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MWM-Array Sensors for *In Situ* Monitoring of High-Temperature Components in Power Plants

Yanko Sheiretov, Dave Grundy, Vladimir Zilberstein, Neil Goldfine, and Susan Maley

Invited Paper

***Abstract*—Utilization of America's substantial coal reserves for energy production has become a national priority. Advanced coal-fired power plants offer an environmentally friendly means to achieve that goal. These power plants, such as ultrasupercritical power plants, will provide high thermal efficiency along with greatly reduced emissions of CO_2 and other pollutants. Life cycle costs for the advanced coal-fired plants can be reduced by enhanced observability in support of condition-based maintenance. The enhanced observability can be achieved by using networks of condition-monitoring sensors that would provide component-level material condition information and through-wall temperature monitoring. This would reduce uncertainties in knowledge of material condition, at the level of individual components, and improve capability to predict remaining life of critical components. One approach being developed under the U.S. Department of Energy Small Business Innovation Research Program is to develop and implement high-temperature versions of the meandering winding magnetometer (HT-MWM) for temperatures up to 1000 °C. These patented sensors, coupled with multivariate inverse methods, would provide superior performance for *in situ* material condition monitoring (material degradation, flaw detection, stress relaxation, and/or creep monitoring) and through-wall temperature measurement. Networks of HT-MWMs will generate material condition information to be used by adaptive life-management algorithms for remaining life prediction and decision support.**

***Index Terms*—Condition monitoring, high-temperature, meandering winding magnetometer (MWM), MWM-array sensors, power plant components.**

I. INTRODUCTION

WITH an estimated 200–300 years of coal reserves, advanced fossil energy plants are poised to make a substantial contribution to America's energy future. Economic operation and maintenance of advanced fossil plants will require advanced decision support tools. Key components of these plants will be subject to a range of degradation and failure mechanisms, including but not limited to creep, creep-fatigue, corrosion, stress corrosion cracking, embrittlement, fouling, and thermal-barrier coating degradation.

Advanced fossil energy plants will operate at significantly higher temperatures than conventional fossil plants, to attain the higher thermal efficiencies that can be achieved at higher operating temperatures. Whereas the typical operating steam temperature in conventional fossil plants is about 538 °C, it can be 620 °C for supercritical units and 700 °C–760 °C for ultrasupercritical units. Moreover, significant undesirable temperature excursions are occasionally experienced in the superheater section such that peak temperatures can be even higher. Thus, there is the specific need for monitoring the condition of critical components at operating conditions in coal-fired supercritical and ultrasupercritical power generating plants to enable advanced decision support tools.

This paper describes the high-temperature meandering winding magnetometer (HT-MWM) sensor capability to monitor/measure specific conditions/properties of interest at temperatures up to 1000 °C. The goal is to provide an integrated life management solution for advanced fossil plant components, based on a family of high-temperature sensors and arrays, along with innovative adaptive-life prediction algorithms that will become available to owners and operators of fossil plants. This will support life management and condition-based maintenance programs and reduce life cycle costs by reducing operating and maintenance costs, improving safety margins, and enhancing plant reliability. In addition, there are many government facilities at which high-temperature condition monitoring can provide substantial value.

High-temperature sensors for condition monitoring have much broader applicability than just power plants. Aircraft engines, e.g., could also benefit from a capability to monitor condition and temperature for high-temperature components such as blades, vanes, and combustors, during operation. The MWM capability to measure temperature through-wall could provide a revolutionary new capability for this and other applications.

The MWM-arrays and networks of MWM-arrays are currently used as surface-mounted or embedded sensors. In programs sponsored by the U.S. Air Force, the National Aeronautics and Space Administration, the U.S. Navy and the Defense Advanced Research Projects Agency, JENTEK has

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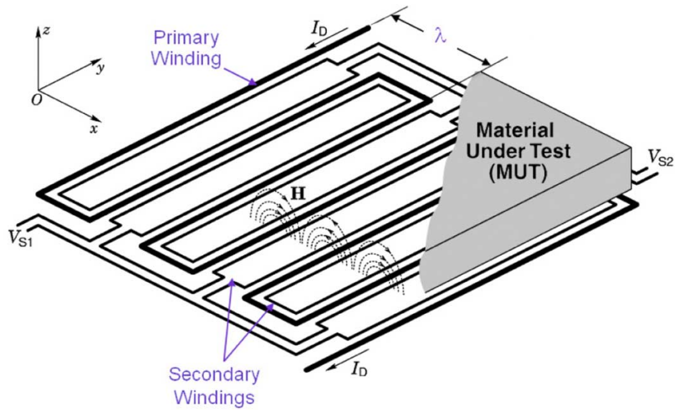
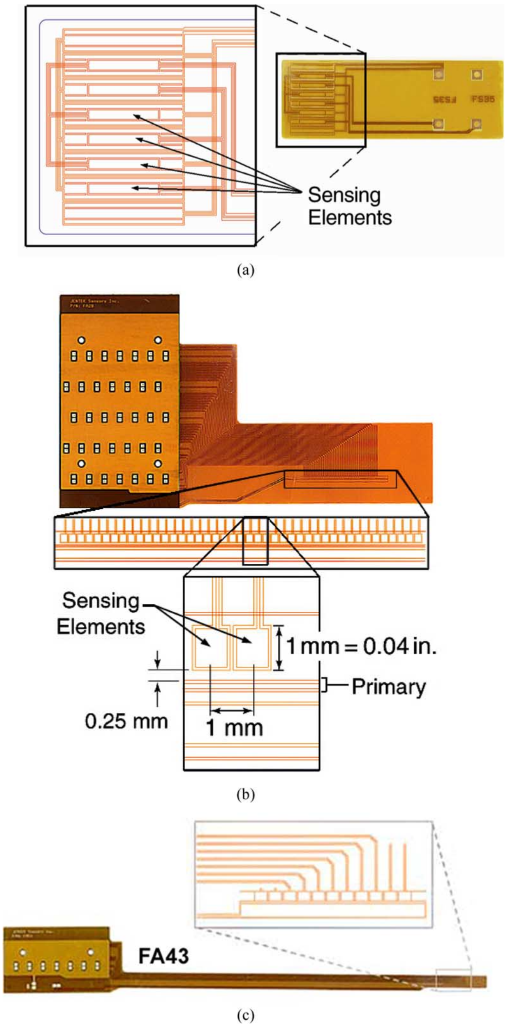


Fig. 1. Schematic of the basic structure of the original MWM winding construct [7]. See Fig. 2 (top) for the modern implementation of the MWM construct. Here, H is the magnetic field created by the primary winding; I_{D} is the current in the primary winding; V_{S1} and V_{S2} are the voltages at the terminals of the secondary windings; λ is the spatial wavelength.



(a)

(b)

(c)

Fig. 2. (a) Single sensing element MWM sensor FS35; (b) 37-channel scanning MWM-array FA28, designed for high sensitivity; and (c) seven-channel FA43, designed for insertion into a tight crevice.

demonstrated the capability of surface-mounted and embedded MWM-arrays to detect initiation and to monitor propagation of fatigue cracks [1]–[4]. This capability is being transitioned to the field in a Navy program that will use embedded MWM-arrays to monitor a critical airframe component at a difficult-to-access location, thus eliminating the need for frequent disassembly for inspection.

The MWM-arrays are also often used in scanning mode to produce digital images of material properties that can reveal as-fabricated quality in production, as well as in-service degradation, e.g., fatigue cracking, stress corrosion cracking, internal damage, wall thickness loss, corrosion damage and, in some materials, precrack fatigue damage, and residual stresses. Scanning MWM-arrays are currently being used by the U.S. Navy to inspect critical rotating engine components, where they have proven capable of detecting fatigue cracks that cannot be detected by other nondestructive testing (NDT) methods.

Development of these sensors and plans for transitioning are described in this paper, along with efforts to construct MWM-arrays for high-temperature (up to 1000 °C) applications relevant to fossil energy power generation. Some applications of MWM and MWM-array sensors for ambient temperature applications relevant to power industry are also presented.

II. BACKGROUND

A. *MWM Sensor and MWM-Array Operation and Modeling*

The MWM and MWM-array are inductive sensors, designed to provide absolute property measurements (e.g., electrical conductivity and magnetic permeability, for metals) [5]–[9]. At its most fundamental level, the MWM sensor consists of a meandering primary (drive) winding for creating the magnetic field $\mathbf{H}$ and a secondary winding adjacent to the primary for sensing the response to a material under test that interacts with the applied field, as shown schematically in Fig. 1. MWM-arrays are produced by fabricating one or more sense elements at desired locations relative to the drive windings [see Fig. 2(b) and (c)], or in other configurations (not shown in the figure). The MWM sensors and arrays are strongly directional, which enable directional measurement of electrical conductivity and magnetic permeability.

The MWM and MWM-array sensors were designed with unique winding constructs that permit the sensor response to be accurately modeled. This dramatically reduces calibration requirements (as described in American Society for Testing of Materials Standard E2338-06) [10]. The accuracy and robustness with which sensor response can be modeled also greatly shorten the design cycle for new sensors to address-specific NDT and materials characterization needs.

The MWM windings are typically deposited on a thin and flexible substrate, producing a conformable sensor capable of inspecting complex components. The microfabrication techniques employed to produce the sensors result in highly reliable and highly repeatable sensors. This is a significant advantage of the MWM over conventional, coil-type eddy current sensors, where nominally identical probes with inductances within 2% have been found to give signals that differ by as much as 35% [7]. But even for MWM-arrays, taking into account small geometric variations (identified through optical examinations) can improve multivariate inverse method performance. Also,

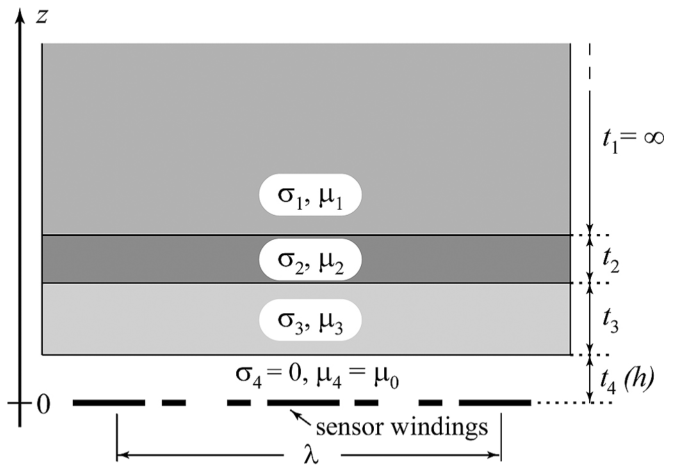


Fig. 3. Material structure consisting of multiple homogeneous layers. Here, σ and μ are the electrical conductivity and the magnetic permeability of a layer, respectively; t is the layer thickness; and λ is the spatial wavelength (see Fig. 1).

the MWM-array design eliminates the cross coupling and temperature sensitivity issues that plague other eddy current array technologies, resulting in substantial improvement in reliability and ease of use.

The sensors are designed to enable assumptions that make it possible to use relatively simple modeling solutions. Substantial improvements from the original MWM designs have dramatically improved the match between the model-predicted response and the sensor response, as well as the dynamic range (frequency and properties) over which the sensor response can be modeled accurately [9], [12]–[14]. For example, the sensor structure is assumed to be periodic in the x-direction (see Fig. 1). Dummy windings/electrodes are typically added on either side to improve agreement with this assumption (see Fig. 2, top). The models also assume that all physical quantities over the width of the sensor are constant in the y-direction. The material properties are assumed to change only in the z-direction, as modeled by a stack of homogeneous layers illustrated in Fig. 3, [6], [8], [9]. Solutions for piecewise linear variations in the z-direction are also available [15].

B. Grid Methods

The Grid methods use precomputed databases of sensor responses to represent the MWM field interactions with the material under test. For example, Fig. 4 shows a measurement grid for a two-unknown permeability (μ)/liftoff (h) measurement. The measurement grid is generated using the model of the MWM field interactions with the neighboring material. The grid is generated once (offline) and stored as a precomputed database for access by the GridStation software environment. To generate the grid, all combinations of liftoff and magnetic permeability over the dynamic range of interest are input into the MWM models to compute the corresponding grid points. The visualization in Fig. 4 includes lines of constant liftoff h (also called permeability lines) and lines of constant magnetic permeability μ (also called liftoff lines). The latter contain data points at the same location on the material under test, but at varying liftoffs, i.e., all these data points fall on the same liftoff line, corresponding to constant permeability.

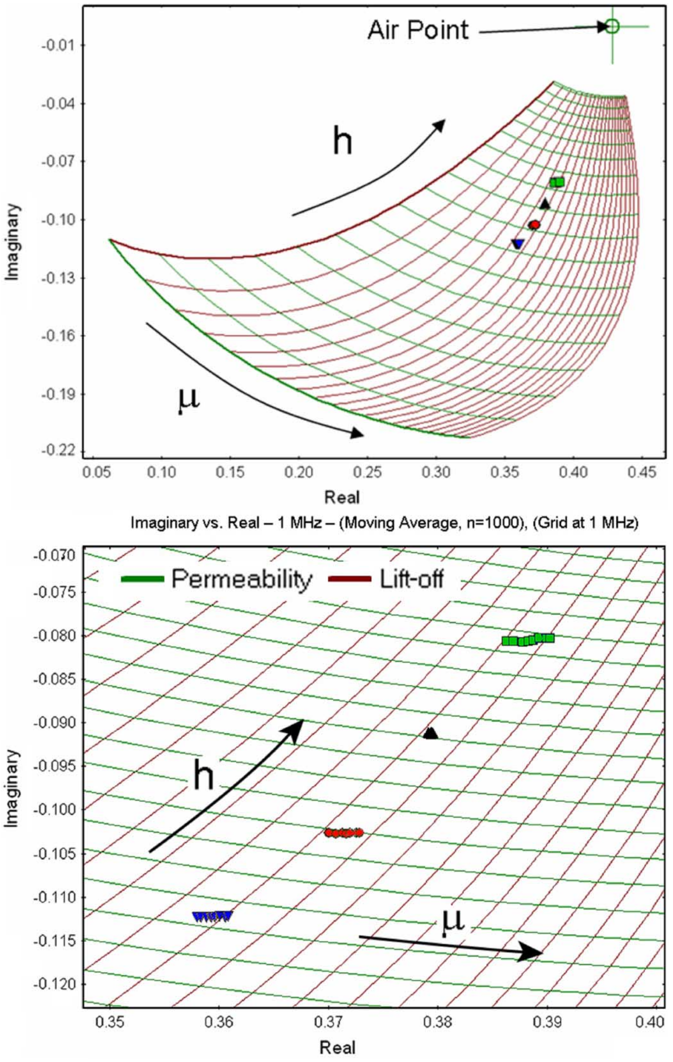


Fig. 4. (Top) Permeability/liftoff measurement grid, with data at four different liftoffs, (bottom) detail of the measurement grid with permeability measurements at four liftoffs.

To perform a permeability/liftoff measurement, first the real and imaginary parts of the complex transinductance ($V_S/j\omega I_D$, where I_D is the drive winding current, V_S is the sense winding voltage, ω is the angular frequency, and $j = \sqrt{-1}$) are measured, at an instant in time, using a parallel architecture impedance instrument with 37 parallel channels. Then, the GridStation software performs a nonlinear search through the 2-D database (Measurement Grid) to provide simultaneous estimates of the liftoff and magnetic permeability.

In general, multidimensional inverse interpolation is very difficult. The problems become exponentially harder for higher numbers of unknowns [16].

Fig. 5 shows a visualization of a higher order (3-D) database, called a lattice. The geometry modeled in this case is a metallic coating on a metallic substrate. The predicted sensor responses are plotted for low and high excitation frequencies as the coating conductivity, coating thickness, and liftoff are varied. The measurement at each frequency provides two pieces of information (the magnitude and phase, or real and imaginary part, of the impedance), so at least two excitation frequencies are required

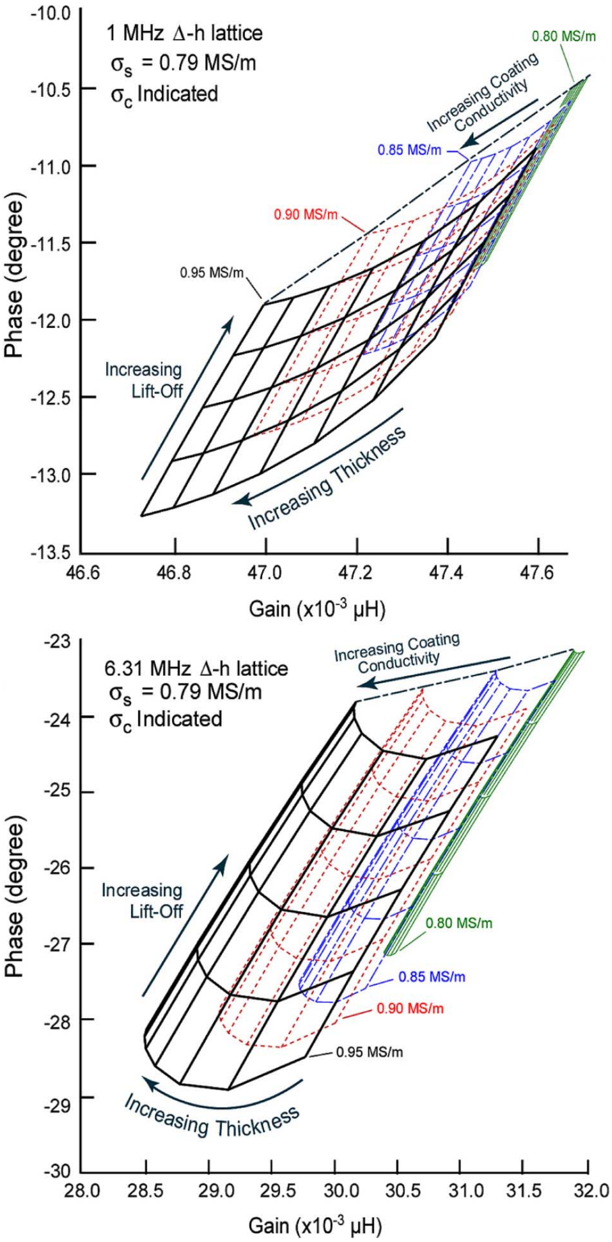


Fig. 5. MWM measurement grid lattices for a three-unknown example [17].

in order to provide sufficient information to determine all three unknown properties.

III. Potential Applications

A. HT-MWM and HT-MWM-Array Sensors for Boiler Component Life Management

The HT-MWM and HT-MWM-array sensors have a strong potential to provide real-time information about condition of critical high-temperature components, including superheater and reheater pendants. These boiler tubes in fossil power plants tend to have finite life because of prolonged exposure to high-temperature, stress, and aggressive environment. Although the tubing materials for the highest temperature components in ultrasupercritical units are expected to be nickel superalloys, the operation at the significantly higher temperatures, compared to current fossil power plants, is likely to limit the tubing life as well. Currently, available MWM sensors have already demonstrated their capability to detect degradation of various alloys, including nickel superalloys. Examples include thermal degradation, as demonstrated in our earlier unpublished work performed for Idaho National Engineering and Environmental Laboratory (INEEL); low-cycle fatigue damage, as demonstrated on samples provided by a major power generation equipment producer; and loss of beneficial compressive residual stresses after a prolonged high-temperature exposure of shot peened samples, provided by the U.S. Air Force for a jet engine related program.

The MWM sensors and MWM-arrays are capable of detecting changes in conductive materials, e.g., in nickel superalloys, not only after an exposure but, as demonstrated in numerous fatigue tests, continuously in real time. MWM sensors and MWM-arrays have also been used for monitoring degradation of metallic coatings, e.g., microstructural changes due to prolonged thermal exposures, thermal fatigue and hot corrosion. This may prove relevant to critical components of future coal-fired plants, since metallic coatings are being considered for protection of high-temperature tubing in ultrasupercritical plants. These capabilities can be used for online monitoring of high-temperature tests, such as creep, creep-fatigue, and hot-corrosion tests, and, ultimately, for component health monitoring inside a boiler.

In discussions with the Electric Power Research Institute Nondestructive Evaluation Center and DOE, the following potential applications, where the sensors could provide significant benefits, were identified.

1) *In situ* detection/monitoring of Inconel 740 components in ultrasupercritical units; the goal is to detect and monitor overaging of the material in service for life management.
2) Periodic inspection of Inconel 740 components during outages of ultrasupercritical units.
3) In-furnace monitoring of 9Cr-1Mo tempering process at 1350–1425 °F to ensure the quality of the heat treatment by ascertaining that no martensite → ferrite transformation has occurred during tempering (this transformation can occur when the tempering temperature is unintentionally exceeded, e.g., into 1450 °F–1480 °F range).
4) Inspection of 9Cr-1Mo products after tempering and/or after hot bending to verify that no martensite → ferrite transformation has occurred during tempering.
5) *In situ* monitoring of 9Cr-1Mo components in supercritical units.
6) *In situ* early detection and monitoring of creep or creep-fatigue damage accumulation at header penetrations in supercritical and ultrasupercritical units.
7) Periodic inspection of the header penetrations during outages of supercritical and ultrasupercritical units.
8) Characterization of shot peening quality inside Type 347 HFG tubing (proper shot peening retards oxidation).
9) Monitoring of high-temperature tests (creep and/or creep-fatigue tests) of candidate materials for ultrasupercritical tests, using a combination of permanently mounted and scanning HT-MWM-arrays.

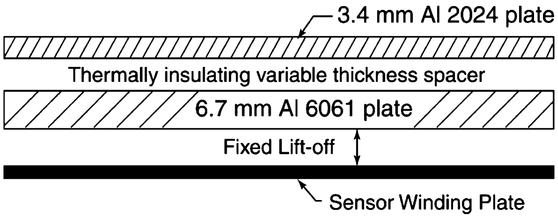


Fig. 6. Remote temperature measurement demonstration required measurement of the conductivity of the top plate by projecting magnetic fields through the intervening metallic layer.

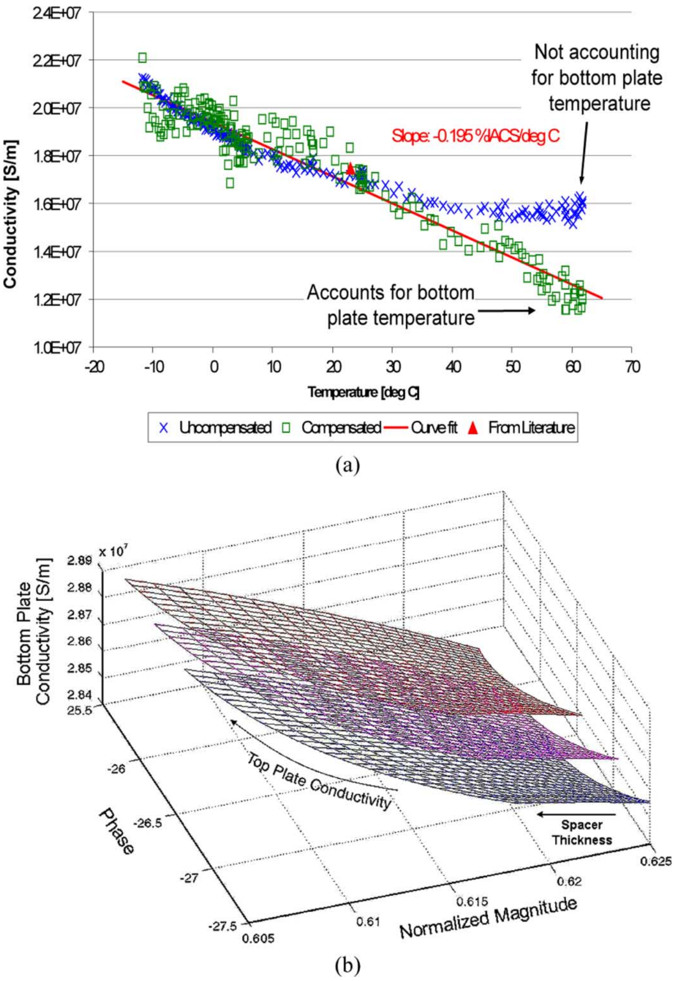
10) Characterization of residual stresses at weld repairs in power plant components.
11) Detection and characterization of recrystallization in cold-formed austenitic stainless steel components.
12) Detection of strain-induced precipitation in components fabricated from precipitation-hardening stainless steels.
13) Monitoring stresses in steel bolts while they are being tightened.

Potential applications of MWM-array sensors for critical balance-of-the-plant components include detection and characterization of torsional vibrations in turbines and generators, early fatigue detection in steel turbine blades, and some applications for nuclear plant components.

B. Through-Wall Temperature Monitoring With HT-MWM-Array Sensors

It is well known that temperature of critical boiler components, e.g., in the superheater section of the boiler, does not remain constant. In addition to normal relatively small temperature variations, there are occasional significant temperature excursions. Thus, temperature monitoring is essential for both optimization of the boiler operation and for component life assessment. MWM sensors and MWM-array sensors provide the capability to monitor metal temperature through short-term changes in material properties with temperature. Gradual long-term changes caused by material degradation can be more accurately assessed when the effect of temperature variations is taken into account.

The use of projected magnetic fields for remote and even through-layer temperature measurement offers the potential to address previously intractable measurement tasks. For example, in an earlier study, a low-frequency MWM method was used to measure the temperature of a target plate through an intervening metal plate [18]. The test setup is shown in Fig. 6, in which the sensor is the bottom plane, the intervening aluminum plate is above it and the target plate is uppermost. Also, there were gaps between the plates, and the upper gap was allowed to vary.



(a)

(b)

Fig. 7. (a) Top plate conductivity as a function of temperature with (□) and without (×) compensation for changes in the conductivity of the bottom plate. The line is a linear fit to the compensated data and the point (▲) is the room temperature conductivity of this material from the literature. (b) Grid lattice used for the top plate conductivity, with adjustments for the conductivity of the bottom plate. Three of the subgrids that comprise the lattice, corresponding to three different values of the bottom plate conductivity, are shown [18].

The measurement approach was to use the MWM to measure the conductivity of the target plate, correlate the conductivity with an independent temperature measurement of the target plate and compare the correlation against literature values of conductivity versus temperature for the material of the plate. Since the sensor was sensitive to both the conductivity of the target plate and of the intervening plate, and the temperature of the intervening plate was allowed to vary, a compensation algorithm was developed in which measurements were made at multiple frequencies and used to account for variations in the temperature of the intervening plate, since the higher frequency measurements were sensitive only to the intervening layer. Fig. 7 provides measured conductivity data for the target plate versus independently measured temperature of the target plate. The red line is the conductivity versus temperature curve from the literature for the material of the target plate. The good agreement between the measured values with the literature values illustrates the effectiveness of the compensation algorithm and the capability to remotely measure temperature through an intervening layer.

The capability to measure temperature through an intervening metallic layer with no penetrations cannot, we believe, be accomplished in any other manner. This capability, combined with high-temperature versions of MWMs, could provide through-wall temperature monitoring in various components in boilers, turbines, and combustors. HT-MWMs could be integrated into an equipment's structure to provide process temperature monitoring capability.

TABLE I
COMPARISON OF FEATURES OF THE NEW MSG WITH CONVENTIONAL STRAIN GAGES AND HIGH-TEMPERATURE STRAIN GAGES. THIS IS A PRELIMINARY EVALUATION. MORE EXTENSIVE COMPARISONS ARE UNDERWAY TO DEFINE AND CLARIFY THE ADVANTAGES OF THIS NEW CAPABILITY, SUCH AS FOR HIGH-TEMPERATURE APPLICATIONS

	Conventional Strain Gages	**Conventional High-Temp. Strain Gages**	**JENTEK MSG**
Surface Preparation	Significant (Paint removal, cleaning, etc)	Significant	Minimal to none
Attachment method	Polymer adhesive	Spot weld or thermally sprayed oxide	Not required
Strain limitations on bond	5%	0.5% (spot weld) 1.5% (flame sprayed oxide)	No limit
Load transfer to sensor required?	Yes	Yes	No
Durability	Low	Low	High
Wide area coverage?	No	No	Yes
Recalibration without reloading structure?	No	No	Yes
Non-contact stress or strain monitoring?	No	No	Yes

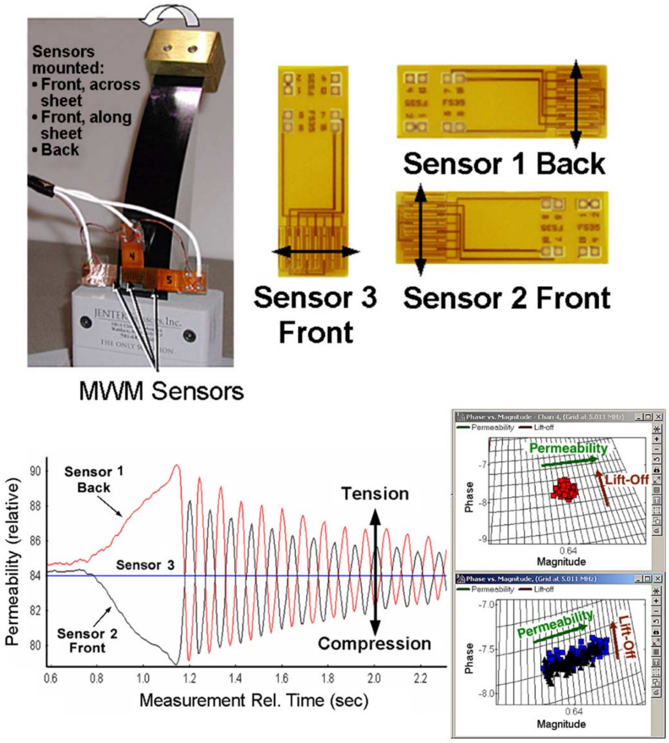


Fig. 8. Demonstration of dynamic stress monitoring in a steel strip using MWM-array sensors.

C. *Stress and Torque Monitoring With MWM-Array Sensors*

Permanently mounted MWMs and MWM-arrays can also be used as magnetic stress gages (MSGs) for stress or torque monitoring [19], [20]. The MSG has numerous advantages, including those listed in Table I. For example, the fact that no load transfer is needed between the sensor, and the material under test not only provides the capability to mount sensors without surface preparation, but will also enable extremely durable sensor operation over years of service in contrast with conventional strain gages where adhesive failure is a major contributor to their lack of reliability. This may also be a significant factor for high-temperature applications, where conventional high-temperature strain gages require either spot welding or thermally sprayed oxide to effect the load transfer, since operating temperatures are typically too high for polymer adhesives. Spot welding on plant components and piping is frequently undesirable, as the change to the local microstructure may serve as an initiation point for future cracking. Also, both spot welding and thermally sprayed oxides are limited in the amount of strain they can be subjected to without a bond failure, whereas an HT-MWM, which can operate without contact, can accommodate unlimited strain without compromising operability.

Calibration of the MSG is accomplished by correlating magnetic permeability of a material with stress. The gage is calibrated simply by taking a data point in air. Thus, if the stress gage fails, it can be readily replaced, and only a quick air calibration of the gage may be required. Furthermore, a wide area array of sensors with JENTEK's real-time parallel architecture impedance electronics, and newly developed multiplexing capability can provide monitoring of stresses/loads over a wide area for complex curved components.

Operation of the MSG in a noncontact mode increases sensor reliability and reduces or eliminates wear in some applications. This noncontact mode permits monitoring of moving components, such as noncontact torque measurement on a rotating shaft.

Initial implementations of the MSG will be for carbon and low-alloy steel components, since for such materials the magnetic permeability varies substantially with applied stress. Sensitivity and reproducibility of the effect have been demonstrated at ambient and moderate temperatures. Further work is required to verify performance of the MSGs over a wide temperature range below the Curie point of steel, e.g., below 740 °C for 9Cr-1Mo steel. For components fabricated from nonferrous alloys or for monitoring ferrous alloys at temperatures above the Curie point, a magnetic coating with a high Curie point, such as cobalt, must be deposited on the component to make MSG operation possible. There are, however, numerous near-term applications for load monitoring in steel components below the Curie point.

Fig. 8 illustrates the use of MSG to monitor stresses in a steel strip. When the steel strip is bent and released so that it is set into a pendulum motion, the two MSGs (Sensor 1 and Sensor 2) mounted across the strip on opposite sides of the material, monitor the bending stresses at the surface. These stress gages measure the alternating tensile and compressive stresses, detect damping of the pendulum, and correctly indicate phase relationship of the stresses.

The third MSG (Sensor 3) was mounted orthogonal to the other two gages and consequently is insensitive to the motion, since it responds to stress in the orthogonal direction. The output from this gage (the straight horizontal line) is also shown in Fig. 8 (bottom left). We have found, however, that a

MSG mounted parallel to the principal stress can provide an indication of an overload event, which affects permeability in both directions due to the plastic deformation that results from such an event.

D. HT-MWM and HT-MWM-Array Sensors in Fabrication of Advanced Power Plant Components

The capability of an MWM sensor to monitor heat treatment in real time was previously demonstrated for an aluminum alloy. In a series of experiments, the MWM sensor was placed on top of an aluminum alloy sample and, during a number of heating and cooling cycles up to 270 °C, the sensor was continuously measuring the electrical conductivity changes that were primarily temperature related. Then, the in-furnace sensor was used to monitor aging of the alloy over a three-day period. The early prototype HT-MWM sensor was used for in-service monitoring of changes, occurring during heating up to 860 °C and cooling of Inconel 718 and Ti-6Al-4 V plate samples. Realistically, HT-MWM sensor or HT-MWM-array sensor should be able to provide in-furnace monitoring of changes in nickel alloy samples and components at temperatures up to 1000 °C.

The high-temperature sensors, such as HT-MWM-array sensor, could then be used for in-furnace monitoring of heat treatment of candidate nickel superalloys that are considered for critical components in ultrasupercritical units. These sensors can be used in noncontact mode and can provide real-time data about actual changes in the material during the entire heat-treatment cycle. This can be used for effective process control and optimization, and, thus, can ensure that specified properties are consistently achieved.

The MWM-Arrays can also be used for baseline inspection of materials and components prior to, as well as after, heat treatment or other fabrication steps. MWM-Arrays are being considered for inspection of rolled and extruded products, both offline and online. An MWM-Array inspection system could be used for detection of surface and near-surface cracks and voids, as well as, for relatively thin plates, plate thickness variability.

IV. PROTOTYPE SENSOR DESIGN, PROCEDURE, AND RESULTS

For the early prototype, we chose platinum wire, placed in periodically spaced grooves in a quartz plate. This simplified the fabrication of the sensor, because it would not have to be sealed. In this design, the coefficient of thermal expansion mismatch was not considered to be a problem, because there were no seals or any mechanical bonds between the wire and the substrate. Among the several thicknesses available, thicker platinum wire with a diameter of 0.25 mm (0.010 in) was purchased, primarily for strength of the leads, but also because it would fill the expected 0.25 mm (0.010 in) deep channels and be restrained by the grooved substrate and cover plate.

The channels in the quartz substrate were made by sandblasting the substrate through cutouts in a steel mask. The sandblasting produced channels that were only 0.15–0.23 mm (0.006–0.009 in) deep. When the 0.5 mm (0.020 in) thick fused quartz cover plate was put in place, the platinum wire was effectively sandwiched between the two quartz plates and the faces of the quartz plates did not touch. A photograph of the completed sensor is shown in Fig. 9.

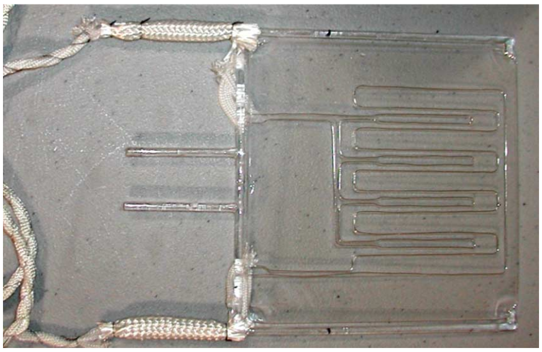


Fig. 9. Photograph of completed prototype HT-MWM sensor. Photo was taken after all high-temperature tests had been carried out.

A. Reference Calibration

As an alternative to air calibration, reference calibration of the sensor can provide certain advantages. It relies on measurements at two different material conditions and typically at two different liftoffs (distance between the sensing plane and surface of material under test). The liftoffs are established with the help of a nonconducting shim of a known thickness. Because two points on the measurement grid are fixed, using this method, there is enough information to compute the parasitic coupling of the sensor. Finally, if the two reference points are chosen to bracket the expected liftoff and, with a conductivity close to that of the specimen, the local alignment of the grid is expected to be very good.

For the reference part calibration test, the sensor was calibrated first with a 1.25-mm-thick stack of shims on the part and then without any shim on the part.

The sensor was placed on the sample with a 0.25-mm shim and measurements were taken. The liftoff was then increased in 0.25-mm increments up to 1.25 mm. The conductivity and liftoff values are shown in Fig. 10 and Table II. Fig. 11 shows raw data on the grid.

This measurement confirmed the accuracy of the model and gave us confidence to proceed to the high-temperature tests.

B. High-Temperature Testing With Titanium Alloy Ti-6Al-4 V Sample

First, we performed a preliminary test in which the HT-MWM was monitoring electrical conductivity changes of alloy 718 at temperatures up to 850 °C. After the test had been completed, we observed a significant increase in the magnetic permeability in the alloy 718 sample. This change indicated that an enhanced procedure may need to be developed to separate electrical conductivity and magnetic permeability measurements to handle situations when both properties are changing. Meanwhile, we opted for an alternate material for the sample to be used in a high-temperature test. The intent was to identify a material that would not be expected to produce a measurable change in magnetic permeability. We opted for a common titanium alloy, Ti-6Al-4 V. This alloy was reported to have a reasonably good resistance to bulk oxidation at temperatures used in our tests, i.e., close to but less than 900 °C. According to the data on high-temperature exposure of

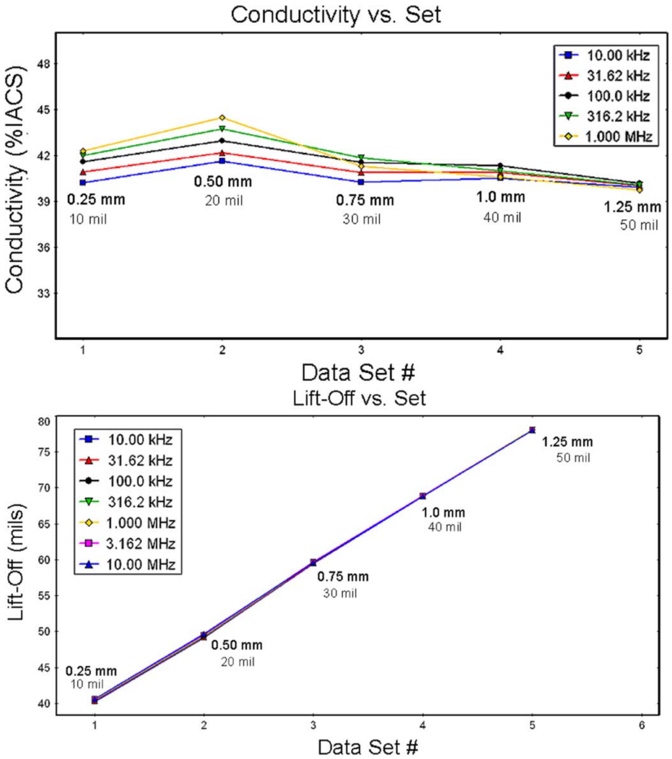


Fig. 10. (Top) Conductivity and (bottom) liftoff measurements with the HT-MWM sensor on an aluminum plate specimen after two-point reference part calibration.

TABLE II
CONDUCTIVITY AND LIFTOFF MEASUREMENTS WITH THE HT-MWM SENSOR ON AN ALUMINUM PLATE SPECIMEN AFTER TWO-POINT REFERENCE PART CALIBRATION

Sets	Conductivity (%IACS)	Lift-Off (mm)	Notes
1	40.914	1.025	0.25 mm shim
2	42.191	1.249	0.50 mm shim
3	40.889	1.512	0.75 mm shim
4	40.888	1.748	1.0 mm shim
5	40.022	1.983	1.25 mm shim

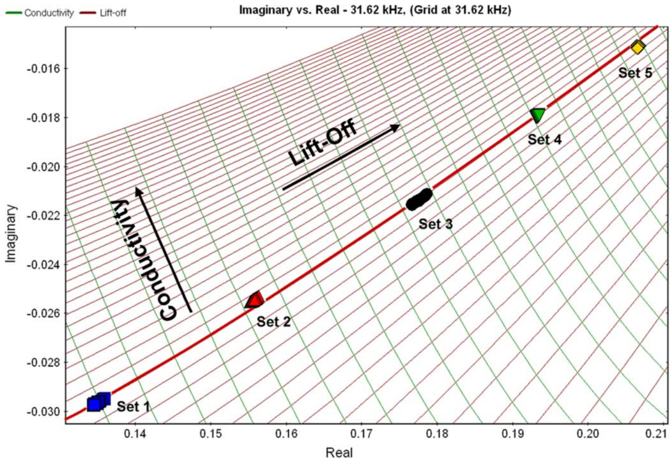


Fig. 11. Raw HT-MWM sensor data plotted on the grid at 31.62 kHz after two-point reference part calibration. Starting with 0.25 mm shim in Set 1, the liftoff increased in increments of 0.25 mm, up to 1.25 mm.

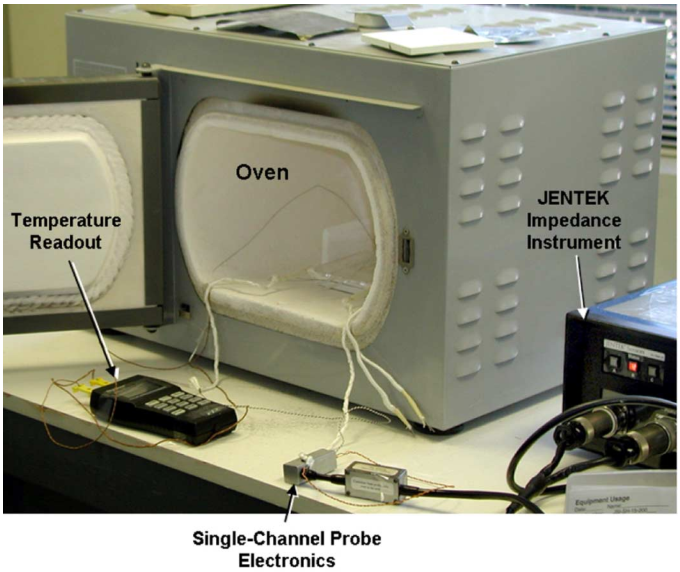


Fig. 12. Experimental setup for high-temperature HT-MWM sensor testing. (top) System setup and (bottom) close up of HT-MWM inside the furnace.

Ti-6Al-4 V in air [22], while some scaling would be expected when exposed to air at 870 °C, the depth of the oxide layer is still relatively small, possibly 50–75 μm. In fact, solution heat treatment temperatures for Ti-6Al-4 V are typically in the range of 955 °C–970 °C, and the heating is performed in furnaces with air atmosphere. The ASM Handbook [22] describes the oxidation effects as follows: "Oxygen pickup during heat treatment results in a surface structure composed predominantly of alpha phase and causes formation of scale… At 955 °C, the alpha structure can extend 0.2–0.3 mm below the surface and must be removed."

For the purpose of our high-temperature test, this surface oxidation should not have presented a problem. The oxidation at the test temperature of about 850 °C should have resulted in a nonconductive scale, increasing the HT-MWM measured liftoff, and in a fairly thin-conductive alpha case with conductivity lower than the nonoxidized substrate. For a low-conductivity material such as the titanium alloy, the sensor response is rather insensitive to the surface alpha case layer at the excitation frequencies used in the test.

The Ti-6Al-4 V sample used in this experiment had dimensions 15.5 cm × 15.5 cm × 0.3175 cm. The sample was first scanned using an MWM-Array (FA28) sensor. This was followed by a local measurement with a single element (FS33) sensor made to verify the conductivity value of the Ti-6Al-4 V sample, which was estimated to be 5.9 MS/m (1.02 %IACS). The sensor was calibrated using the reference calibration method, using two glass shims, first a 1.6-mm-thick and then 0.6-mm-thick shim, with the sensor placed on the sample. The experimental setup is shown in Fig. 12.

In this experiment, the maximum temperature reached was 850 °C. The estimated conductivity is shown as a function of temperature in Fig. 13. The conductivity decreased monotonically with increasing temperature and fairly closely retraced the curve during cooling. The overall behavior of the conductivity measured in this test versus temperature was significantly different than reported elsewhere [23]. The difference in conductivity measured during heating and cooling could have been due

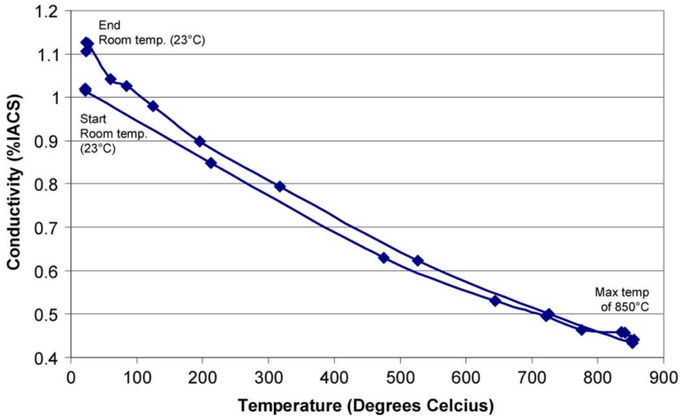


Fig. 13. HT-MWM-measured conductivity of the Ti-6Al-4 V sample as a function of temperature. The apparent difference in conductivity before and after thermal cycling is considered an artifact of the sensor geometry change, rather than a change on the properties of the alloy.

to small changes in the geometry of the prototype sensor, rather than in the material, because thermal exposure is expected to, if anything, slightly reduce the conductivity of the Ti-6Al-4 V sample.

The sample did, however, form thicker oxide scale than expected, some of which readily spalled from the surface of the sample.

This measurement concluded our tests with the prototype HT-MWM. This series of tests helped to identify needed improvements in the HT-MWM design and measurement procedure. The experiments with the prototype HT-MWM successfully demonstrated the feasibility of fabricating an MWM, capable of operating at the high-temperatures typical of coal-fired power plants, and its use to monitor material changes in high-temperature harsh environments.

V. CONCLUSION

The experiments with the prototype HT-MWM successfully demonstrated the feasibility of fabricating an MWM, capable of operating at the high-temperatures typical of coal-fired power plants, and its use to monitor material changes in high-temperature harsh environments.

Other sensor geometries, materials, and fabrication techniques are being investigated, with the goal to improve sensor performance.

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