EDDY CURRENT SENSING OF DEFORMATION PROCESSING

by

A. H. Kahn, M. L. Mester

National Institute of Standards and Technology
Gaithersburg, Maryland 20899

H. N. G. Wadley

University of Virginia
Charlottesville, Virginia 22903-2442

ABSTRACT

Eddy current methods have been developed to sense deformation and interior temperature of metals and alloys undergoing deformation processing. In hot isostatic pressing (HIP) a multi-frequency method is used to perform in situ monitoring of the cross-sectional area of the test sample; in extrusion processing multifrequency measurements are used to determine sample cross section and a single (lower) frequency measurement to determine the temperature. In both cases, a two-coil technique has been used to eliminate effects associated with the variation of sensor temperature due to the processing environment. These non-contact sensors have been used at temperatures up to 1100°C and under pressures of 150 MPa. In the HIP environment, dimensional changes of ±3μm have been detected, and in laboratory measurements on extrusion samples the temperature accuracy is ±5°C.
Introduction

Eddy currents can be induced in a conducting sample by the changing magnetic flux of a nearby solenoid excited with an alternating current. The induced currents depend upon the distance between the solenoid and testpiece, the detailed geometries of testpiece and solenoid, the frequency and current in the solenoid and the electrical properties (conductivity, permeability) of the sample. Changes in any of these parameters results in a change in the eddy current distribution which can be "sensed" with a second coil located near the sample. By varying frequency while holding coil geometry and coil-sample distance constant, it is possible to infer the electrical conductivity of the test piece, and since this is a strong function of temperature, the sample temperature. It is also possible to measure the distance from the coil to the sample, and to thus infer sample dimensions.

These effects are being investigated for sensing the subsurface temperatures of aluminum during extrusion\(^1\) and the densification of P/M alloys during hot isostatic pressing\(^2\). Here, we report on the principle of each application, and give results of studies to verifying these sensor concepts.

Internal Temperature Sensing

Optimization of production speed and the quality control of extruded aluminum products requires the measurement of the temperature of the extruded product during processing. This temperature measurement should be by a non-contact sensor placed as close as possible to the extrusion die, and the measurement should be accomplished and reported with sufficient rapidity to be used in a feedback control loop. For this purpose, an eddy current sensor, which performs an on-line measurement of resistivity and converts the measurement to the corresponding temperature, has been developed.

A schematic diagram illustrating how the sensor would be integrated into a closed-loop control system for regulating extrusion processing is shown in Fig. 1. The temperature of the extruded product depends on the initial temperature of the input billet and the speed of extrusion, which is determined by the hydraulic ram pressure. Friction in the die generates heat which can damage the product if excessive. On-line feedback is to be used to regulate extrusion speed. The temperature measurement also would be used to control the furnace which prepares the billets for extrusion. In this report, results are presented on
laboratory tests and a plant demonstration of temperature measurements on solid round, solid square, and hollow square extrusion shapes.

**ALUMINUM EXTRUSION TEMPERATURE SENSOR**

![Diagram of a temperature sensor in an extrusion process]

Figure 1. Schematic diagram of the integration of an eddy current temperature sensor into an extrusion processing control system.

**Sensor Design**

Our approach is to measure the electrical resistivity which at the temperature of importance in extrusion, is a function of temperature and only weakly affected by composition. To perform the measurement of resistivity, a two-coil system based on a commercially available Impedance/Gain-Phase Analyzer was used. The coil assembly is shown in Fig. 2. The primary coil, seen on the outside, is cooled by compressed air when in plant use. The secondary is concentric with the primary, and is cooled by circulating water. The interior is protected by a tube of
electrically insulating boron nitride which also provides lubricity for the passing product.

Figure 2. Coil assembly prior to mounting in canister. During processing the extruded products pass through the four graphite lined channels; the sensor resides in one of the channels.

The equivalent circuit is shown in Fig. 3. The primary solenoid, driven by the analyzer's oscillator through an audio power amplifier, impresses a uniform AC magnetic field on the test material. The voltage across the resistor in the primary circuit is proportional to the primary current and gives a measure of the AC field on the sample; this is detected in the reference channel of the analyzer. The emf
induced in the secondary coil depends on the resistivity of the test material; this is measured in the test channel of the analyzer. The analyzer is programmed to report the ratio of the secondary emf to the primary current and the relative phase of these quantities at each frequency of interest. From these measurements taken on the empty coil system and again with the test material present, the normalized impedance curves can be obtained in the conventional form [3] also given by Libby [4].

**GAIN/PHASE MODE OPERATION**

Figure 3. Circuit diagram of the two-coil impedance measurement system. The coils and test sample are concentric, with the primary outer-most and the shorter secondary centered just inside the primary.

This approach has three principal advantages over a single coil design:

1) The determination of resistivity from a transfer impedance allows a power amplifier to be used to enhance signal strength at low frequencies, while using readily available impedance measurement instrumentation.
2) The field impresses on the test material is very uniform over the region being
sampled by the shorter secondary test winding. This allows a simple
electromagnetic analysis which does not need to take into account end effects
related to fringing fields, as would be the case in a single coil system.

3) The system is insensitive to temperature variation in the coils. The output
signal from the secondary is directed to a high impedance input of the a
commercial impedance analyzer; hence the variation of the coil resistance with
temperature does not influence the measurement. Variation of the primary coil
resistance is insignificant because the primary current, and thus the exciting
field, is measured directly via the primary circuit resistor.

Defining gain in this context as the ratio of secondary emf to primary voltage
drop across the primary standard resistor, and \( \phi \) as the corresponding phase
difference, we obtain the normalized impedance at each frequency by the relation:

\[
Z_N = \left( \frac{\text{gain}}{\text{gain}_0} \right) j \exp\left( -j(\phi - \phi_0) \right)
\]  

(1)

where zero subscripts on the right represent empty coil values, and unsubscripted
terms refer to values with the test sample present. In Fig. 4 we show several
normalized impedance curves measured on a series of aluminum rods of varying
diameters.

The resistivity is obtained by the following procedure. From measurement of the
impedance at one frequency we may determine the angle \( \alpha \), as shown in Fig. 3.
When angle \( \alpha \), is known, the quantity

\[
X(\alpha) = R \sqrt{\sigma \omega \mu_0}
\]

(2)

is determined uniquely. In Eq. (1) \( \sigma \) is the conductivity, \( \omega \) the angular frequency,
\( \mu_0 \) the free space permeability, and \( R \) the sample radius. All impedance curves of
uniform cylinders with the same value of \( \alpha \) have the same value of \( x \). We have
prepared a computer lookup table for determining \( x \) from \( \alpha \). The most precise
measurement of conductivity is obtained when the frequency is selected so that the
impedance value lies near the knee of the curve. For extrusions of other cross-
sectional shapes, the impedance curves must be calculated specially. We have
used previous work [5] to calculate the relation of angle \( \alpha \) to \( x = a \sqrt{\sigma \omega \mu_0} \), where \( a \)
is now the edge of the square cross section. Another lookup table was prepared for
this purpose.
Figure 4. Impedance curves of three aluminum rods of varied diameters, measured under laboratory conditions. Angle $\alpha$ is a parameter used in computing the value of $x = R \sqrt{\sigma \mu}$ for any point on the curves.

The variation of resistivity with temperature for alloys 6061 and 6063 was obtained in the laboratory. Drilled aluminum rods in which thermocouples were placed were heated and placed in the sensor. Resistivity vs. temperature curves were recorded during cooling. Data from these runs were averaged to determine a resistivity vs. temperature lookup table. The use of lookup tables was preferred to evaluation of analytic formulas because of its greater speed. In measurements performed in the laboratory, the computed temperature obtained by the sensor and the values measured by a thermocouple at the center of the solid sample agreed within $\pm 10^\circ F$ during cooling from 1100$^\circ F$ to 950$^\circ F$. Each temperature measurement required 1.2 sec. In future designs this time could be reduced.

In addition to the temperature measurement, it is also possible to use the high frequency limit of the impedance curve to obtain the fill-factor of the sample with respect to the secondary coil. This yields the cross-sectional area of the sample, or the equivalent diameter in the case of a cylindrical rod. In laboratory tests, the
diameter measurements were accurate to ±0.001 in for rods ranging from 0.75 in to 1.375 in. The diameter measurement takes three seconds to be performed. The greater time is needed because the measurement requires impedance at five frequencies and a least squares extrapolation of the curve to the imaginary axis.

**Plant Trials**

The sensor system described above was installed for testing at the Cressona Aluminum Co., Cressona, PA. The coil system was placed in one channel of a four channel canister. During extrusion, the canister is mounted close to the die with the sensor within one foot of the die. Four aluminum shapes pass through graphite guides; one of the channels houses the sensor. Extrusion speeds were approximately 70 ft/min, but this varied because of billet temperature inhomogeneity; it also was varied for experimental purposes.

Fig. 5 shows a typical temperature measurement sequence for extrusion of round rod. Initially the colder from part of the billet was extruded; also the die was cool.

![Graph](image)

**Figure 5.** Measured temperature as a function of time for 6061 aluminum 1" round rod during extrusion.
This produced a slow extrusion rate. As the die heats from friction, and as the hotter part of the billet reaches the die, the extrusion speed increases and less ram pressure was needed. Typically the temperature rose to a plateau as the operator adjusts ram pressure to hold a constant extrusion speed. After 70 sec, see Fig. 5, the billet was exhausted, extrusion stopped, and the product was severed from the die. The sensor then monitored the cooling of the stationary material in the coil.

The same extrusion press, canister, and sensor arrangement was used for temperature measurements on solid square aluminum stock, as shown in Fig. 6. The behavior was similar to the previous case. In this case the appropriate impedance curves for square sample cross-section was used to interpret the measurements. In this run the speed was intentionally varied to demonstrate heating effects.

Figure 6. Measured temperature as a function of time for 6061 aluminum 3/4" square stock during extrusion. The speed was intentionally varied to demonstrate heating effects.
Dimensional Measurements

Analysis of the impedance of a solenoid containing a cylindrical conducting sample shows that the cross sectional area of the sample affects the impedance over a wide range of frequencies. At very high frequencies, the measured impedance can be used to determine the cross sectional area of the sample. Here, we report on the use of this principle to measure the diameter of powder metallurgy samples undergoing consolidation in a hot isostatic press.

Sensor Design

The eddy current system consists of two coaxial solenoids surrounding a sealed test cylinder which contains the powders being sintered, as shown in Fig. 7. Electrical connections to the coil system are made using feed-through lines provided for thermocouples in the furnace interior. A block diagram of the entire system is shown in Fig. 8. The electrical measurements are performed using a gain-phase analyzer (Hewlett Packard 419A) which is configured to operate at a series of frequencies, measuring the ratio of the induced secondary voltage to the current of the primary winding, and the relative phases of these quantities. The results of these measurements of the transfer impedance between primary and secondary coils depend upon the dimensions and conductivity of the material in the core; in this case the measurement is dominated by the effect of the canister surrounding the powder. The operation of the system is controlled by a personal computer and the results are reported on the screen, typically once per minute; the data are saved to disk for further analysis.
Figure 7. Eddy current coil system for measuring cross-sectional area during hot isostatic pressing.
Connections to the gain phase analyzer were made through 50Ω coaxial cables approximately 25 ft in length. Preamplifiers were used in the lines to the reference and test channels of the analyzer in order to buffer the coils from the capacitance of the cables. A power amplifier (25 watts) was used to raise the measurement signal above the noise level from the harmonic content of the chopped current in the heater coils of the furnace. It was necessary to use an impedance matching transformer between the power amplifier and the primary winding to avoid distortion at low frequencies; the matching transformer was constructed by winding transmission line on a ferrite toroidal form. Because of the enhancement of the primary current by the power amplifier, resistive network attenuators were needed to prevent overloading of the preamplifiers.

**Dimensional Measurements and Analysis**

The transfer impedance between the primary and secondary windings is the ratio of the electromotive force induced in the secondary to the current in the primary.
The emf induced in the secondary winding is equal to the time rate of change of linked magnetic flux in the sample and in the annulus between the sample and the secondary itself. The primary coil produces a uniform magnetic field $H_0 = n_0 I_0 \exp(-i \omega t)$, where the symbols are defined in Table 1. The transfer impedance is then given by

$$Z = -\frac{i \omega n_2}{H_0} \left[ \frac{\Phi_{\text{sample}} + \mu_0 H_0 \pi \left( a_2^2 - R^2 \right)}{n_1 n_0} \right], \quad (3)$$

where the second term in the brackets represents the magnetic flux through the cross-sectional area of the annulus between the coil of radius $a$ and the sample of radius $R$. In electromagnetic NDE it is customary to normalize the impedance to the negative of the imaginary part of the impedance of the empty coil,

$$-\text{Im} \ Z_0 = i \omega n_{1,0} n_2 \mu_0 \pi a_1^2,$$ \quad (4)

where $n_{1,0}$ is the number of turns per unit length of the primary coil and $a_1$ is the radius of the secondary coil, both at room temperature. The observed normalized impedance during the HIP cycle is then given by

$$Z_N = -i \frac{n_1}{n_{1,0}} \left[ \frac{\Phi_{\text{sample}}}{\mu_0 H_0 \pi R^2} \frac{R^2}{a_1^2} + \left( \frac{a^2 - R^2}{a_1^2} \right) \right], \quad (5)$$

Table 1. Symbol Definitions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>$Z$</td>
<td>Transfer impedance</td>
</tr>
<tr>
<td>$Z_N$</td>
<td>Transfer impedance normalized</td>
</tr>
<tr>
<td>$I_0$</td>
<td>Primary current</td>
</tr>
<tr>
<td>$i$</td>
<td>Square root of -1</td>
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<tr>
<td>$\omega$</td>
<td>Angular frequency</td>
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</table>
Table 1. Symbol Definitions (continued)

\[ n_1 \quad \text{Turns/length of primary} \\
 n_{1,2} \quad \text{Turns/length of primary, cold} \\
 n_2 \quad \text{Turns of secondary} \\
 H_0 \quad \text{Applied magnetic field} \\
 a \quad \text{Radius of secondary} \\
 R \quad \text{Radius of sample} \\
 R^* \quad \text{Apparent radius of sample} \\
 \varnothing \quad \text{Magnetic flux} \\
 \mu_0 \quad \text{Permeability of free space} \\
 \alpha_c \quad \text{Lin. expans. coeff. of sec. coil} \\

We note that in the limit of high frequency, the flux through the sample must vanish, due to exclusion by the skin effect. The first factor on the right side of Eq. 5, which represents the effect of the thermal expansion of the length of the primary coil, was found to be negligibly small in our boron nitride coil system. Under this assumption, the high frequency limit of the normalized impedance intersects the imaginary axis at the intercept

\[ \text{INTCPT} = \frac{a(T)^2}{a_1^2} \cdot \frac{R(T)^2}{a_1^2}. \] (6)
Here we emphasize that the values of the coil and sample radii depend on the temperature. Moreover, the sample radius will decrease during the HIP cycle. Assuming a linear expansion factor $\alpha_c$ for the coil, we obtain

$$\text{INTCPT} = 1 + 2 \alpha_c \Delta T \frac{R(T)}{a_1^2}.$$  \hfill (7)

We may define an apparent radius, $R^*(T)$, as the value that would be obtained if thermal expansion of the coil were neglected. (The intercept is calculated and displayed by the analyzer during the run.) The apparent radius is determined from the measured intercept by the relation

$$\text{INTCPT} = 1 \cdot \frac{R^*(T)}{a_1^2}$$  \hfill (8)

where $R^*$ is the value obtained if thermal expansion of the coils is ignored. The effect of thermal expansion for the coil can then be obtained as a correction to the apparent sample radius through

$$R(T) = R^*(T) \left[ 1 + \alpha_c \Delta T \frac{a_1^2}{R^*(T)^2} \right]$$  \hfill (9)

Thus the correction to the apparent radius is proportional to the thermal expansion of the coil, but is augmented by a factor of the order of magnitude of the reciprocal of the fill-factor of the sample relative to the secondary coil. Eq. 9 has been tested with a solid bar of copper, for which the dimensions and thermal expansion coefficient are known. Satisfactory agreement was obtained when the expansion factor for the coil was taken as the linear expansion factor of the wire used in the winding. This is reasonable, since the coil wires were wound in a loosely fitting groove in the boron nitride forms, permitting their radial expansion. Using Eq. 9, the radius of the cylinder being HIPped was measured at a typical rate of once every minute during the HIP cycle.

Values of density as a function of time were obtained from the radius measurements off-line after completion of the run. They were based on the room temperature values of the dimensions of the sample before and after HIPping.
The following assumptions were used to obtain the density vs. time plots:

a) The ratios of the relative densities during and after the run are inversely proportional to the corresponding ratios of the volumes of the powders.

b) The volume of the encasing tube material is conserved. As the tube shrinks, the wall thickness correspondingly increases.

c) The fractional change of length of the tube is proportional to the fractional change of diameter of the tube, with a constant proportionality during the whole run.

Using these considerations, the diameter could be recorded during the run, and the density plotted in the analysis afterward. At this stage of the research we preferred to do this post-analysis to obtain the density, rather than to use the initial densities, estimates of which were subject to errors because of looseness of packing.

**Experimental Results**

A typical impedance curve characteristic of a thin-walled tube is shown in Fig. 9. Each measured point represents an impedance measurement at a fixed frequency. The in-phase component of the impedance is plotted along the abscissa and the out-of-phase component is plotted along the ordinate. Increasing frequency corresponds to movement of the point in a clockwise direction around the curve. The circular locus is the signature of a thin-walled tube (round, rectangular, or other closed shape). The transition to a straight line occurs as a frequency sufficiently high that the skin-effect prevents penetration of the magnetic field into the interior of the tube. Extrapolation of the straight line part to the imaginary axis yields the intercept used to obtain the sample radius in Eq. 8.
Figure 9. Impedance curve of a thin-walled tube. The straight line section occurs at high frequencies for which the skin depth is less than the wall thickness.

Histories of the two runs on copper powder samples HIPped in copper canisters are shown in Fig. 10 and Fig. 11. These runs differ primarily in the high temperature part of the cycles.
The more rapid rate of high temperature consolidation in Cycle BOB13 is clearly visible and demonstrates the usefulness of the sensor system for monitoring the HIP cycle. Fig. 12 shows a similar cycle in which the canister developed a leak approximately two hours into the run. Consolidation did not continue after that point.

![Copper HIP Cycle (BOB16)](image)

Figure 10. Record of temperature, pressure, and computed relative density during processing of copper powder HIP sample BOB16. Markers are placed at every tenth measurement.
Figure 11. Record of temperature, pressure, and relative density during processing of copper powder HIP sample BOB13. The higher temperature produces a more rapid consolidation than that of BOB16 shown in the previous figure.
COPPER HIP CYCLE (BOB08)

Figure 12. Record of temperature, pressure, and measured diameter of copper powder HIP sample BOB08. At time 2 hours the canister developed a leak, terminating further consideration.

TIAL HIP CYCLE (TIAL21)

Figure 13. Record of temperature, pressure, and relative density of titanium aluminide powder HIP sample TIAL21.
An example of the use of the sensor system at temperatures above 1000°C is illustrated in Fig. 13. For this run, titanium aluminide powder was HIPped in a titanium canister. (The spike in temperature at 2.6 hr was caused by an erratic thermocouple connection.) Characteristic of the material was the very rapid densification that occurred when the temperature reached the vicinity of 1000°C.

The impedance plane plots for cycle TIAL21 demonstrate the way in which the sensor follows the consolidation process. Fig. 14 shows the impedance curve, as seen on the analyzer screen at the beginning of the run, with the furnace at room temperature. The straight-line section which is extrapolated to the imaginary axis to obtain the dimensional measurement is well defined. The curved part of the line corresponds to the beginning of the circular part seen in Fig. 9, and is

![Impedance plot](image)

Figure 14. Impedance plot for titanium aluminide sample TIAL21 at room temperature. Measurements were made at 50 frequencies from 200 KHz to 2 MHz. The shape is characteristic of a tube.
indicative that the tubular canister is being seen. Fig. 15 was recorded at 788°C. Because the resistivity of the canister increased, the frequency points have shifted up the curve, but a small straight part is still available for extrapolation. At 866°C, Fig. 16, the upper part of the curve has almost merged smoothly with the lower part, indicating that the consolidating material has begun to conduct induced eddy currents. Finally, Fig. 17, taken at 1102°C, shows a complete coalescence of the two parts of the curve. In this case the conductivity of the consolidated titanium aluminide is indistinguishable from that of the titanium canister.

Figure 15. Impedance plot for titanium aluminide sample TIAL21 at 788°C.
Figure 16. Impedance plot for titanium aluminide sample TIAL21 at 866°C.

Figure 17. Impedance plot for titanium aluminide sample TIAL21 at 1102°C. The consolidated material is indistinguishable in conductivity from the tubular canister, as evidenced by the merging of the two sections of the curve.
References


