

3D Assessment of Subsurface Microcracks on Metallic Materials Through Nondestructive Characterization

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Internal microcracks, which are microscopic fissures within materials, can significantly impact their mechanical, thermal, and electrical properties. This paper addresses the challenges in inspecting these defects by employing eddy current nondestructive testing. It focuses on numerically modeling a steel sheet under varying stress states and characterizing eddy current indices influenced by factors such as delamination and defect geometry. The study explores the relationships between microcrack characteristics like location, orientation, and size within single and multilayer conductive plates. The researchers compiled a comprehensive database of model signals from defects of varying geometric parameters, as well as experimental signals from artificially created defects with known characteristics in multilayer structures.

Index Terms—Eddy current, Impedance, Microcrack, Multilayer structures, Nondestructive evaluation, Sensors.

I. INTRODUCTION

THE modern machines and systems, including railways, automobiles, and power plants, are complex and rely on numerous components to function effectively. Ensuring the reliability of these components is vital, as the quality of products depends on design, materials, and manufacturing techniques. Defects can arise not only during production but also during operation, influenced by design and service conditions. Understanding and identifying these defects is crucial for minimizing them and enhancing quality. For example, steam turbines can experience wear and fatigue damage due to metal loss, necessitating defect detection during manufacturing or maintenance [1]. Early diagnosis of microcracks is essential to avoid unnecessary replacements. The objective of this study was to develop an effective method for detecting microcracks using eddy current non-destructive testing. This study aims to identify the most suitable techniques for detecting these microcracks, emphasizing their respective advantages and limitations.

II. NDT COIL CONFIGURATION AND MODELING TOOLS

Nondestructive eddy current testing (NDT) utilizes electromagnetic interactions between an eddy current sensor and the material being tested. The process involves a coil inducing an electromagnetic field, which generates eddy currents. Changes in the material's electromagnetic properties, such as conductivity and permeability, can indicate defects by altering the coil's impedance. Various configurations exist for detecting these changes, including separate driver and receiver coils, and differential testing using two coils wound in opposite directions [2]. The latter enhances sensitivity to abrupt changes like cracks while canceling out gradual impedance variations. NDT modeling relies on calculating physical quantities guided by Maxwell's equations to define the relationship between electric and magnetic fields and the medium's parameters [3].

TABLE I
GEOMETRICAL AND PHYSICAL PARAMETERS OF THE BENCHMARK

Parameter	Value	Parameter	Value
Thickness plate	1.25 mm	Length plate	140 mm
Width plate	140 mm	Depth defect h	0.75 mm
Width defect w	0.20 mm	Length defect c	10 mm
Inner coil radius r_1	10 mm	Outer coil radius r_2	10 mm
Coil height b	10 mm	Frequency	150-5 MHz

III. PROBLEM DEFINITION AND NUMERICAL SETUP

Our problem is defined as a conductive plate of thickness 1.25 mm, having conductivity of 1.02 MS/m relative permeability 1. The plate is affected by a single rectangular subsurface crack such as mentioned by Figure 1. The model parameters are presented in Table 1. The finite element model includes the air domain, the excitation coil, the receiving coil, and the specimen. The excitation coil and the receiving coil are made of copper, while the test piece is made of stainless steel [4]. The areas of refined mesh have been applied to the skin layer to enhance the computing quality. The voltage of the AC depends on various factors such as material conductivity, lift-off distance, magnetic permeability, geometric irregularities, frequency, excitation current, and the spatial structure and size of the excitation and detection coils [5].

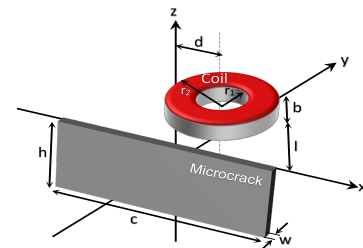


Fig. 1. Geometrical Model with crack shape illustration.

The analysis involves plotting the real and imaginary parts of normalized impedance over a frequency range of 500 Hz to 2 MHz as shown in Figure 2. Notably, conductivity within a crack can compensate for assumptions regarding the crack's width, meaning precise measurements of crack width may not be necessary for simulations of fatigue microcracks. However, significant discrepancies between simulated and experimental data, particularly between 80 kHz and 300 kHz, highlight the need for improved experimental design and simulation methodologies to enhance the reliability and accuracy of findings in this field [6].

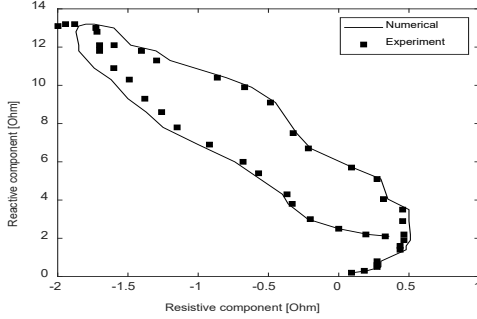


Fig. 2. Impedance plane diagram.

We have performed the simulation of multiple configurations in order, in particular, to construct the couple (Impedance, air gap). For these simulations, the thickness of the upper metal layer is set to 0.42 mm while the thickness of the second lower conductive layer is 0.53 millimeters. We consider that the air gap between the two conductive layers can vary from 0 to 300 μm . Figure 3 illustrates the normalized impedance curves derived from measurements conducted across five different air gap thicknesses, ranging from 0 to 300 μm . The effects of

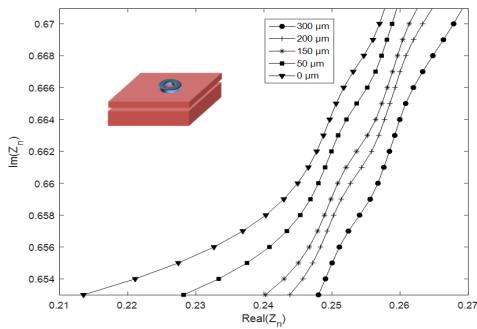


Fig. 3. Effect of air gap thickness variation on normalized impedance.

varying lift-off distances of conductive plates with different thicknesses is was discussed. It emphasizes the significance of maintaining an optimal lift-off distance to ensure accurate eddy current responses, avoiding issues like coil saturation from being too close and reduced sensitivity from being too far. A multilayer perceptron (MLP) was adopted for its intrinsic capability to efficiently perform complex tasks within a short duration. The thickness of the upper conductive layer is the same for all simulations (1.25 mm), 20 clearance values

ranging from 10 μm to 300 μm are simulated and this, for 5 frequencies ranging from 500 Hz to 2500 Hz. Like the network built from simulated data, the network built from experimental data has as input a vector of multiple elements of the impedance measured at 5 frequencies. Figure 4 illustrate real crack depth as function as the estimated one for two Lift-off distance. There exists a strong agreement between the reconstructed and true crack parameters, which supports the assumption that the depths of the cracks have been accurately estimated, with the reconstructed profiles being very similar to the actual ones

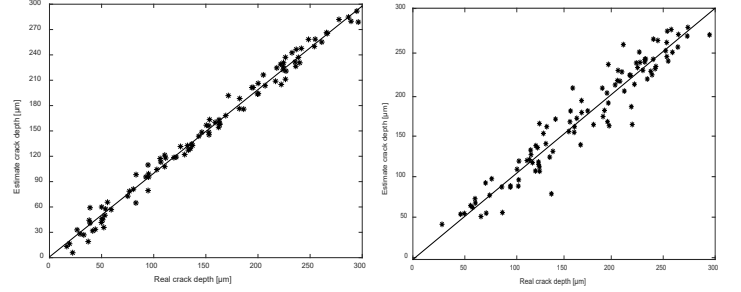


Fig. 4. Crack depth profile for 500 μm (at left) and 850 μm (at right).

IV. CONCLUSION

This study focuses on evaluating computational models of microcracks through eddy current nondestructive testing simulations. It highlights the importance of determining the impedance distribution along the probe coil's surface for assessing sensitivity and spatial resolution. Using finite element simulations, the study analyzes the working principle and response to cracks, proposing an algorithm to understand the impact of crack dimensions. The research gathers data by moving the probe across a conductive plate, comparing experimental results with simulation models. To address the inverse problem, a Multi-Layer Perceptron (MLP) neural network is employed to estimate crack depth and length simultaneously, using variations in resistance or reactance as input vectors. The developed approach demonstrates good accuracy in estimating the geometric parameters of cracks.

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