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APPLICATIONS OF SPATIALLY PERIODIC FIELD EDDY CURRENT SENSORS FOR SURFACE LAYER CHARACTERIZATION IN METALLIC ALLOYS

Vladimir Zilberstein, Yanko Sheiretov, Andrew Washabaugh, Yonghua Chen, Neil J. Goldfine

JENTEK Sensors, Inc., 200 Dexter Avenue, Watertown, MA 02472

Abstract. Spatially periodic field eddy current sensors such as the Meandering Winding Magnetometer (MWM) with Grid Methods provide a powerful capability to nondestructively characterize surface layers introduced during fabrication as well as those modified by service exposure. This is critical for process quality control and component condition assessment. Conformable MWM sensors provide absolute property measurements (conductivity, permeability) and dimensional data (coating thickness, proximity) over flat and curved surfaces with minimal calibration requirements. Using a three-layer (substrate, coating, air) model and an inversion algorithm, a new measurement module has been developed to estimate the thickness of a process-affected zone and to provide a measure of property variations in this zone in real time. This paper presents results for two specific process quality control applications: (1) alpha case thickness measurements in a titanium alloy and (2) characterization of shot peening for aluminum alloys.

INTRODUCTION

Many process quality control and condition assessment applications require near-surface inspections to determine layer or coating properties. The inspection materials may involve discrete layers, such as metallic overlay or bond coats on metal substrates for thermal protection of turbine blades, or distributed layers, such as those due to manufacturing processes like shot peening or roll burnishing. In both situations, the properties of the coating or the effective layers provide information about the efficacy of the manufacturing processes or service related aging processes.

One of the critical issues involved with characterizing surface layers is the inversion of the measured data from the sensor into the effective material properties of the surface layer. This is often complicated by the fact that many parameters can be varying at the same time. For example, when using an eddy current sensor to inspect nonmagnetic metallic coatings on nonmagnetic metallic substrates, the measurement depends upon the substrate electrical conductivity, the coating electrical conductivity and thickness, and the air gap (lift-off) of the sensor over the article surface. With conventional eddy current sensors, extensive sets of reference components that have a similar geometry as the test article and that have been exposed to similar process conditions are often required for effective measurements. With new, model-based spatially periodic field eddy current sensors, one of which is the Meandering Winding Magnetometer (MWM^{TM}), this requirement for extensive reference sets can be relaxed. This paper describes the use of spatially periodic field eddy current sensors for several inspection applications and the use of models that accurately describe the sensor response to layered media for solving the inverse problem.

BACKGROUND ON MWM-ARRAY TECHNOLOGY

Figure 1 provides a schematic of a standard MWM, a standard MWM-Array and a tapered MWM-Array. In each case a time varying current in the drive winding produces a spatially periodic magnetic field that diffuses into the material under test (MUT) and induces a spatially periodic pattern of eddy currents in the conducting layers of the MUT. This induced eddy current pattern is determined by the MWM drive winding geometry, the absolute material properties of the MUT, geometric features such as a coating thicknesses and anomalies such as cracks and pits. The eddy current patterns produce magnetic fields that diffuse back to the drive winding. When the drive current is varied at a prescribed frequency, the time varying drive field and the time varying field produced by the eddy currents combine to produce a time varying magnetic flux that passes through the area covered by the sensing windings. This produces a voltage at the sensing winding terminals as in a conventional eddy current sensor. The properties of the MUT affect both the magnitude of the field passing through the sensing windings and the time for the magnetic fields to diffuse into the MUT and back to the MWM winding plane. The result is a measured magnitude and phase of the impedance (=voltage at the sensing elements/current applied to primary windings) that is related to the material under test properties. By designing the MWM to minimize difficult-to-model inductive coupling, computer models can be used to generate databases of sensor responses so that measurement of absolute properties can be performed quickly in real-time using two or three-dimensional table look-up algorithms to apply a patented "Grid Measurement Method" [Goldfine, May 1997].

Photolithography and flexible circuit technologies are generally used for the manufacture of these sensors. This results in highly reliable and highly repeatable (i.e., essentially identical) sensors, which have inherent advantages over the coils used in conventional eddy current sensors. As indicated by Auld and Moulder, for conventional eddy current sensors "nominally identical probes have been found to give signals that differ by as much as 35%, even though the probe inductances were identical to better than 2%." [Auld, 1999] The detection of inclusions and cracks in electrically "noisy" materials, such as titanium, with conventional eddy current sensors is severely limited by this lack of reproducibility. In contrast, duplicate MWM sensor tips have nearly identical magnetic field distributions around the windings as standard micro-fabrication (etching) techniques have both high spatial reproducibility and resolution. Furthermore, the windings are typically fabricated onto a thin and flexible substrate, producing a conformable sensor.

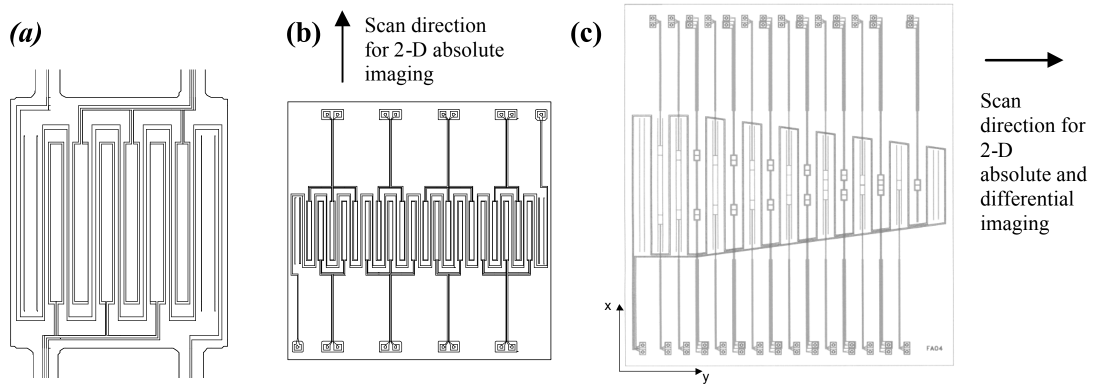

Figure 1. (a) Single sensing element MWM Sensor, (b) MWM-Array, and (c) tapered array with deep penetration drive and differential and absolute sensing elements for high resolution imaging.

The MWM sensor, shown in Figure 1a, has a single sensing element that produces an average of the conductivity over the footprint region. The MWM-Array shown in Figure 1b, has five relatively large footprint sensing elements, which produce a spatial image (C-Scan) when scanned in the direction shown. The image resolution is limited to the sensing element footprint in the transverse direction, but the resolution can be relatively high in the longitudinal direction. The tapered MWM-Array produces high-resolution images in both the transverse and longitudinal directions, using both differential and absolute sensing elements. The absolute elements permit use of the Grid Methods to measure absolute properties of interest, such as layer thickness (e.g., alpha case thickness) while both the differential and absolute elements provide sensitivity to local anomalies, such as cracks.

The principal development required to implement this approach, beyond the winding designs and the grid methods, is the availability of a parallel architecture multiple channel impedance instrument that can provide an accurate and precise measure of transimpedance over a wide frequency range. The next generation impedance instrumentation provides this capability. The JENTEK Multiple Channel Extended Remote Instrument Module (MC-ERIM) is shown in Figure 2, along with probe electronics and several interchangeable sensor tips for the MWM-Array (shown earlier in Figure 1b). This instrument is scalable and versions are now being tested to support tapered MWM-Arrays with numerous channels. Potential for up to 100 channels of high quality rapid and parallel impedance measurement are expected to be available in the near term.

The MWM sensor response is converted into material or geometric properties using JENTEK's GridStation Measurement System. Measurement grid methods are typically used to map the magnitude and phase of the sensor impedance into the properties to be determined and provide for a real-time measurement capability. The measurement grids are two-dimensional databases that can be visualized as "grids" that relate two measured parameters to two unknowns, such as the conductivity and lift-off (where lift-off is defined as the proximity of the material under test to the plane of the MWM windings). For the characterization of coatings or surface layer properties, three-dimensional versions of the measurement grids called grid lattices can be used. Alternatively, the surface layer parameters can be determined from parameter estimation numerical algorithms. The GridStation software also controls the data acquisition instrumentation and provides a graphical user interface that permits immediate display of inspection results with minimal user interpretation.

Figure 2. Left: the MWM scanning/imaging array, and right: the JENTEK Multiple Channel Extended Remote Instrument Module (MC-ERIM).

For characterizing surface layers, a layered media model for the material, as shown in Figure 3a, can be used. For nonmagnetic materials, the sensor response depends upon four unknown parameters associated with the MUT: the electrical conductivity of the substrate, the electrical conductivity and thickness of the coating or surface layer, and the thickness of the air gap. A representative measurement grid relating the coating thickness and lift-off to the sensor magnitude and phase, for a fixed substrate conductivity, coating conductivity, and frequency, is given in Figure 3b.

In many applications, the conductivity of the substrate is known because measurements can be performed on uncoated or un-processed areas of the test article. For these situations, a multiple frequency algorithm was developed to solve for the remaining three unknowns: coating conductivity and thickness, and the lift-off. The multiple frequency measurements provide the ability to vary the depth of sensitivity of the sensor, with lower frequency measurements being sensitive to the substrate as well as the coating and higher frequency measurements being sensitive primarily to the coating. The patented multiple frequency algorithm takes advantage of the fact that although coating thickness is not known, the coating thickness does not change during the course of a multiple frequency measurement [Goldfine, November 1997]. This algorithm has been applied to systems having both discrete and distributed layers, as described below.

Each grid lattice used in the GridStation measurement system is a collection of measurement grids, each one of which provides a two-dimensional database of the sensor responses as the coating thickness and liftoff are varied for a given coating conductivity. For the grid lattice, measurement grids are created for a range of coating conductivities that span the range of interest for a given material and form a three-dimensional database for the sensor response.

Representative grid lattices for the characterizations of turbine blade coatings are shown in Figure 4. The lattices show coating thickness-liftoff grids for four coating conductivities at a relatively "low" frequency of 1 MHz and an "intermediate" frequency of 6.31 MHz. In each measurement grid, the spacing between the grid points illustrates the sensitivity for independently estimating the coating thickness and the liftoff. The grid spacing and sensitivity is large when the coating and the substrate have significantly different conductivities; the grid collapses when the conductivities of the coating and the substrate are equal, which is expected for an uncoated specimen. The lattices of Figure 4 are relatively coarse, for visualization purposes, as only 140 lattice points (5 coating thicknesses, 7 liftoffs, and 4 coating conductivities) are shown; a typical lattice used in the analysis has on the order of 20,000 points.

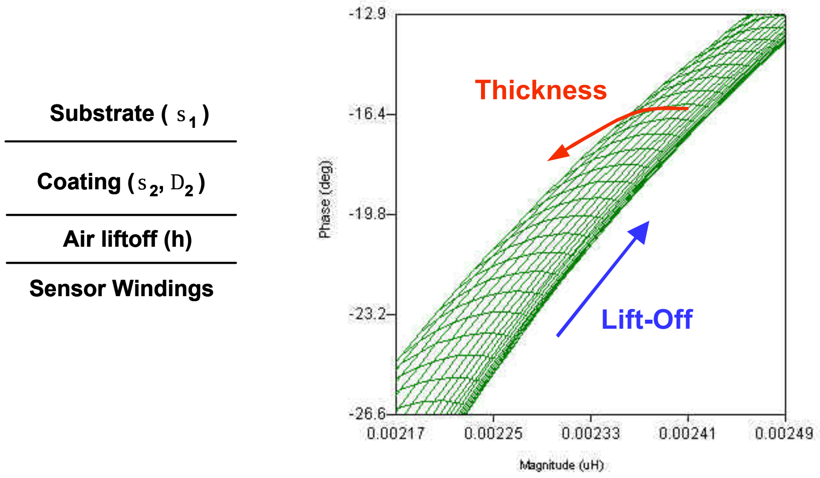

Figure 3. (a) Three layer model for coating property estimations. (b) A representative conducting coating thickness - lift-off measurement grid.

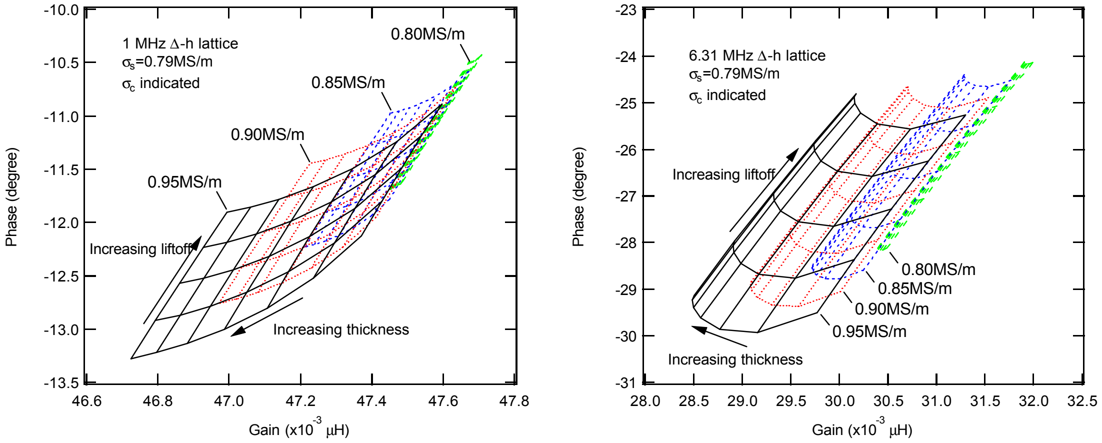

Figure 4. Coating thickness - lift-off grid lattices for and MCrAlY coating family at 1.0 MHz and 6.31 MHz.

CONDUCTIVE COATING THICKNESS MEASUREMENT

The multiple frequency method for the three-unknown problem was originally developed for coatings on turbine blades (and other coatings such as protective aluminum cladding on aircraft skins). For example, coatings protect the blades and vanes in gas turbines from oxidation and high temperature corrosion as well as excessively high thermal and mechanical stresses during exposure to hot gases. The coatings act as a sacrificial layer on the blades since the coatings degrade with exposure to high temperatures throughout service and lose their protective capabilities. Determining the properties of these coatings is important for both as-manufactured coatings and for service-aged coatings. Information on thickness and porosity of as-manufactured coatings can be used for process quality control, and scanning of the sensors across the blades, including areas of complex curvature, can verify that sufficient coverage has been achieved across the component. Effective condition monitoring for service-aged coatings allows the blades to be refurbished as long as the blade material itself has not begun to degrade.

Figure 5 shows a representative set of measurements on as-manufactured specimens consisting of a MCrAlY overlay coating on an IN738 substrate. In Figure 5a, the effective conductivity measured with the MWM is plotted against the frequency. For the uncoated specimens, the effective conductivity is constant with frequency. For the coated specimens, the low frequency response approaches the substrate conductivity as the skin depth of the magnetic field becomes large compared to the coating thickness. The high frequency response approaches the coating conductivity as the skin depth of the magnetic field becomes small compared to the coating thickness. The data with a 25-micron (1 mil) thick shim placed between the sensor and the specimens yields exactly the same effective conductivity estimate as the data without a shim, which provides confidence in the quality of the calibration and the measurements. As shown in Figure 5b, there is good agreement with destructive metallographic measurements of the coating thickness for coatings thicknesses of 100 to 350 microns (4 to 14 mils).

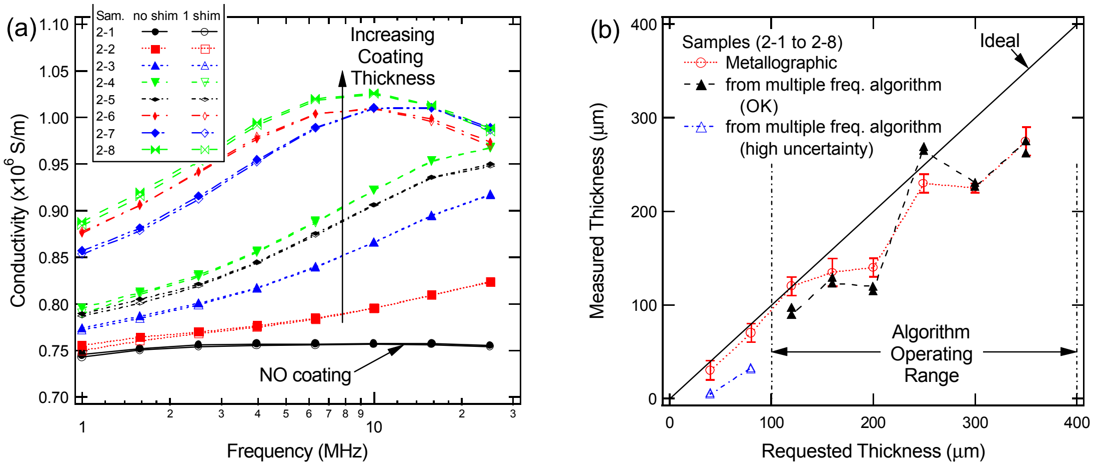

Figure 5. MWM results for MCrAlY coatings on IN 738 substrates; (a) multiple-frequency MWM conductivity data for different coating thicknesses, (b) MWM/GridStation metallic coating thickness results compared to actual thickness from metallography and original requested thickness (ideal).

ALPHA CASE THICKNESS MEASUREMENT IN TITANIUM ALLOYS

Alpha case can form at the surface of titanium alloys as the result of aggressive machining or during cooling of titanium castings in a mold. This oxygen-rich phase is relatively brittle and can provide initiation sites for cracks. As a demonstration of the MWM capability to detect alpha case and provide a measure of its thickness, measurements were performed on cast titanium samples that had varying alpha case thickness. One of these samples is a stair-step cast sample, supplied by Howmet, as shown in Figure 6, that has eight regions with reported alpha case thicknesses of 5.1 to 24.5 mils. The alpha case thickness varies along the surface due to the differences in cooling rates associated with the sample thickness variations.

Multiple frequency measurements and inversion algorithms were used to estimate the thickness of the alpha case. Figure 7 shows a representative plot of the effective conductivity of the titanium alpha case specimens. In these measurements, a reference part calibration was performed on a standard having a nominal conductivity of 600 kS/m, which was determined from an MWM "air calibration" measurement using conductivity-liftoff measurement grids assuming a homogeneous conducting material. The effective conductivity of Figure 7 represents the effective conductivity of a homogeneous material over the sensor. The reduction in the effective conductivity with increasing frequency indicates the presence of the alpha case as the material near the surface has a lower conductivity than the material in the bulk.

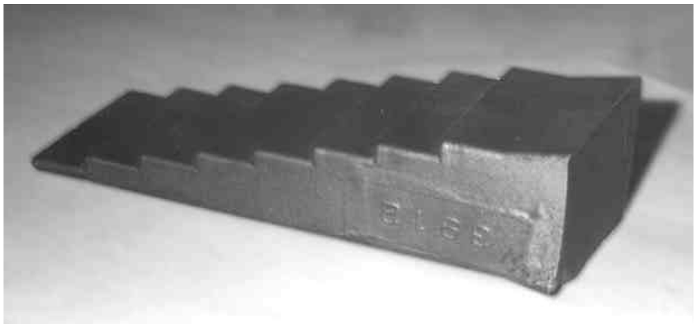

Figure 6. Photograph of the Howmet titanium specimen used for alpha case thickness measurements.

To estimate the thickness of the alpha case thickness from the multiple frequency measurements, a nonlinear least-squares multiple frequency parameter estimation algorithm was applied to the data of Figure 7. In this analysis, it was assumed that the alpha case could be represented as a discrete layer of reduced conductivity over the titanium substrate, the substrate conductivity was 600 kS/m, and the surface layer conductivity was 560 kS/m. Figure 8 shows the results of the layer thickness-liftoff parameter estimation. While the slope of the correlation curve varied with the assumed value for the alpha case conductivity, the trends were similar. Even though this simple one layer model does not completely describe the distributed spatial profile of the alpha case, the assumed "average" alpha case conductivity yields a good correlation with the nominal thickness. Similar results were obtained with the three-unknown multiple frequency algorithm developed for turbine blade inspections.

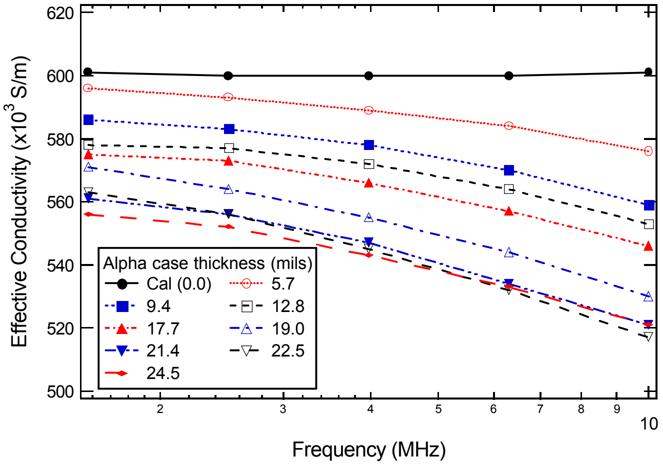

Figure 7. Effective conductivity of the titanium alpha case specimens.

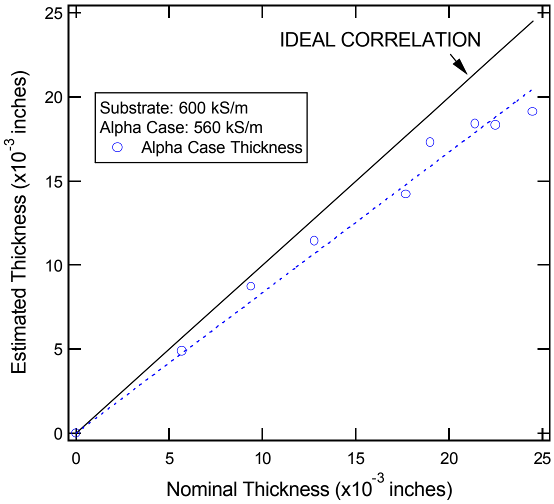

Figure 8. Comparison of estimated and nominal alpha case thickness.

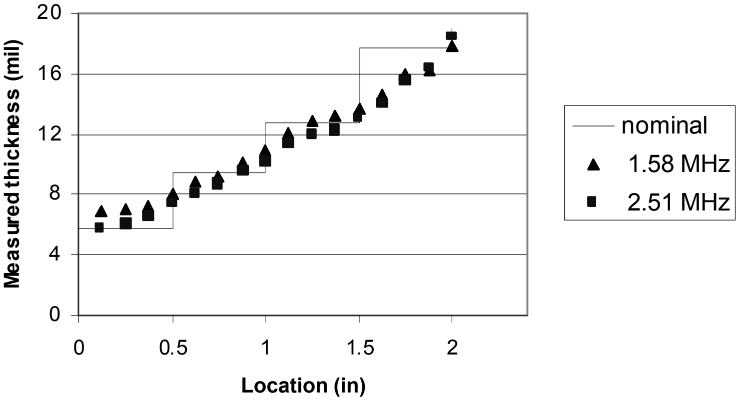

Figure 9. Comparison of MWM measured and reported alpha case thickness across the stair-step cast sample.

Single frequency measurements can also be used to determine the thickness of the alpha case. Assuming again that the alpha case can be represented as a discrete layer on the titanium alloy substrate and that the conductivities of both phases are known, then coating thickness - lift-off measurements grids, similar to the grid shown in Figure 3b, can be used. Figure 9 shows a comparison of the alpha case thickness determined from MWM measurements and the thickness reported by the specimen manufacturer. In this case, measurements were made on the flat surface of the specimen opposite each of the steps. The measurements were made with a 1/4 in. x 1/4 in. footprint MWM in a manual, incremental scanning mode. Similar results have been obtained in a continuous scanning mode. There is a good correlation between the MWM-measured and reported alpha case thicknesses. The consistency of the measurements is demonstrated by the same results being obtained from two different frequencies. The results demonstrate the potential to "map" alpha case regions and thickness, i.e., generate images showing alpha case distribution and thickness over a surface.

SHOT PEENING PROCESS QUALITY CONTROL MONITORING

Shot peening is a commonly used process for introducing compressive residual stresses at the surface of fatigue-critical areas of components. In this process, a high-velocity stream of small beads (shot) or a special flapper tool is used to plastically deform a near-surface layer. The intensity of the shot peening process is generally measured with Almen strips placed at various positions around the part. Within the plastically deformed, i.e. cold worked layer, high compressive residual stresses are locked in; these compressive stresses are balanced by tensile residual stresses in the unaffected “substrate”, that is in the base metal which has not undergone cold work during shot peening. The electrical conductivity of the cold worked layer is distinctly lower than the conductivity of the underlying base metal. This difference in conductivity is readily revealed by MWM measurements over a range of frequencies.

Figure 10 shows the results of multiple frequency measurements using the MWM with grid measurement methods for two aluminum alloys. The plot on the left of Figure 10 shows the results for Al 2024 samples, prepared and peened by Boeing to Almen intensities of 0.005, 0.012, and 0.017, Scale A. The plot on the right of Figure 10 shows the results for Al 7076 propeller blades, provided by Warner Robins, which contained areas peened to Almen intensities of 0.005, 0.008, 0.011, 0.014, and 0.017, Scale A. In these MWM measurements, the unpeened sample conductivity was essentially constant with frequency, which validated the quality of the reference part calibration performed prior to the measurements. For the peened samples, the effective conductivity varies with frequency. At the low frequencies, the sensor MWM depth of sensitivity is larger than the cold worked layer thickness and the effective conductivity approaches the conductivity of the unaffected material. At the high frequencies, the MWM depth of sensitivity is smaller than or comparable to the cold worked layer thickness so that the effective conductivity primarily reflects the reduction in conductivity associated with the cold work from peening. Clearly, a higher peening intensity leads to a greater reduction in the effective conductivity at the surface.

Based on the multiple frequency data, the thickness of the process-affected zone can be estimated. Assuming that the processed zone is a discrete layer over an unprocessed substrate, the three-unknown multiple frequency algorithm can be used. The effective affected zone thicknesses, shown in Figure 11 for both the Boeing and Warner Robins samples, vary essentially linearly with the shot peen intensity. Although the residual stresses and plastic deformation are not uniform throughout the process-affected zone, the use of the multiple frequency algorithm provides an effective thickness consistent with the thickness of stress profiles measured using destructive techniques.

For quality control monitoring during manufacturing processes, it is generally more desirable to monitor the intensity of the shot peening process directly on the peened surfaces rather than indirectly with Almen strips. This can be accomplished using a simplified, two frequency approach, through the ratio of effective conductivities measured at a relatively high frequency (such as 1 MHz) and a relatively low frequency (such as 100 kHz). As shown in Figure 12, for Aluminum 2024, this conductivity ratio is essentially linearly related to the shot peen Almen intensity. Once parameters based on MWM conductivity measurements are correlated with Almen intensity of a training set, the shot peen intensity can be determined at any location on shot-peened parts using MWM with Grid methods.

In creating this conductivity ratio correlation with Almen intensity, it is critical for the effective conductivity measurements to be insensitive to surface roughness. Since the peening process roughens the surface, the roughness can contaminate the conductivity measurements.

As shown in Figure 13, the effective lift-off measured by the MWM increases with Almen intensity because of increased roughness. The capability of the MWM with Grid methods to independently determine the conductivity and lift-off reduces the effect of surface roughness.

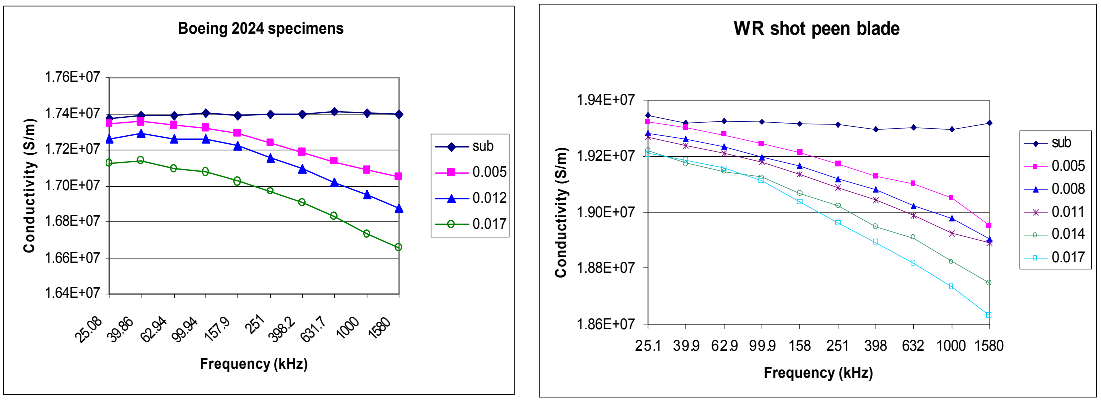

Figure 10. Multiple frequency measurements of the effective conductivity of shot-peened aluminum components.

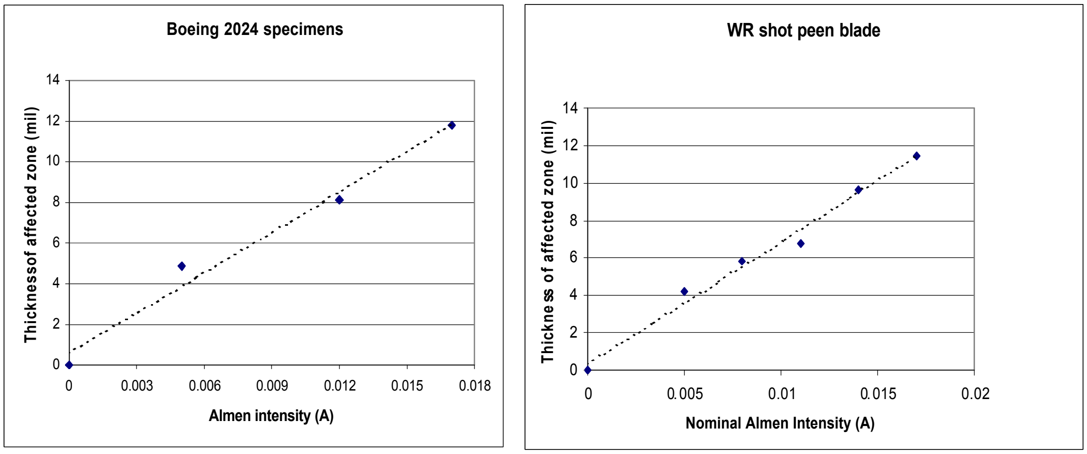

Figure 11. Effective thickness estimation for the shot peen process-affected zone using the data of Figure 10.

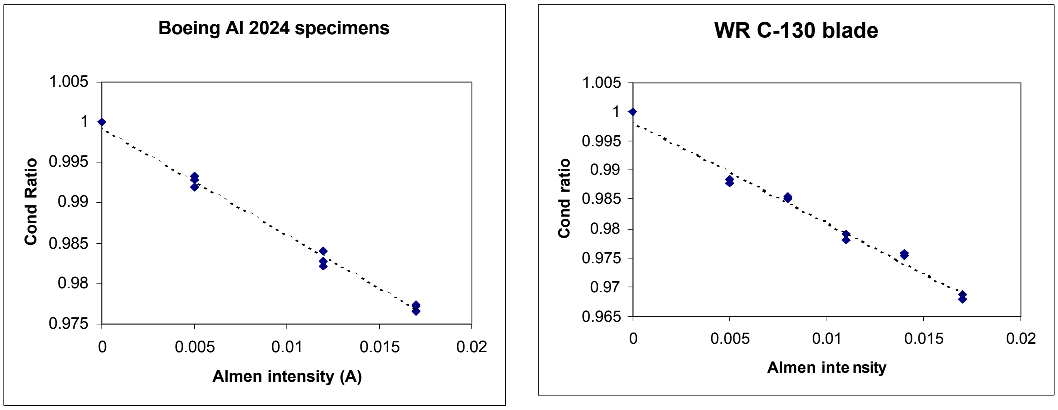

Figure 12. Correlation between shot peen process intensity and a two frequency conductivity ratio.

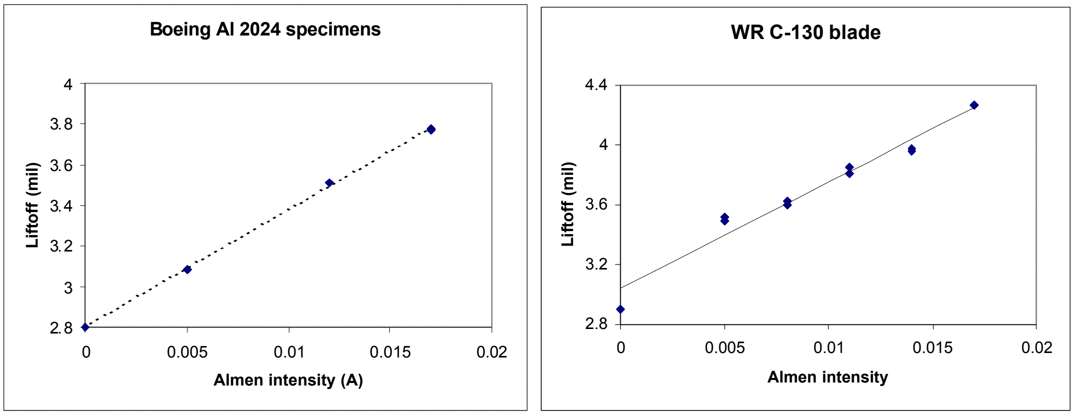

Figure 13. Correlation between shot peen process intensity and sensor lift-off, which provides an indication of surface roughness.

CONCLUSIONS

Surface layers for metallic alloys can be readily characterized using multiple frequency eddy current measurements with model-based sensor designs and inversion algorithms. These surface layers may be discrete layers on a substrate, such as a uniform conductive coating, or a distributed property, such as a process-affected zone. Ongoing work, involving MWM-Arrays and the development of parallel architecture instrumentation, will provide the capability for imaging of surface layer properties over wide areas.

REFERENCES

1. Auld, B.A. and Moulder, J.C., "*Review of Advances in Quantitative Eddy Current Nondestructive Evaluation*," Journal of Nondestructive Evaluation, vol. 18, No. 1, 1999.

2. Goldfine, N. J., "Magnetometers for Improved Materials Characterization in Aerospace Applications," Materials Evaluation 51, (3), March 1993 edition, pp. 396-405.

3. Goldfine, N. J., *"Uncalibrated, Absolute Property Estimation and Measurement Optimization for Conducting and Magnetic Media Using Imposed w-k Magnetometry"*, Thesis for the degree of Doctor of Science at the Massachusetts Institute of Technology, September 1990.

4. Goldfine, N. J., Melcher, J. R., "*Apparatus and Methods for Obtaining Increased Sensitivity, Selectivity and Dynamic Range in Property Measurement Using Magnetometers*," U.S. Patent Number 5,629,621, May 13, 1997.

5. Goldfine, N. J., Melcher, J. R., *"Magnetometer having Periodic Winding Structure and Material Property Estimator,"* U.S. Patent Number 5,453,689, September 26, 1995.

6. Goldfine, N. J., Rhoads, K.G., Walrath, K.E., Clark, D.C., "*Multiple Frequency Quantitative Coating Characterization*," U.S. Patent Pending, Application No. 60/065,545, November 14, 1997.

7. Goldfine, N. J., Schlicker, D., Walrath, K., Washabaugh, A., Zilberstein, V., "*Application of MWM-Array Eddy Current Sensors to Corrosion Mapping,"* 4th International Aircraft Corrosion Workshop, Naval Air Warfare Center, Patuxent River, MD, August 2000.

8. Goldfine, N., Schlicker, D., Washabaugh, A., *"Surface-Mounted Eddy-Current Sensors for On-Line Monitoring of Fatigue tests and for Aircraft Health Monitoring,"* August 1998.

9. Goldfine, N., Washabaugh, A., Walrath, K., Zombo, P., Miller, R., *"Conformable Eddy-Current Sensors and Methods for Gas Turbine Inspection and Health Monitoring"*, ASM International, Gas Turbines Technology Conference, Materials Solutions '98, Rosemont, IL, October 12-15, 1998. Also published in *Gas Turbine Materials Technology*, 1999; Oct. 1998 pp. 105-114.

10. Goldfine, N. J., Fisher, M.F., Zilberstein, V., *"Recent Applications of Meandering Winding Magnetometers to Materials Characterization,"* The 38th Annual British Conference on NDT, Poole, Dorset, UK September 13-16, 1999. Also published in *Insight: Non-Destructive Testing and Condition Monitoring* v 42 n 1 2000. P14-165.

11. Yentzer, T., Zilberstein, V., Goldfine, N., Schlicker, D., Clark, D., *"Anisotropic Conductivity Measurements for Quality Control of C-130/P-3 Propeller Blades Using MWMä-Sensors with Grid Methods,"* Fourth DoD/FAA/NASA Conference on Aging Aircraft, St. Louis, MO, May 15-18, 2000.