FACTORS AFFECTING THE PERFORMANCE OF EDDY CURRENT DENSIFICATION SENSORS

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INTRODUCTION

Hot Isostatic Pressing (HIP) is an increasingly important near net shape process for producing fully dense components from powders [1]. It involves filling a preshaped metal canister with alloy powder, followed by evacuation, and sealing. The can is then placed in a HIP (a furnace that can be pressurized to ~200MPa with an inert gas such as argon). The can is subjected to a heating/pressurization cycle that softens and compacts the powder particles to a fully dense mass and a shape determined by the can shape, the powders initial packing and the thermal-mechanical cycle imposed [2]. Today, many metals, alloys and intermetallics are processed this way (including nickel based superalloys, titanium alloys, NiAl, etc.) and it is increasingly used to produce metal matrix composites.

In-situ eddy current sensors are used by several groups for the precise measurement of the canister’s physical dimensions (and thus density) during the consolidation cycle [3-7]. They are used both to guide the development of the predictive models that materials researchers utilize to optimize the powders and their consolidation conditions [8] and by process engineers for on-line feedback control of densification [6,9,10]. The sensor’s principle of operation is based-upon the well known lift-off effect. For work on cylindrical samples, an encircling coil surrounds the sample and excites a fluctuating electromagnetic field. A secondary pick-up coil senses the field (which is perturbed by the sample). At high frequencies, when the electromagnetic skin depth of the sample, \( \delta = (2\omega \mu \sigma)^{1/2} \) where \( \omega \) is the radial frequency, \( \mu \) the permeability and \( \sigma \) the electrical conductivity is much less than the sample radius, the complex impedance approaches the imaginary axis (with a slope of 45°) on a plot like that shown in Fig. 1. The high frequency intercept with the imaginary axis (for a semi-infinite coil) has the value \( 1 - \left( r_{sam}/r_{sec}\right)^2 \) where \( r_{sam} \) is the sample radius and \( r_{sec} \) the secondary coil radius. This provides a measurement of the sample radius if \( r_{sec} \) is known.

These sensors have given quite good results when used for low temperature work (≤600°C) but have exhibited irreproducibility and unexplained responses when used at the higher temperatures needed for consolidating refractory metals and intermetallics. The work reported here investigates this and seeks to identify those effects that can directly be
associated with temperature dependent properties of the sensor. In particular, we study the
effect of constraining thermal expansion (upon heating) of the secondary coil. A future
paper will report the indirect contributions these effects have upon the circuit response of
the sensor and its monitoring instrumentation.

**EDDY CURRENT SENSOR PRINCIPLE**

![Diagram of Eddy Current Sensor Principle](image)

Fig. 1 Complex impedance plane plot for an encircling eddy current sensor. The axes are
normalized by the empty coil's impedance.

**UNCONSTRAINED SENSOR DESIGN**

A schematic design of the encircling sensor studied is shown in Fig. 2, together
with a higher resolution detail of the secondary coil geometry (a). For the tests reported
here, 2.5 secondary turns were wound on a Boron Nitride (BN) preform. This design was
identical to that reported elsewhere [3] with the exception that the number of secondary
turns was reduced to increase the sensor's resonance frequency. In this design, the grooves
of the preform allowed unconstrained radial expansion of the windings upon heating. A HP
4194A impedance analyzer (in the gain-phase mode), and a circuit like that reported
elsewhere [4] were used to measure impedance.
Tests were conducted to investigate the response of the sensor during heating to 900°C. These consisted of centrally positioning a known (15.88mm) diameter 304 stainless steel cylinder in the sensor and measuring (at 18 logarithmically spaced frequency points from 200-450kHz) impedance curves (normalized to the empty coil's room temperature impedance) during heating. This was repeated seven times. The temperature dependent diameter of the sample was then calculated from its tabulated thermal expansion coefficients at different temperatures [11]. Given this, and the extrapolated intercept value, we were able to compute the "apparent" diameter change of the secondary. The average of this for the seven runs is plotted against temperature as curve(a) in Fig. 3.

The reproducibility (see Table 1) of the "apparent" diameter was good throughout the temperature range. However the degree of the expansion appeared much larger than the predicted thermal expansion at 900°C (\(\Delta d=218\mu m=d_{sec}\cdot \alpha \cdot \Delta T\) where \(\alpha\) is the wire's thermal expansion coefficient). We also noted an increase in the high frequency slope from the expected value of 45° to 50° or more on heating. While these effects (provided they remain reproducible) do not necessarily affect the sensor's usefulness, they suggest that the
Figure 3: Temperature dependence of "apparent" secondary coil diameter for (a) unconstrained and (b) constrained secondary designs.

The sensor's response to temperature may not be as simple as previously proposed [4]. Several things can happen on heating including a change in the sample and sensor's wire conductivity, thermal expansion of the BN both radially and longitudinally and radial and longitudinal expansion of the primary and secondary windings. To investigate the role of each, a detailed analysis of the sensor was conducted by simulating its multifrequency response to heating using the formulation of Dodd and Deeds [12].

Table 1. Standard Deviation of Diameter and Slope Change for the Unconstrained Sensor.

<table>
<thead>
<tr>
<th>Temp Range(°C)</th>
<th>25-100</th>
<th>100-200</th>
<th>200-300</th>
<th>300-400</th>
<th>400-500</th>
<th>500-600</th>
<th>600-700</th>
<th>700-800</th>
<th>800-900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Deviation of Diameter Change (µm)</td>
<td>20</td>
<td>15</td>
<td>20</td>
<td>12</td>
<td>14</td>
<td>21</td>
<td>7</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Slope (degree)</td>
<td>45.8-48.1</td>
<td>48.1-48.3</td>
<td>48.3-48.8</td>
<td>48.8-49.3</td>
<td>49.3-49.7</td>
<td>49.7-49.9</td>
<td>49.9-50.2</td>
<td>50.2-50.4</td>
<td>50.4-50.7</td>
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</tbody>
</table>
SIMULATION RESULTS

The geometry modelled is shown in Fig. 4. It consisted of a seven turn primary and two turn secondary coil with radii and spacings defined by those in Fig. 2. A sample containing two conducting regions of radii "a" and "b" was placed at the center of the coils. The 304 stainless steel sample and coils were given ambient temperature conductivities and the impedance of the sensor evaluated at 201 frequencies between 100kHz and 100MHz. The geometry was then expanded (to values determined by thermal expansion), and the conductivities decreased to those expected at either 500 °C and 900°C [13], and new (high temperature) impedances calculated. The empty coil impedances were also obtained by specifying the conductivities of regions I and II to be zero.

Curves (a) in Fig. 5 show the normalized impedance obtained by this approach at the three temperatures for the unconstrained sensor. The symbols connected by lines are results normalized by room temperature empty coil impedances (as done experimentally) and the unconnected symbols show the same results but now normalized by the empty coil impedance at the test temperature. The infinite frequency intercepts (using calculated data near 100MHz where the slope is 45°) for the high temperature normalized curves corresponded exactly to those predicted by allowing the secondary and sample radii to increase linearly with temperature in the manner proposed in earlier work [4]. But, we have found that the measurement frequency range for the conductivities encountered does not extend into the regime of the straight line with 45° slope. The extrapolated intercept from a best fit through data in the measurement frequency range does not agree with simple expression. Furthermore, a substantially different intercept was obtained using the room temperature normalization procedure (even when using calculated values where the slope was 45°).

Fig. 4 A Schematic diagram of the geometry used for simulating temperature effects on an encircling coil.
The unconstrained sensor's "apparent" diameter change calculated using the experiment's data reduction protocol is plotted in Fig. 6. The calculated coil expansion at 900°C was 5631μm, substantially greater than the 2181μm predicted by simple radial expansion, but it still remained (2361μm) less than that measured. The change of slope seen in the experiments was accounted for in part by the shifting of frequency points toward the origin of the impedance curve due to the decrease in sample conductivity with temperature.

![Fig. 5 Calculated normalized impedance curves at three test temperatures for (a) unconstrained and (b) constrained sensor designs.](image)

**CONSTRAINED SENSOR DESIGN**

To reduce the radial thermal expansion of the secondary coil, a secondary coil mandrel was constructed whose outer diameter made an interference fit with the primary coil preform, Fig. 2(b). The grooves for the wire were 250μm deep, the same as the wire diameter. The first version of the sensor utilized 2.5 turns on the secondary. Using identical procedures as before, the "apparent" secondary diameter was determined and the average of seven runs shown as curve (b) on Fig. 3. Table 2 shows the standard deviations for the secondary coil diameter. We note that the apparent coil radius has decreased by about 284μm. However, the diameter at 900°C exceeded that predicted by simulation (allowing the radial expansion to be due only to BN expansion), Fig. 6.

Further tests indicated that the response of both sensors was quite sensitive to changes in the spacing of lead wires connecting the primary and secondary coils to the HIP feed throughs. Because these wires also heated during the test, and moved apart, we suspected that a significant part of the anomalous expansion was due to this effect. To reduce its contribution to a measurement we increased the number of turns in the secondary to 6.5 so that the contribution of the coil windings to the induced voltage was increased. The measured "apparent" diameter was then found to be in significantly better agreement with the calculated response, Fig. 6. The small negative deviation at the highest
Table 2. Standard Deviation of Diameter and Slope Change for the constrained Sensor.

<table>
<thead>
<tr>
<th>Temp Range(°C)</th>
<th>25-100</th>
<th>100-200</th>
<th>200-300</th>
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<th>600-700</th>
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<tbody>
<tr>
<td>Standard Deviation of Diameter Change (µm)</td>
<td>19</td>
<td>28</td>
<td>24</td>
<td>13</td>
<td>21</td>
<td>15</td>
<td>10</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Slope (degree)</td>
<td>47.2- 48.0</td>
<td>47.8- 48.0</td>
<td>48.0- 48.5</td>
<td>48.5- 48.5</td>
<td>48.5- 48.6</td>
<td>48.6- 48.9</td>
<td>48.9- 48.8</td>
<td>48.8- 48.1</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6 Comparisons of experimental (points) and simulated (dotted curves) secondary coil expansions for constrained and unconstrained sensors plotted against temperature.
temperatures may be a consequence of the increased slope of the impedance curves in the measurement frequency range at those temperatures.

CONCLUSIONS

The factors affecting the performance of eddy current sensors for measuring densification at high temperatures (≤900°C) have been investigated. Using a combination of secondary coil designs, and an eddy current simulation code, it has been possible to identify the anomalous contributions of thermal expansions of the secondary coil to a sensor's high temperature response and to devise designs to eliminate them. The calculations also provided insight into the correct normalization protocol to use. Experiments identified the importance of reducing stray contributions to the measurements from lead wire expansions. When these factors were implemented in a new sensor design, it was found to give sample diameters good to 25 μm between ambient temperature and 900°C. Future improvements upon this are under investigation.

ACKNOWLEDGMENTS

We are very grateful to Arnold H. Kahn of NIST who has made numerous suggestions and given much advise during the conduct of this research. The work has been supported by BDM International (C.Coe, Project Manager) through a program funded by DARPA and managed by the Naval Air Warfare Center and the Defense Advanced Research Projects Agency managed by W. Frazier at NAWC and W. Barker at DARPA (Contract N.62269-91C-0274)

REFERENCES