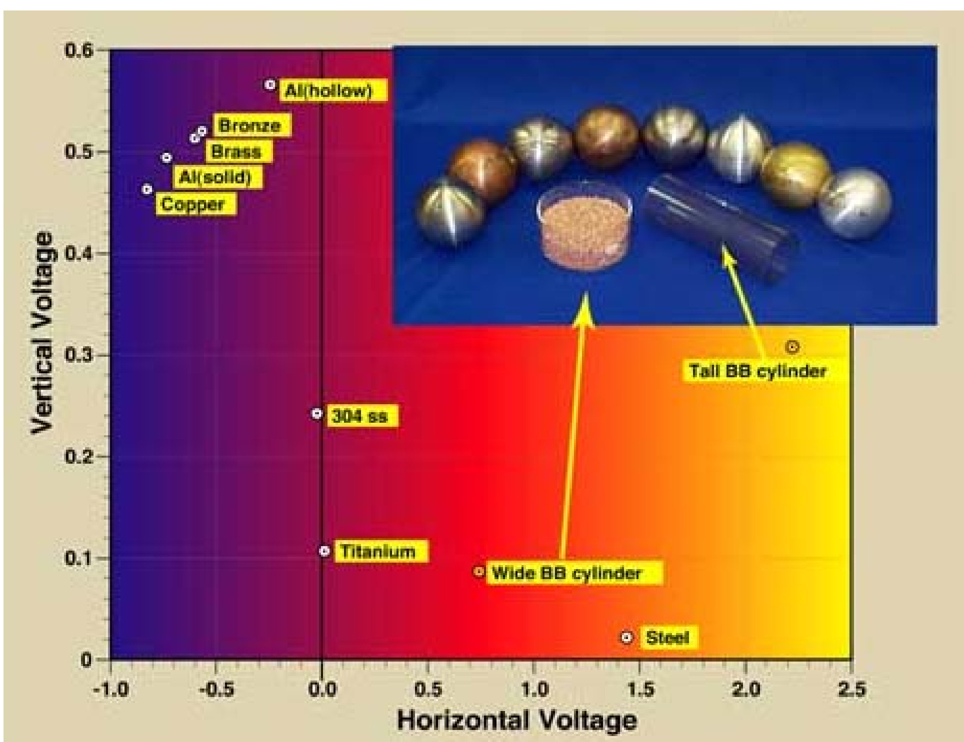
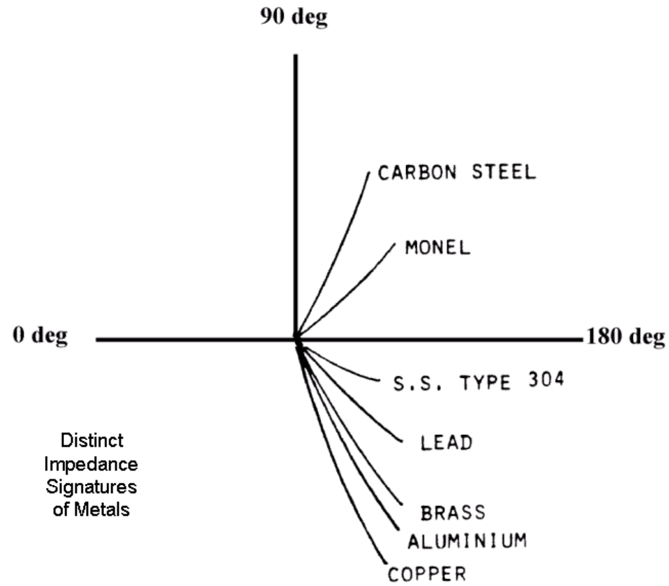


Figure 8. Eddy Current output for spheres of different metals placed in steel drum surrounded by a custom coil fabricated by PNNL.

Dual-Use Metal Sorter-Electromagnetic Signatures of Metals: PNNL has designed and fabricated a system capable of sorting metals based on a unique electromagnetic signature (impedance). This technology is of particular interest to US and world agencies responsible for detecting materials that are considered "dual-use", or items that have a legitimate commercial use, but could be used for other, illegitimate purposes.

US Customs and Border Patrol, the Federal Bureau of Investigation, U.S. Department of Transportation, and foreign agencies have shown interest in this technology. By measuring the electromagnetic signature of a particular material or alloy, a database was formed to compare real-time data on materials of interest.

(A) Photograph of Dual-Use Metal Sorter



(B) Data Illustrating Sorting Capability of Selected Structural Alloys and Metals

Figure 9. A custom eddy current instrument was integrated into the peripheral slot of a lap-top computer for the purpose of identifying materials.

Safety Analysis of EM Techniques Being Used at Pantex

Several Eddy current measurement campaigns were conducted on primary weapons components at the Pantex Plant near Amarillo, Texas. To conduct these measurements a Failure Modes and Effects Analysis (FMEA) study was required, establishing and evaluating all potential risks[1]. The documentation from this study shows that the worst case scenarios do not pose a safety

[1] FMEA is a detailed, systematic safety analysis technique that examines how components and hardware can contribute to system failure and identifies the effects of such failures. The purpose of an FMEA is to provide insights to designers to assist in improving the designs of systems, particularly safety-related systems, with respect to safety and reliability, documents existing safety and reliability-related provisions in the design, and provides suggested design changes that could improve safety and reliability. The FMEA done for the eddy current system included only one iteration. The suggested changes to the test system, safety precautions, and test procedures that result from this iteration of the FMEA were considered before approval to run the test was given. Additional information on the FMEA approach is given in MIL-STD-1629A (DOD 1980).

hazard. A similar safety analysis, using the same test equipment, could be performed for this work should it become necessary.

Near Surface Inspection of Scratched 304L Stainless Steel Using Electromagnetic Testing

A need exists to detect and size small surface breaking scratches on a 304L stainless steel part using a non-invasive and non-contact inspection method.

Proposed solutions include a custom eddy current system, a FMR system, or a combination of either with optical measurements. Eddy current could perform detection and sizing but another option is to employ eddy current for rapid detection and to use slower optical means to characterize detected anomalies.

An eddy current probe excitation frequency will be calculated to provide a penetration depth on the order of 25-µm in 304L stainless steel. This should provide near optimal sensitivity to detect a 25-µm deep scratch but may also be too sensitive to shallower scratches that may not be of high interest. Tradeoffs would include detection sensitivity, the range and accuracy for estimating scratch depth, and the offset displacement to assure a non-contact inspection. As stated earlier, an obvious factor is to not be overly sensitive to scratches of a depth much less than the minimal critical size of interest.

The primary criterion for selection of ET or FMR is performance. Preliminary data, (See Figure 5), indicate ET has a high probability of satisfying the technical need; however, another evaluation criteria is estimating the width of the indication. Lateral resolutions of ET and FMR are expected to be better than 0.5 mm (0.020-in.) and the field of an eddy current probe can be focused to enhance lateral resolution. Signal processing by point-spread-function analysis and-or deconvolution should be able to enhance this by a factor of 5. Examples of improvements are provided by commercial suppliers of such software [11].

A customized 900-MHz FMR system should be very sensitive for detecting small-scale defects such as a 25-µm deep scratch on an object made from 304L stainless steel. A unique advantage of the FMR system operating at 900 MHz is its high sensitivity for detecting a 25-µm deep scratch in 304L stainless steel material since the eddy current skin depth of 14-µm is less than the minimum scratch dept of interest. Thus, a very high sensitivity should exist for a 25 µm-deep scratch or scratches with less depth, if desired.

Development of the FMR system was performed for the Air Force Wright Aeronautical Laboratories in the 1984. Work did not continue thereafter, since most eddy current evaluations were directed at much larger anomalies. To resurrect the YIG sphere capability, a $70,000 effort is envisioned as a proof-of-concept test for detecting 25-µm deep scratches on a flat surface.

A conclusion is that both ET and FMR have the capability to detect and size surface anomalies or be used to quickly detect surface anomalies that then would be characterized by an automated optical process. An evaluation to be performed in fiscal year 2004 is suggested to provide guidance for system development in fiscal year 2005.

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