Inspection of aluminum sheets using a multi-element eddy current sensor: 2d and 3d imaging of surface defects of various sizes and internal defects at various depths

Inspeção de chapas de alumínio usando um sensor de correntes parasitas multielementar: imagens 2D e 3D de defeitos superficiais de vários tamanhos e defeitos internos em várias profundidades

Inspección de láminas de aluminio mediante un sensor de corrientes de Foucault de elementos múltiples: imágenes 2D y 3D de defectos superficiales de varios tamaños y defectos internos a varias profundidades

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**ABSTRACT**

In the industrial sector, ensuring reliability and durability is of paramount importance. Our research aims to advance beyond conventional non-destructive testing methods by focusing on thorough defect detection and imaging. We utilize advanced, sensor-enhanced eddy current testing, featuring multiple elements arranged in a cutting-edge serial array. This innovative configuration addresses the issue of magnetic repulsion between sensor elements, thereby speeding up the testing process and ensuring precise results through both 3D and 2D imaging. This sophisticated approach allows us to more effectively characterize defects of varying sizes and depths in aluminum sheets. By meticulously collecting and analyzing data from the sensors, we can identify the appearance and nature of these defects with greater clarity. Our findings introduce a pioneering method for defect detection, highlighting the efficacy of our advanced testing technique. Our research underscores the potential of multi-element eddy current sensors in revolutionizing the inspection process. The ability to produce detailed 3D and 2D images of surface and internal defects represents a significant leap forward in non-destructive testing. This comprehensive imaging capability not only accelerates the detection process but also enhances the accuracy and reliability of defect characterization. By employing this state-of-the-art technology, we can detect even the smallest and most deeply embedded defects that traditional methods might miss. The precise imaging provided by our approach ensures that defects of various sizes and depths are accurately identified and characterized. This level of detail is crucial for maintaining the structural integrity and performance of aluminum sheets used in industrial applications. Our research demonstrates a groundbreaking approach to defect detection in aluminum sheets, leveraging the advanced capabilities of multi-element eddy current sensors. The innovative use of a serial array of sensors, combined with sophisticated data analysis techniques, allows for rapid, accurate, and detailed imaging of defects. These findings pave the way for improved reliability and durability in industrial applications, setting a new standard for non-destructive testing.

**Keywords:** Eddy Current Testing. Multi-Sensors. Imaging Defect. Finite Element Method.
RESUMEN
No sector industrial, garantir confiabilidad e durabilidad es de suma importancia. Nuestra pesquisa visa avanzar además de los métodos convencionales de testes no destructivos, concentrándose en la detección e generación de imágenes completas de defectos. Utilizamos testes avanzados de correntes parasitas aprimorados por sensores, presentando varios elementos organizados en una matriz serial de última geração. Esta configuración innovadora aborda la repulsión magnética entre los elementos sensores, acelerando así el proceso de prueba y garantizando resultados precisos a través de imágenes 3D y 2D. 


RESUMO
En el sector industrial, garantizar la fiabilidad y la durabilidad es de suma importancia. Nuestra investigación tiene como objetivo avanzar más allá de los métodos de prueba no destructivos convencionales centrándose en la detección e imágenes exhaustivas de defectos. Utilizamos pruebas avanzadas de corrientes parasitas mejoradas por sensores, con múltiples elementos dispuestos en una matriz en serie de última generación. Esta configuración innovadora aborda el problema de la repulsión magnética entre elementos sensores, acelerando así el proceso de prueba y garantizando resultados precisos a través de imágenes 3D y 2D. 

Nuestros hallazgos introducen un método pionero para la detección de defectos, destacando la eficacia de nuestra técnica de prueba avanzada. Nuestra investigación subraya el potencial de los sensores de corrientes parásitas de elementos múltiples para revolucionar el proceso de inspección. La capacidad de producir imágenes detalladas en 3D y 2D de defectos internos y de superficie representa un importante avance en las pruebas no destructivas. Esta capacidad integral de obtención de imágenes no solo acelera el proceso de detección sino que también mejora la precisión y confiabilidad de la caracterización de defectos. Al emplear esta tecnología de vanguardia, podemos detectar incluso los defectos más pequeños y más profundamente arraigados que los métodos tradicionales podrían pasar por alto. Las imágenes precisas proporcionadas por nuestro enfoque garantizan que los defectos de diversos tamaños y profundidades se identifiquen y caractericen con precisión. Este nivel de detalle es crucial para mantener la integridad estructural y el rendimiento de las láminas de aluminio utilizadas en aplicaciones industriales. Nuestra investigación demuestra un enfoque innovador para la detección de defectos en láminas de aluminio, aprovechando las capacidades avanzadas de los sensores de corrientes parásitas de múltiples elementos. El uso innovador de una serie de sensores, combinado con sofisticadas técnicas de análisis de datos, permite obtener imágenes rápidas, precisas y detalladas de los defectos. Estos hallazgos allanaron el camino para mejorar la confiabilidad y durabilidad en aplicaciones industriales, estableciendo un nuevo estándar para pruebas no destructivas.

**Palabras clave:** Teste de Correntes Parasitas. Multissensores. Defeito de Imagem. Método de Elementos Finitos.

1 INTRODUCTION

In the realm of non-destructive evaluation (NDE) for conductive materials, eddy current testing (ECT) emerges as one of the most critical electromagnetic techniques. This technique is firmly rooted in the principles of electromagnetic induction, harnessing this phenomenon to deliver its remarkable capabilities. ECT operates by generating eddy currents within a material when it is subjected to a time-varying magnetic field. These currents, when disrupted by anomalies such as cracks or deformations, cause detectable changes in the material's electromagnetic properties, allowing for the identification and characterization of these defects [1]. The applications of ECT are extensive and varied. In industrial settings, ECT is employed for measuring material thickness, evaluating the proximity of components, assessing wear, and sorting materials based on their electromagnetic properties [2]. These capabilities make ECT indispensable in
quality control and maintenance across various industries, including aerospace [3], automotive, and power generation.

Historically, one of the primary applications of ECT was to identify discontinuities and diagnose potential problems in critical components. For example, in the maintenance of steam generators and aircraft wing panels, ECT has been instrumental in detecting stress corrosion cracks (SCC) and fatigue cracks (FC) [4],[5]. These forms of structural deterioration are prevalent in high-stress environments and can lead to catastrophic failures if not detected and mitigated promptly. Despite the effectiveness of ECT in identifying such defects, certain types of anomalies, such as cavitation and internal corrosion, present unique challenges. These defects are often concealed within the material, making them difficult to detect using conventional inspection methods [6].

Traditional defect detection in ECT relies on monitoring changes in the impedance signal provided by the eddy current sensor. While this method is effective in identifying the presence of a defect, it falls short in providing detailed information about the shape and path of the defect. Advanced techniques, including those that leverage artificial intelligence (AI), inverse problem-solving, support vector machines (SVM) [7],[8], and neural networks, have been developed to address this limitation. These techniques enhance the capability of ECT by providing more detailed and accurate characterizations of defects [9].

In our research endeavor, we aimed to advance the capabilities of ECT through the use of 3D simulations within the COMSOL Multiphysics software. Our focus was on an aluminum plate, a common material in various industrial applications. We intentionally introduced defects of different sizes and depths into the simulation model to analyze the total impedance signals emitted by the eddy current sensors. To enhance the resolution and accuracy of the defect detection, we employed a multiplexing scheme. The use of a multiplexing system in our research enabled the creation of 3D images of the defects. This approach resulted in new and improved results, providing clearer and more accurate visualizations of the defects [10]. The enhanced clarity and accuracy of 3D imaging not only,[11],[19] improve the detection capabilities of ECT but also open up new avenues for advanced research and development in the field [12].
By visualizing and clearly describing these defects, our research makes a qualitative contribution to the field of non-destructive evaluation [13]. Improved defect detection and characterization promote increased safety and security, particularly in critical applications where the failure of components can have severe consequences. For instance, in nuclear reactors, the early detection of defects can prevent potentially catastrophic accidents, thereby ensuring the safety of both the facility and the surrounding population. Beyond its implications for reactor safety, our research holds significant humanitarian value. By emphasizing the importance of robust inspection procedures, our work underscores the critical role these advancements play in ensuring the safety of both personnel and the general public. The ability to detect and characterize defects more accurately contributes to the prevention of accidents and the preservation of human life. Thus, our research not only advances the technical capabilities of ECT but also reinforces the importance of safety and reliability in industrial and public infrastructure. The objective of this article is to enhance the defect detection and characterization capabilities of ECT through advanced 3D simulations and multiplexing techniques, ultimately contributing to improved safety and reliability in critical industrial applications.

2 MATHEMATICAL MODEL

The Eddy Current Non-Destructive Testing (ECNDT) method is deeply rooted in the principles of electromagnetic fields. The examination process and the mathematical representation used to compute the induced currents within steam generator tubes are based on the laws of electromagnetism, specifically utilizing quasistatic approximations of Maxwell's equations. Various strategies exist to describe the interaction between the probe and the structure being tested, especially in complex geometries where numerical methods are commonly applied. Modeling and simulating eddy current testing provide a robust foundation for early assessment of parts during inspection. Numerous numerical formulations, particularly those using the finite element method (FEM)[14],[18], have been proposed to address the well-known challenges of this open boundary problem, both in its differential and integral aspects[20].
Prominent among the differential formulations are the H-Φ formulation introduced by Bossavit and Verite, the T-Ω formulation described by Carpenter and further developed by Brown, Albanese, and Rubinacci, and the A-V formulation proposed by Biro [15]. The primary advantage of the differential formulation is the sparsity of the matrices in the solving system, which is crucial for minimizing computational costs.

In this manuscript, we employ a three-dimensional Finite Element (FE) methodology to compute signals from eddy current probes caused by the presence of cracks, with the goal of characterizing material properties [14]. The system of equations governing the dynamics of multiphysics systems, with evolving variables, can be derived from Maxwell's equations. These equations are outlined below:

\[ \mathbf{V} \cdot \mathbf{D} = \rho \]  
\[ \mathbf{V} \cdot \mathbf{B} = 0 \]  
\[ \mathbf{V} \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  
\[ \mathbf{V} \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \]

By employing Galerkin techniques, the imposition of Dirichlet boundary conditions necessitates fixing nodal potentials at known values. Conventional Neumann conditions can be incorporated naturally. In our specific scenario, where both magnetic vector potential and electric scalar potential are utilized [15], we adopt the Galerkin weak form represented by expressions where \( \Psi \) and \( \Psi \) correspond to the weighting functions, which coincide with the shape functions in a finite element implementation [16]. Subsequently, the weak forms of Maxwell's equations are represented as:

\[ \int_{\Omega} (\mathbf{V} \times \mathbf{A}) \cdot (\mathbf{V} \times \Psi) d\Omega = \int_{\Omega} \mathbf{J} \cdot \Psi d\Omega \]  
\[ \int_{\Omega} \mathbf{V} \phi \cdot \nabla \psi d\Omega = 0 \]
The elements of impedance in this context are delineated as follows:

\[ Z = R + j\omega L \quad (7) \]

In this instance, the unspecified parameters \( P \) and \( W \) can be articulated respectively as:

\[ P = \int_{\Omega} E \cdot J d\Omega \quad (8) \]

\[ W = \int_{\Omega} (\nabla \times A) \cdot (\nabla \times A) d\Omega \quad (9) \]

where:

- \( E \) is the electric field,
- \( J \) is the current density,
- \( A \) is the magnetic vector potential, and
- \( \phi \) is the electric scalar potential.

Through this sophisticated modeling approach, we can accurately simulate the behavior of eddy currents in response to defects, providing a powerful tool for early detection and characterization of material properties in non-destructive testing applications.

3 MESH CONFIGURATION OF THE PROPOSED MODEL

In this study, we proposed two models. The first model features an aluminum plate with three straight surface defects, all 15 mm in length and depth 1 mm but with varying widths of 2 mm, 1.5 mm, and 1 mm. The second model incorporates a square-shaped defect located in the center of the plate with length 100, width 100 and depth 8 mm, with a side length of 10 mm and depth 1 mm. Initially, this defect is superficial, but it is then progressively lowered beneath the surface, creating internal defects situated 0.5 mm, 1 mm, and 2 mm below the surface.

To examine these defects, we used six sensors positioned on the plate, each situated 0.5 mm away from it, as detailed in Table 1. These sensors are
alternately activated to prevent mutual induction. The sensors move in 1 mm increments for each inspection step.

Each volume comprising the study domain needs to be discretized using geometric elements that create a mesh at the nodes where physical quantities will be numerically determined. COMSOL Multiphysics offers various types of discretization elements, including tetrahedral, hexahedral, and prism elements. The choice of element type influences the number of degrees of freedom required for the numerical solution of the problem. In our case, we opted for a mesh with tetrahedral elements because this option facilitates the automatic meshing of different geometries, as illustrated in Figures 1, 2, and 3.

<table>
<thead>
<tr>
<th>Parameter values</th>
<th>Sensor parameter value [mm]</th>
<th>Coil inner 1</th>
<th>Coil outer 3</th>
<th>Coil height 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical parameter value</td>
<td>Relative Permeability 1</td>
<td>Frequency 10000 Hz/1600Hz</td>
<td>Lift-off 0.5 mm</td>
<td></td>
</tr>
</tbody>
</table>

Source: Authors

Considering that the probe is a multi-element sensor [21], each element has a coil wire cross-sectional area of $0.04 \times 10^{-6}$ m², 150 turns, and a conductivity of $6 \times 10^7$ S/m. The scanning procedure is positioned parallel to the y-axis with a lift-off of 0.5 mm. Each sensor element advances by one step along the aluminum plate structure, which has a conductivity of $3.774 \times 10^7$ S/m and contains three distinct defects.

Figure 1: 3D Finite Element Mesh of Square Surface Defect

Source: Authors
4 EVALUATING AND DISCUSSING FINDINGS

4.1 CORRELATION BETWEEN INDUCTIVE CURRENTS AND DEFECT SIZE

To verify the simulation model, we must first compare the results obtained from the induced currents in the aluminum plate for a single coil at multiple sensor positions, as illustrated in Figure 4.
Figures 4 and 5 illustrate the intensity of the currents induced by the sensor at two distinct defect locations. In the first location, the defect measures 1.5 mm in width and 15 mm in length, where the induced current density reaches $6.65 \times 10^6 \text{ A/m}^2$. In contrast, the second location features a square defect with a side length of 10 mm, where the induced current density significantly decreases to $3.22 \times 10^6 \text{ A/m}^2$.

This reduction in current intensity is primarily attributed to the difference in defect size. A larger defect creates a greater gap and distance between the plate and the sensor, decreasing the induced current intensity provided by the sensor. These observations validate the reliability of the models designed in COMSOL Multiphysics, enabling us to proceed to the next step: extracting the impedance values at each sensor position.

### 4.2 Imaging Defects Via Impedance Data Collection

Employing multiplexing technology on a sensor outfitted with multiple elements, each advancing in 1 mm steps, enables the development of a comprehensive inspection system for various sites. In this context, each mode incorporates impedance signal data from individual sensing elements. For surface defects, we utilized a relatively standard frequency of 10,000 Hz, while reducing the frequency to 1,600 Hz to maximize the penetration depth of eddy currents.
Figure 5: 3D illustration of Three Surface Defects Using an Imaginary Part of Impedance at Fr 10KHz

Source: Authors

Figure 6: 3D Illustration of Surface Square Defect Using Imaginary Impedance at Fr 10 kHz

Source: Authors

Figure 7: 3D Illustration of Inner Square Defect 0.5mm from Surface Using Imaginary Impedance at Fr 1.6 KHz

Source: Authors

Figure 8: 3D Illustration of Inner Square Defect 1mm from Surface Using Imaginary Impedance at Fr 1.6 KHz

Source: Authors
Figures 5 and 6 present 3D and 2D representations resulting from top projection imaging of straight and square surface defects. This imaging was achieved by collecting the imaginary impedance values at a frequency of 10 kHz, where the impedance values ranged from $2.02 \times 10^{-7}$ Ω as a minimum to $2.12 \times 10^{-7}$ Ω. The imaging is clearer and more accurate in reflecting the defect's shape.

In the second scenario, illustrated in Figures 7, 8, and 9, the internal defects are positioned 0.5 mm, 1 mm, and 2 mm below the surface, respectively. Here, we used a lower frequency of 1600 Hz to allow the eddy currents to penetrate to the maximum possible depth. We observed that the impedance value decreases to $3.45 \times 10^{-8}$ Ω, and the imaging quality declines as the depth of the defect increases. This can be attributed to the decrease in eddy currents as we move further from the surface towards greater depths, making it difficult to fully cover all aspects of the defect. This limitation highlights the challenges of using eddy current inspection for detecting deep internal defects, which underscores the significance of being able to image a defect at a depth of 2 mm.

5 CONCLUSION

In this conclusion, the authors reflect on how the results of their research can benefit society and academia. After successfully implementing the CND-CF system in COMSOL Multiphysics, we simulated the detection of wear defects effectively. Using multiple sensors, the system enabled efficient inspection of large areas, while multiplexing reduced signal cross-talk, enhancing result clarity. Our findings demonstrate the system’s effectiveness in imaging defects of various sizes and depths, including surface corrosion, subcutaneous anomalies, and internal flaws. These high-resolution images provide a comprehensive view of part quality,
revealing hidden defects. Validating its suitability for non-destructive evaluation, our research offers detailed visualizations that enhance quality control processes. It opens avenues for future research aiming at more thorough defect descriptions, promising improved safety and reliability in industrial applications. Our research contributes by enhancing safety in critical infrastructures and providing a framework for future academic exploration. Despite its promise, limitations include testing on a limited range of defect types and materials. Future work should expand testing to increase generalizability and optimize multiplexing in complex environments. Integration of machine learning for automated defect detection and classification should also be explored to enhance system efficiency and accuracy. Addressing these areas will advance non-destructive evaluation methods.

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