Estimating Al 1230 clad thicknesses over Al 2024 alloys using apparent eddy current conductivity measurements

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Abstract. The recent developments in apparent eddy current conductivity (AECC) spectroscopy have made it a viable candidate for clad thickness estimation where both clad and substrate are nonmagnetic metals. It negates the previous requirement of establishing a probe characteristic curve with a consistent lift-off distance between the measured sample and the calibration blocks. This eliminates the adverse effects in measurement uncertainty that occurred earlier due to lift-off variations. This study presents a practical approach for clad thickness estimation using AECC spectroscopy targeting clad thicknesses relevant to the industry. The technique once validated both numerically and experimentally has shown to deliver a measurement uncertainty of 3% over the entire coating thickness range of interest at a ±25.4 μm lift-off range. Furthermore, it also reduces the coil diameter requirement to as low as 3 mm without the need of any correction factors.

1. Introduction

Aluminum alloys are known for their high resistance to fatigue as well as high strength-to-weight ratio characteristics. These properties have made them widely popular in both the automotive and aerospace industries [1-3]. The basic strengths of these metal alloys can be further enhanced by coating them with nonmagnetic metals that will not only improve their surface mechanical properties, but will also aid in shielding the substrate alloy [4,5]. The increased use of such cladded structures calls for a dependable nondestructive evaluation (NDE) procedure to accurately estimate its clad thicknesses.

To assess metallic coatings over nonmagnetic metals, phase-sensitive eddy current techniques can be implemented per ISO 21968 [6]. This requires a probe characteristic curve to be established with a consistent lift-off distance between the sample and those used over the calibration blocks to ensure measurement accuracy. Implementing Dodd and Deeds inductive eddy current solutions to the forward problem [7,8] can be used for determining coating thicknesses [9] is such a rectangular conductive layered structure. Numerical assessment may also be utilized as another approach to assess the coil complex impedance spectrum using commercially available tools like COMSOL Multiphysics, which is a cross-platform finite element analysis, solver and multiphysics simulation software [10]. However, manufacturing processes do not deliver the exact coating substrate conductivities as those measured over the calibration blocks which negatively affect the estimation accuracy. Even spring loading the coil to maintain the lift-off distance still results in a measurement uncertainty of around 10% using the impedance-based model [9].
Apparent eddy current conductivity (AECC) measurement technology has shown to be a strong candidate for such clad thickness estimation [10]. Reducing the lift-off effect in high-frequency AECC spectroscopy delivers an uncertainty of ±0.1% for frequencies up to 80-100MHz within a lift-off range of ±25.4μm [10-19]. A more recent study optimized the coil design to a 3-mm diameter coil while applying a correction factor for low conductivity clad/substrate range [20]. This study aims at the experimental evaluation of AECC spectrums to measure Al 1230 coating or clad thicknesses above Al 2024 alloys of high conductivity range without the need for applying any correction factors.

2. AECC forward problem
The conductivity profile for a nonmagnetic alloy over another nonmagnetic alloy is rectangular in nature. Capturing the AECC profile of such structures can be done through both direct and indirect means. The direct method employs the plane-wave electromagnetic approximation whereas the indirect method can be done experimentally [9, 15] or numerically simulated [10, 20]. To use the indirect way mandates two subsequent steps. The first step requires capturing the coil complex impedance spectrum \( Z(f) \) at any lift-off distance within a range of interest. The second step is system calibration where the coil impedance over the sample is bracketed with coil impedances over two homogeneous calibration blocks estimated with and lift-offs. AECC is then estimated using a 4-point linear interpolation at a given frequency. This procedure makes AECC more robust to the constraints offered in impedance-based techniques as it measures the sample conductive properties with depth instead of relying only on the coil impedance.

Figure 1 shows a rectangular conductivity profile of an Al 1230 alloy clad over an Al 2024 plate as a function of depth \( (d) \) and its corresponding AECC spectrum \( (\Gamma) \). The solid line represents the AECC spectrum generated using the plane-wave electromagnetic approximation and the markers represent COMSOL numerical simulations. To maintain consistency with the practical measurements the simulated AECC spectrum using COMSOL was done between 0.1 to 15 MHz.

![Figure 1](image-url)

**Figure 1.** The rectangular conductivity profile of Al 1230 alloy over an Al 2024 plate with its AECC spectrum using the plane-wave electromagnetic approximation (line) and COMSOL simulation (markers).

To estimate the AECC spectrum for a large conductivity variation between the substrate and the coating initially required a relatively large coil diameter \( (D = 50 \text{ mm}) \) [10]. This rendered the technique impractical as available coil diameters in the industry are relatively smaller. A follow up study optimized the coil design to go as low as 3 mm [20]. For the purpose of this study, a practical coil diameter need to be selected to meet the plane-wave electromagnetic approximation operating between of 0.1 to 15 MHz. Through simulations, it was determined that for this specific coating/substrate combination,
coil diameters ranging from 3 to 30 mm offered similar AECC spectrums that match the plane-wave approximation as shown in Figure 2. The decision for using the 3 mm coil diameter is further strengthened in Figure 2(b) where the AECC spectrum matches the plane-wave approximation for a coating thickness ($t_c$) range of interest. This allowed the use of a 3-mm diameter coil for the experimental phase of this study.

**Figure 2.** Determining the smallest diameter of the coil required to meet the plane-wave electromagnetic approximation for a nominal coating thickness of 50µm.

### 3. Results and discussion

To illustrate the advantages of the proposed AECC inversion algorithm, Figure 3 shows a comparison between the AECC-based inversion and the impedance-based inversion in estimating coating thicknesses. Typically, a 0.1% AECC uncertainty occurs in ±25.4µm lift-off range. A 0.5% measurement uncertainty was superimposed over simulated AECC spectrums for all samples, which gives a more conservative analysis for AECC measurement. Due to the constraints mentioned earlier, the impedance method provides a 25% uncertainty in thickness estimation compared to the 3.5% offered by the AECC-based measurement for clad thicknesses ranging from 20.8 to 120.3µm in a ±25.4µm lift-off range.

The significant reduction in measurement uncertainty is due to the fact that AECC is able to capture a physical property of the sample under inspection rather than relying on coil impedance alone. Furthermore, this analysis eliminates the dependency of calibrating the system over cladded calibration blocks of known clad thicknesses where impedance-based measurements over the sample needs to match that over the sample in terms of the coating conductivity, substrate conductivity and coil lift-off distance from the sample. Lift-off variation of ±25.4µm alone delivers the 25% uncertainty in clad thickness estimation following the impedance-based method. On the other hand, calibrating the eddy current system using homogenous calibration blocks measured with and without lift-off eliminates all these inherent impedance-based variations and dependency on coil diameter by capturing the AECC spectrum delivering a 3.5% uncertainty in clad thickness estimation.
Figure 3. Comparison between the impedance and AECC-based inversion methods in coating thickness estimation for a clad thickness range of 20.8 to 120.3µm.

For the experimental section of this study, three samples with unknown thicknesses were purchased from McMaster-Carr.com. The dimensions of the three samples were 38mm × 38mm with a 3.2-mm thickness for each sample. The AECC spectrum was generated for each sample between 0.1 to 15 MHz as shown in Figure 4. Using the AECC spectrums, each sample’s clad thickness was estimated.

Figure 4. AECC spectrums for the three different clad thicknesses using the plane wave approximation (solid lines) and the UniWest eddy current instrument with a 3mm coil (empty markers)

These estimates were then verified by cutting the samples at the location from which the measurements were taken. The cross sections of these samples were then etched using Kellers Etch and placed under a microscope operating at 5× magnification to measure the clad thickness. The algorithm’s convergence with iterations (n) to one of the sample’s estimated thickness (t_{est}) with the actual clad thickness (t_c) along with its microscopic image is shown in Figure 5. The figure shows that the thickness estimated by the proposed inversion algorithm and the actual thickness obtained from the microscopic images are in agreement with each other with approximately 1% measurement uncertainty.
Figure 5. Convergence of the estimated AECC spectrum and the estimated thickness to the actual values and the corresponding microscopic image of the sample’s cross section for a clad thickness of 82.8μm

4. Conclusions
This study took a first step in experimentally validating AECC technology to assess nonmagnetic coatings over nonmagnetic substrates. The coating/substrate combination of Al 1230 over Al 2024 was assessed over different clad thicknesses. The measurement calibration, sample design, frequency range and coil diameter reduction was done numerically using COMSOL. This resulted in ≈ 3% measurement uncertainty for coating thickness estimation. The uncertainty in the estimation of clad thicknesses for the experimental phase of this study was around 1% without the need of any correction factors. With experiment validation, it can be concluded that AECC technology is a strong candidate for nonmagnetic clad alloy thickness evaluation over nonmagnetic alloys.

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