MULTIFREQUENCY EDDY CURRENT CLAD THICKNESS MEASUREMENT OF THIN ALUMINUM ALLOY COMBINATIONS HAVING SIMILAR CONDUCTIVITIES

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INTRODUCTION

Clad materials can offer several performance advantages over unclad materials including better corrosion resistance, increased mechanical wear, improved joining qualities, and enhanced metallurgical properties. Clad materials are used extensively in automotive and building products, aerospace applications, and air conditioning equipment. Clad products pose special production problems due to their unique composition. These products might require clad on one or both sides and, depending on the product, the clad and core alloys come in several combinations. For proper process and quality control, products are required to be sampled to ensure that the clad layer is within a certain tolerance band for maximum and minimum thickness. The eddy current method described here can be employed to make a rapid, nondestructive determination of the clad thickness.

The eddy current thickness measurement makes use of the electrical conductivity differences between the clad and core alloys. When an AC current is driven through a coil of wire, a second coil in close proximity will receive a radiated signal through electromagnetic induction. If the coil pair is placed near a conductive material, the mutual impedance will change depending on certain material parameters. If the material is clad, changes in the clad thickness will cause corresponding changes in the measured coil impedance. Unfortunately, several other parameters can also cause impedance changes which can make clad thickness effects difficult or impossible to detect. Some published theoretical calculations have shown the relative effects of these parameters for different material combinations [1,2]. Multifrequency techniques can be used to estimate the effects of these parameters. The skin effect causes certain parameters to have larger or smaller impedance contributions depending on operating frequency; because of this, individual parameters can be isolated and compensated for by using mathematical techniques [3].

This paper explores the extreme case where the clad material is one aluminum alloy and the core material is a different aluminum alloy. In such a case, the conductivity difference between the clad and core alloys is very small (as little as 3% of the nominal conductivities), thereby requiring careful measurement and correction for certain material parameters which might interfere with an accurate clad thickness measurement.

THEORY

An example impedance curve for the coil pair used in these measurements is shown in Figure 1 and the schematic for the measurement equipment is shown in Figure 2. The shape of the curve is dependent upon the composition of the conductor. For clad samples, the impedance curve is affected by the clad thickness and conductivity, core thickness and conductivity, lift-off distance, and total sample thickness. The standard depth of penetration of an

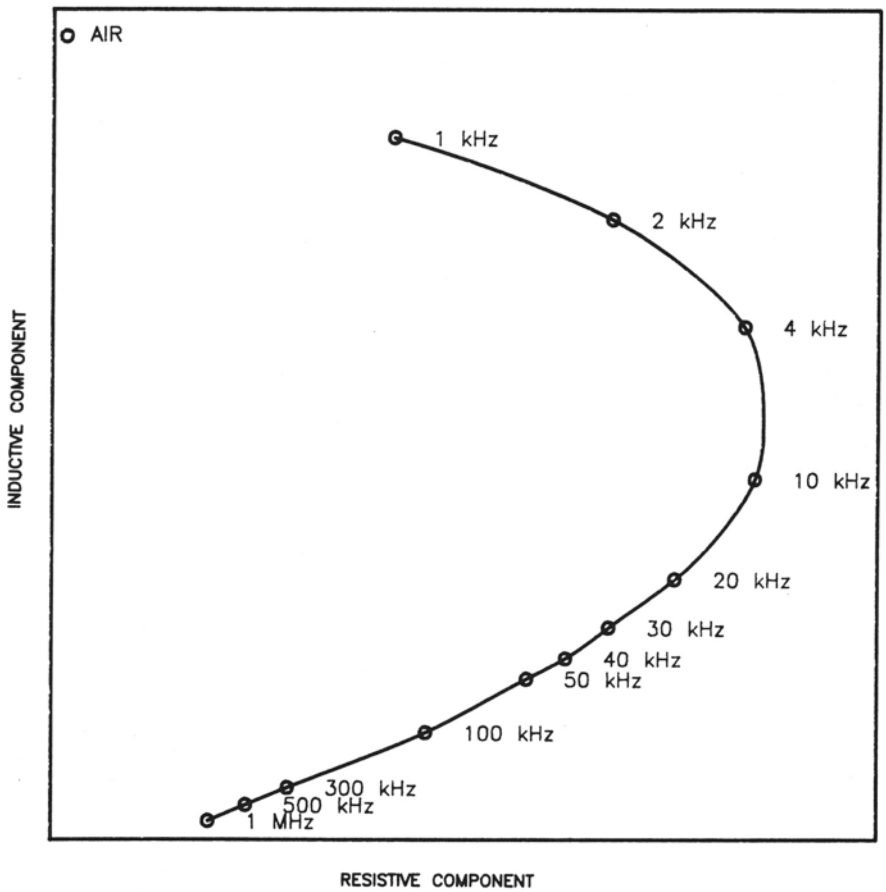

Fig. 1. Impedance curve for the measurement coil configuration.

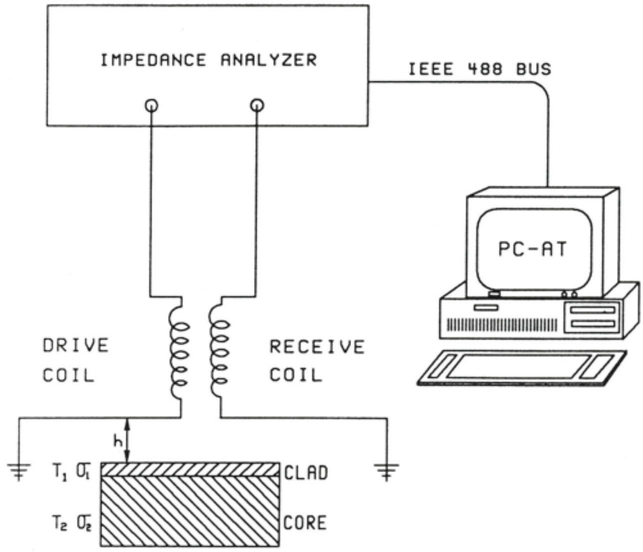

Fig. 2. Diagram for instrumentation used in measurements.

AC electromagnetic signal in a conductor is given by:

$$\delta = 1.98(417.41/\sigma f \mu_r)^{1/2} \tag{1}$$

where δ is in inches, σ is the conductivity in percent IACS, f is the frequency in hertz, and μ_r is the relative permeability of the conductor. As the frequency increases, the signal is confined only to the clad layer. At lower frequencies, the signal penetrates deeper into the material so more of the parameters affect the impedance curve.

By selecting the measurement frequencies carefully and by making some assumptions, some of the material parameters can be ignored. The core conductivity is relatively constant and since its conductivity is close to that of the clad alloy, we assume its impedance contribution to be constant. By measuring at frequencies which penetrate the clad layer but not through the core layer, the total and core thicknesses can be ignored. Measurements made at high frequencies (skin depth less than the clad thickness) are only affected by the lift-off and clad conductivity. Since these effects are nearly orthogonal at high frequencies, they can be determined at a single high frequency. By using these conditions, the measurement problem can be greatly simplified.

Lift-off and clad conductivity can be measured individually on unclad standards, for all of the measurement frequencies, and their responses can be recorded and modeled for use in measuring unknown clad thickness samples. Lift-off is measured by using unclad conductors and gradually increasing the lift-off distance, using an external device to measure the separation distance. Relations are then obtained for impedance change as a function of distance for frequencies of interest. Clad conductivity changes can also be simulated by measuring several conductivity standards and fitting the relationship of impedance changes as a function of conductivity for frequencies of interest. Because the lift-off and clad conductivity can be isolated at high frequency, their effects can be compensated for at lower frequencies where the clad thickness is measured using the above mentioned relations.

METHOD

Before any measurement can be made, the equipment is normalized for drift by measuring a conductivity standard at zero lift-off. All subsequent measurements are referenced to this measurement. To separate the lift-off from the clad conductivity effects for an unknown sample, first the lift-off is determined then the conductivity (see Figure 3). An unknown clad sample is measured at a nominal lift-off at several frequencies and a curve is fit through the measured points. The intersection point between the unknown clad sample curve and the predetermined lift-off curve is found at 1 MHz. The impedance change between the 1 MHz zero lift-off point and the 1 MHz intersection point is due to lift-off. The

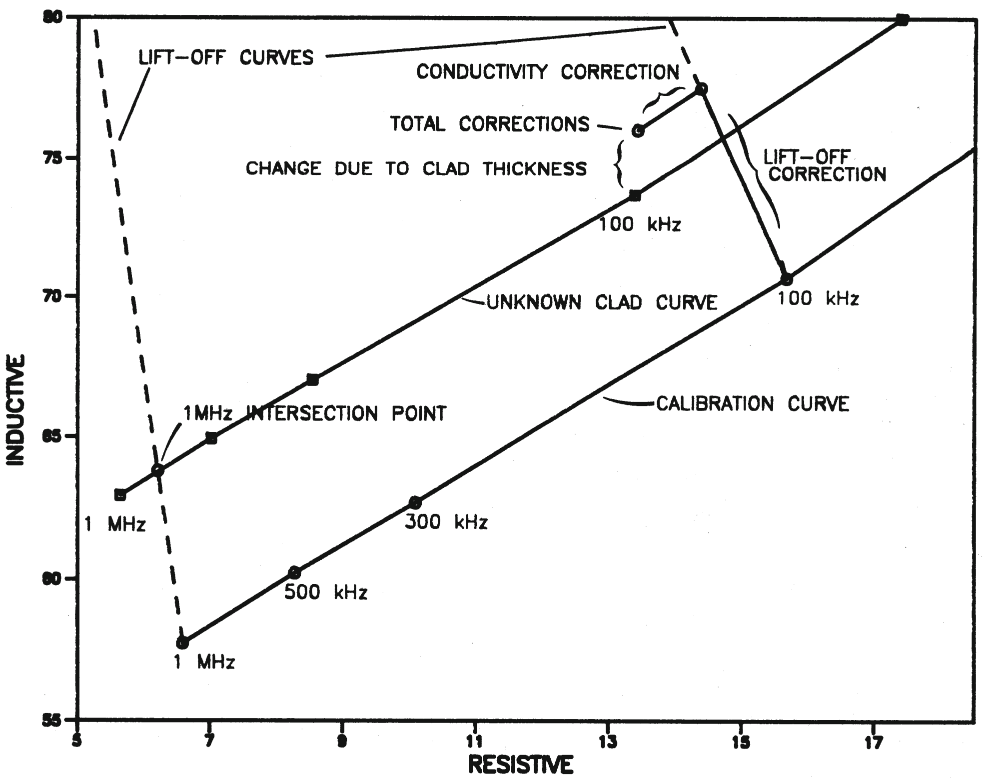

Fig. 3. Correction technique for measurement of clad sample having an unknown thickness.

impedance change between the unknown clad sample 1 MHz point and the 1 MHz intersection point is due to clad conductivity. The previously measured conductivity relation is then used to estimate the conductivity. Once the lift-off and clad conductivity are known, impedance corrections can be made at lower frequencies (100 kHz and 30 kHz) where the clad thickness effect should be largest. The impedance corrections are added to the zero lift-off point at 100 kHz and 30 kHz and the resultant impedance point is compared to the corresponding frequency point of the measured unknown sample. Since the resultant impedance point should be the same as the measured point, if there were no clad present, any difference between the points can only be due to clad thickness.

RESULTS

More than 80 samples, clad on one or both sides, were measured. All of the samples were measured at 100 kHz and thicker samples were also measured at 30 kHz. After the samples were measured with eddy currents, the clad thicknesses were measured using optical methods; least squares approximations were performed on the eddy current data as a function of the optical data. A summary of these results is shown in Table 1 and graphical representation can be seen in Figures 4, 5 and 6. (Note: 1 mil = .001 inches = 25.4 μm).

Table 1

Fig.	Component	Freq. (kHz)	Range (mils)	Std.Dev. (mils)	Max/Min Error (mils)
4	resistive	100	5.5- 16	.65	1.43/-2.01
5	inductive	100	3 - 10	.46	1.35/-1.22
6	inductive	30	10 - 16	.89	2.11/-1.95
---	resistive	30	----------inconclusive------------		

ERROR ANALYSIS AND DISCUSSION

The scatter in the collected data can be attributed to measurement noise, physical measurement limitations, changes in relative clad and core conductivity differences, conductivity correction nonlinearities, and differences in the measurement location between the optical and eddy current methods.

Measurement noise appears to be a small problem and it shows up as instrument noise and temperature drift. Extensive temperature drift tests have not been conducted but indications are that a 10 $^{\circ}$F change might produce a .2 mil error in clad thickness measurement. Instrument noise is also on the order of .2-.3 mils when sampling at 1.6 seconds per frequency.

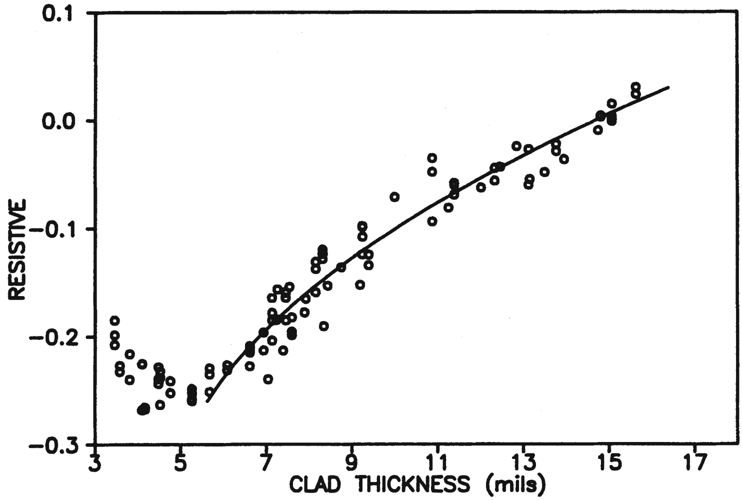

Fig. 4. Clad thickness relationship for resistive change against thickness at 100 kHz.

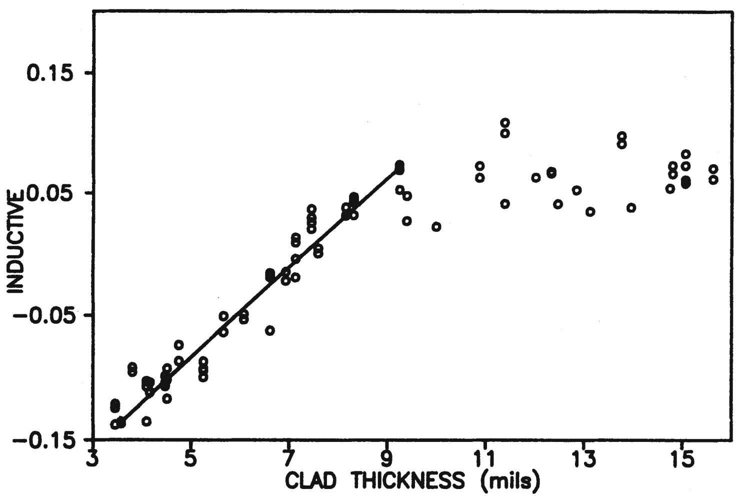

Fig. 5. Clad thickness relationship for inductive change against thickness at 100 kHz.

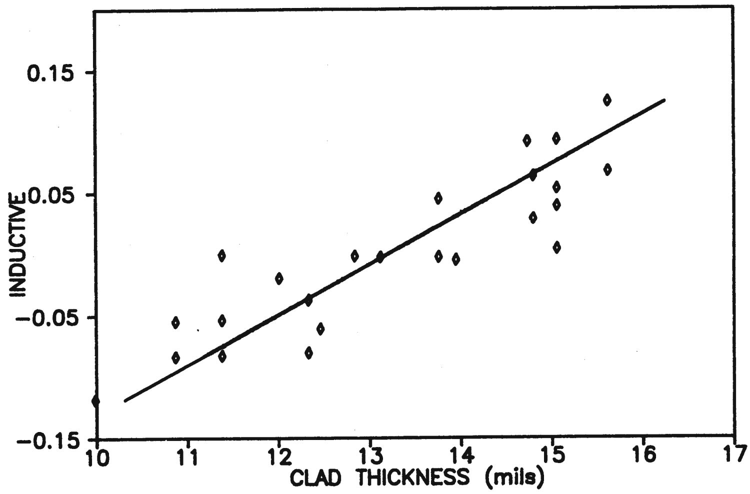

Fig. 6. Clad thickness relationship for inductive change against thickness at 30 kHz.

The scatter in the inductive data above eight mils clad thickness (Figure 5) and the roll off of the resistive component at less than five mils (Figure 4) at 100 kHz is most likely due to a combination of physical phenomenon and parameter correction limitations at 1 MHz. In Figure 4, the resistive component starts to increase again once the clad thickness is less than five mils. This may be due to the fact that the clad is so thin that it allows the signal to penetrate into the core material when the clad conductivity is being measured at 1 MHz. Instead of measuring only the clad conductivity, a combination of clad and core conductivities has been measured. The measurement routine makes an adjustment for this composite conductivity, rather than for just the clad conductivity, and the adjustment is, therefore, incorrect. In Figure 5, the inductive component flattens out after about eight mils. This flattening may just be a natural phenomenon. Published data [1] shows a similar lack of change in the inductive term as the clad thickness approaches one skin depth.

No sensitivity corrections were made for changes in the relative conductivity difference between the clad and core alloys. Obviously, as the conductivity difference between the alloys increases, the impedance change for a given clad thickness will also increase. The relative conductivity difference was assumed to be constant for simplicity in these measurements, but, in reality, the variability in differences was significant. To reduce this large error contribution, future measurements would require the use of a sensitivity compensation.

The 30 kHz measurements also show some scatter (Figure 5). The scatter in the inductive term may be caused by the nonuniformity in the clad conductivity parameter corrections. The conductivity standards used for calibration purposes have large gaps between successive conductivity points. The correction functions were well behaved at 100 kHz, but, at 30 kHz, these functions were not as nice. The use of additional standards to fill in these gaps could reduce the error in conductivity corrections and therefore reduce the scatter in the final clad thickness readings.

Of the samples measured at both 100 kHz and 30 kHz, there is a range from about 10-16 mils where valid data was collected at both frequencies. Large errors, between the optical and eddy current data, were usually of similar magnitude and direction (+/-) at both frequencies. This reproducibility with the eddy current method suggests that the optical measurements may have been made on a different thickness than the eddy current ones were or the optical technique is sometimes not accurate.

CONCLUSIONS

It has been shown that clad thickness of aluminum alloy combinations having small conductivity differences can be accurately and quickly measured by correcting for conductivity and lift-off using this multifrequency method. This method can also be expanded to correct for sensitivity changes caused by variations in the conductivity difference between the clad and core alloys and other conditions as they become necessary.

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REFERENCES

1. R. P. Holt and K. D. Boness, "A Theoretical Study of the Uses of Eddy Current Impedance Methods for the Measurement of Claddings", Harwell Report AERE-R-11998, 1986.
2. J. K. Hulbert and B. W. Maxfield, "Thin, Finite-Plate, Clad Thickness Determination Using Eddy Currents" in Review of Progress in Quantitative NDE, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1988), Vol. 1A, pp. 199-206.
3. R. Saglio and M. Pigeon, "Concepts of Multifrequency Eddy Current Testing" in Nondestructive Testing Handbook, Second Edition, Vol. 4, Electromagnetic Testing, edited by R. C. McMaster, P. McIntire, and M. L. Mester (ASNT, Columbus, Ohio, 1986), pp 591-598.