PULSED EDDY-CURRENT MEASUREMENTS FOR THE CHARACTERIZATION OF THIN LAYERS AND SURFACE TREATMENTS

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INTRODUCTION

By using a transient excitation, eddy-current probes exhibit a diffuse pulse-echo response in the presence of stratified conductors. The response has been investigated in order to evaluate pulsed eddy-current signals due to a single conducting layer over a uniform substrate of dissimilar conductivity. The aim of the investigation is to assess the feasibility of measuring the thickness and quality of surface treatments including the diffusion of aluminum into nickel parts and the case hardening of steel components.

EXPERIMENTAL PROCEDURE

Experiments have been carried out on control specimens as well as on aluminized nickel ingots and case-hardened steel specimens. The control specimens each consist of an aluminum foil, whose conductivity and thickness is known accurately, in close contact with an aluminum alloy plate of known conductivity. In all the experiments, an eddy-current probe is excited by a regular series of pulses that rise and fall exponentially in time. By considering just one half-cycle of the excitation, the current variation of a pulse initiated at time $t = 0$, can be expressed as

$$I(t) = I_0(1 - e^{-t/\tau})u(t), \tag{1}$$

where I_0 is the asymptotic coil current, τ the current time constant and $u(t)$ a unit step

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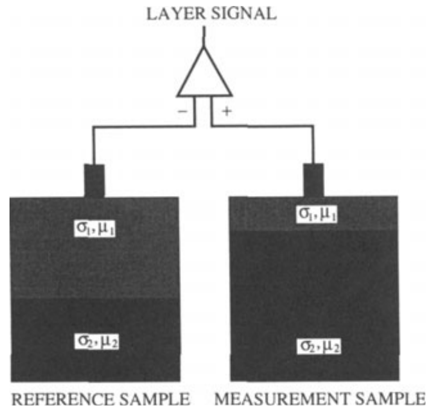

Figure 1. Differential probe configuration used for measurements on layered samples.

function defined such that $u(t) = 1.0$ for $t > 0$ and $u(t) = 0$ otherwise. By using a current rather that a voltage drive, the primary magnetic field due to the probe is a predefined function of time and is unaffected by changes in coil resistance due to temperature variations.

A differential probe configuration has been used consisting of two coils, referred to as C1 and C2, whose parameters are given in Table 1. One coil is placed on the measurement sample and the other on a reference sample. The coils are driven in series and the signal voltages across the individual coils are differentially amplified. Stability problems due to resonances in the system can occur if the leading edge of the differential signal rises rapidly but ringing effects can be minimised without compromising the system bandwidth through a judicious choice of reference sample, Figure 1. By ensuring that the conductivity and permeability of the reference sample is similar to that at the surface of the test sample, the initial rapid excursion of the differential signal, Figure 2, is minimised and spurious oscillations are reduced.

CONTROL EXPERIMENTS

A number of controlled experiments have been performed in order to compare

Table 1. Parameters of the matched air-cored coils C1 and C2.

Coil Parameters	C1	C2
Length (mm)	2.7	2.7
Outer diameter (mm)	4.326	4.338
Inner diameter (mm)	1	1
Liftoff (mm)	0.1310	0.2963
Wire diameter (mm)	0.1	0.1
Turns	311	311
Self-inductance at 150 kHz (μH)	108.11	107.68
Resistance (Ω)	7.54	7.55
Resonant frequency (MHz)	2.5	2.5

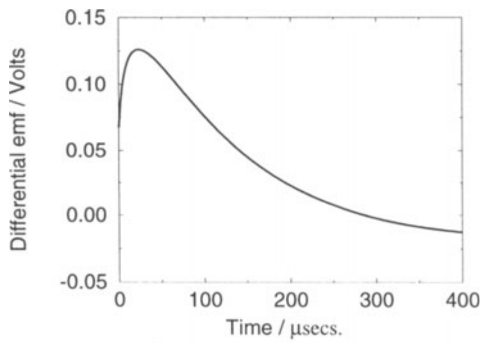

Figure 2. Induced emf when the reference and measurement samples have different surface conductivities. The differential emf will have a step at $t = 0$.

theoretical predictions of the pulse response[1] with experiment and to evaluate the performance of the system for measurements on thin layers. The reference sample chosen was a plate of 99.99% purity aluminum, of thickness 2 mm, above an aluminum alloy substrate. Five control specimens, consisting of 99.99% purity aluminum foils on the aluminum alloy substrate have been used. The foil thicknesses ranged from between 12.5 μm and 0.457 mm, Table 2. The high purity aluminum plate was of similar conductivity to the foils thus minimizing very rapid initial changes in the differential induced emf.

Coils C1 and C2, used in the controlled experiments, were characterized by comparing impedance measurements carried out over a range of frequencies with calculations performed using equations given by Dodd and Deeds for a normal coil over a half-space conductor[2]. Because the lift-off parameter is difficult to measure accurately by direct means, its value, given in Table 1, is chosen to optimise agreement between theoretical and experimental impedances.

Two sets of pulsed eddy-current results were obtained, firstly with coil C1 on the reference sample and then with coil C2 providing the reference signal. These results differ slightly because the coils are not identical. Experimental results are compared with predictions in Figure 3. The most obvious feature of these graphs is the change of signal polarity between the two sets of results. The eddy-current contribution to the induced emf is always of the same polarity regardless of which probe is used for the measurements. Although the role of the probes have been reversed, their inputs to the summing amplifier have not. The summing amplifier has one inverting input and one non-inverting input therefore if the reference and measurement probes are reversed then the polarity of the eddy-current signal will also be reversed.

The pulsed eddy-current technique appears to be highly sensitive to thin layers. In

Table 2. Aluminum foil details.

Foil thickness (mm)	0.0125	0.0600	0.1250	0.2500	0.4570
Conductivity	35.71×10^6 Sm^{-1} (61.57% IACS)				

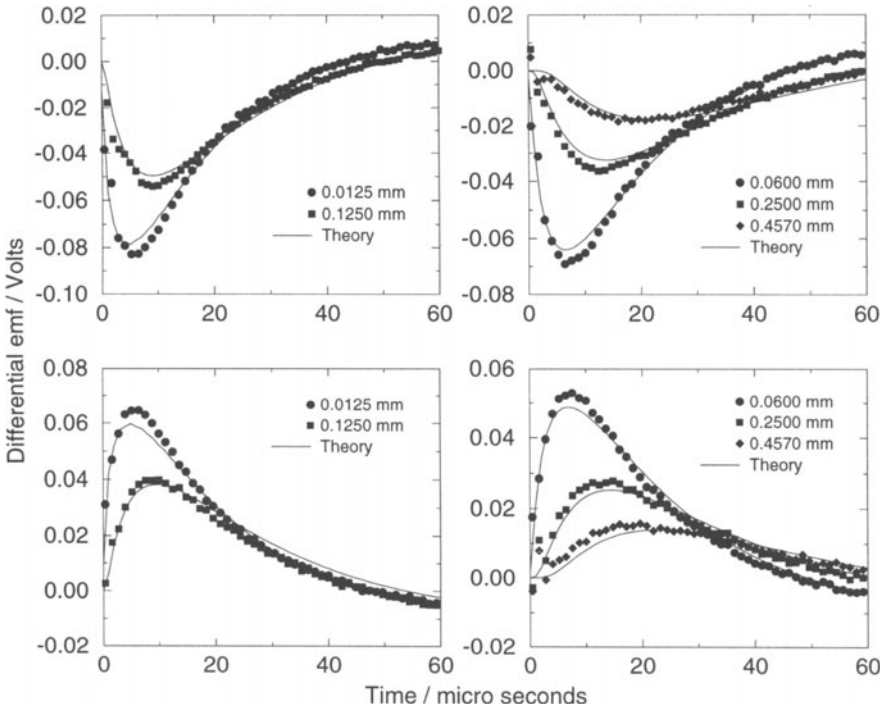

Figure 3. Transient emf measurements and theoretical predictions for the aluminum foil samples using the normal coils, C1 and C2. Plots show the differential emf (Volts) versus time (μsecs.). The upper two plots were obtained with coil C1 placed on the reference sample while in the lower two plots coil C2 was used on the reference sample.

experiments on the control specimens, the magnitude of the differential pulse signals increases with decreasing layer thickness. This is due to the fact that the reference sample consists of a thick slab of material of similar conductivity to that of the surface layer of the sample under investigation. As the layers become thinner, a greater contribution to the induced emf is due to the dissimilar substrate creating a larger out-of-balance signal. The thin aluminum foils generate large, narrow peaks while the thicker layers produce small, broad peaks. These observations are consistent with the interpretation of the signals as a diffused pulse-echo response. The echo from the back face of a thick foil will be delayed compared with that from a thin foil. There is a slight difference in the overall magnitude of the signals between the two sets of results due to a difference in the coil liftoffs and these difference have been correctly predicted by the model. Overall agreement between theory and experiment is very good.

CARBURIZED STEEL BARS

A set of carburized steel bars having various case depths, Table 3, have been studied experimentally using the differential coils, C1 and C2. The bars, used as control samples during the process of carburizing steel gear teeth, have both hardened and soft surfaces on which measurements may be made. A slice has been cut from the bars to leave a wedge of material and a standard hardness test performed on the inclined face to give a measure of the case depth for each of the samples. In these tests, an unhardened surface was used as the reference specimen. This means that one coil was placed on the unhardened surface and the output from this coil subtracted from the signal from the other coil placed on the hardened surfaces of each of the other specimens in turn.

The out-of-balance signal was recorded firstly with the measurement coil on an unhardened sample surface, secondly on the hardened surface and then finally back on the unhardened surface. Several measurements were made in each configuration and the results averaged. Measurements from the unhardened surface were subtracted from the hardened surface measurements.

Signal levels were found to be highly sensitive to changes in coil liftoff which meant that hand held probes would not give repeatable signals. In addition, the proximity of the windings to the bottom of the probes case meant the results were affected by the force holding the probe on the surface of the sample. These problems were overcome using a lightly sprung loaded support to maintain consistent contact between probe and the specimen.

When the probe is placed on a sample, the temperature of the windings drops leading to a fall in the coil resistance. Therefore it is necessary to wait a few seconds until the arrangement reaches a steady thermal state before recording the data.

The results are normalized to a fixed amplitude in order to minimise the liftoff contributions to the signal, Figure 4. A clear trend is visible from these results: the deeper the case depth, the broader the out-of-balance signal. From the initial portion of the signal, where $t < 25\mu$sec., there is evidence that for specimens with a larger case depth there is a difference in the properties of the material at the surface of the specimen. The width at half height of the pulse signals has been plotted against case depth to show the correlation between these parameters and a spline fit to the data carried out, Figure 5.

ALUMINIZED NICKEL INGOTS

The process of aluminizing is often carried on nickel alloys for the purpose of improving oxidation resistance at elevated temperatures. Nickel ingots are used as control samples during the aluminizing process. The ingots are placed in the same environment as the components to be aluminized. Tests are then carried out on the ingots to determine the extent of the treatment. The assumption is made that components in the same environment and with the same properties as the ingots will attain the same level of treatment. Three aluminized nickel samples were measured, Table 4, using an an untreated specimen for the reference signal. Destructive tests were then carried to determine the treatment depths.

Two sets of results were obtained on the aluminized specimens using coils C1 and C2. Coil C1 was in permanent contact with the untreated ingot to provide the reference signal. In order to improve the differential null, a secondary, software reference was obtained. The secondary reference was the differential emf measured with coil C2 on the untreated surface

Table 3. The case depths of the carburized steel bars.

Sample name	SB18	SB32	SB47	SB60
Case depth (0.001 inch)	18	32	47	60
Case depth (mm)	0.457	0.813	1.194	1.524

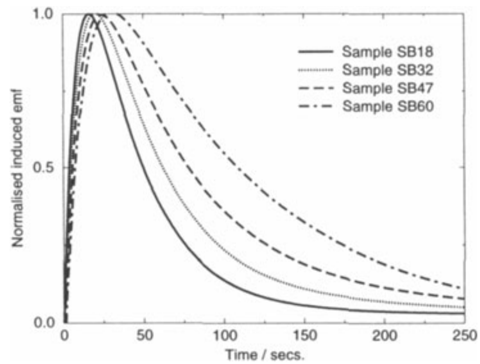

Figure 4. Normalized pulse response of the case-hardened bars using coils C1 and C2.

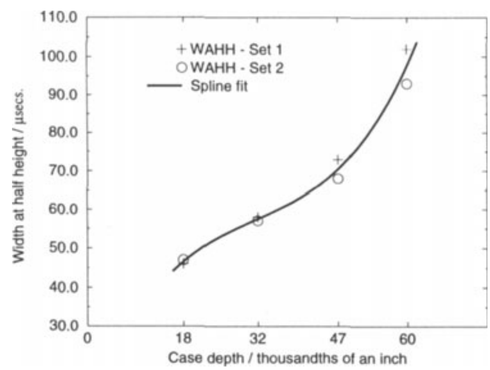

Figure 5. Width at half height (WAHH) of the normalized transient response signals (Figure 4) as a function of case depth for the hardened steel bars.

of one of the ingots. The secondary reference signal was stored and then subtracted from subsequent measurements. Two sets of results were obtained, with set 1, the untreated surface of sample AN21 was used as the secondary reference. With set 2, the untreated surfaces of the individual samples were used to obtain the secondary reference signals. Several measurements were made in each configuration for averaging purposes. Both sets of measurements were carried out twice as a check of repeatability. A graph of the pulse height at 18 μsecs. versus treatment thickness, Figure 6, shows that the amplitude of the pulse is dependent on treatment thickness.

DISCUSSION

Pulsed-eddy current measurements on the aluminum foil control specimens have been carried out and show good agreement with theoretical predictions. The results demonstrate that pulsed eddy-current data can be used to characterize thin conducting layers. By using

Table 4. Depth of treatment on aluminized nickel samples.

Sample name	AN9	AN17	AN21
Treatment depth (0.001 inch)	$\frac{9}{10}$	$\frac{17}{10}$	$\frac{21}{10}$
Treatment depth (mm)	0.02286	0.04318	0.05334

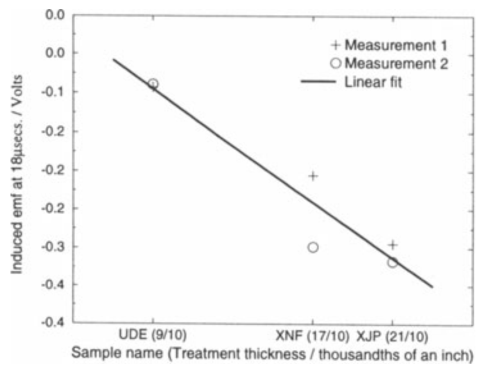

Figure 6. Pulse height variation with aluminized treatment thickness.

a parametric inversion scheme it should be possible to obtain estimates of the layer thickness and conductivity.

Measurements on case-hardened steel bars show that the width of the pulse response varies with case depth; the thinner layers giving sharper peaks and the thicker layers giving broader peaks. Changes in surface layer properties can be detected from the initial part of the transient signal. A definite trend in the initial response would seem to indicate an increase in surface resistivity which is associated with an increase of case depth.

In testing aluminized nickel ingots a correlation was found between the peak height of the differential pulse signal and the depth of the aluminized layer. Using this relationship, it should be possible to estimate treatment depth using pulsed eddy-currents.

REFERENCES

1. J. R. Bowler, in *Review of Progress in Quantitative Nondestructive Evaluation* Vol. 11, eds. D. O. Thompson and D. E. Chimenti (Plenum, New York, 1992), p.241.

2. C. V. Dodd and W. E. Deeds, J. Appl. Phys. 39, 2829 (1968).