Feasibility Study of Eddy Current Heating Thermography Non-Destructive Testing Method Under Varied Dimensions of Hidden Crack

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Abstract

This article presents a comprehensive analysis of the feasibility of using an axisymmetric magnetothermal model, solved through the finite element method (FEM), to detect hidden cracks in specimens. The study explores the impact of crack radius, crack depth, and sheet thickness as key parameters in the interaction between the specimen and electromagnetic stimulation. The analysis involves the use of a current-carrying coil to generate a magnetic field, inducing eddy currents in the specimen, subsequently leading to localized heating. Temperature distributions are examined to identify potential defects within the specimen. Mesh independency analysis is initially conducted to ensure the reliability of the results. The study finds that the FEM results remain consistent with varying mesh densities. Subsequent temperature analysis reveals that the presence of cracks significantly alters temperature distributions, with larger cracks causing more pronounced changes. The maximum temperature and temperature gradient are found to be promising indicators for crack detection. Furthermore, variations in crack depth and sheet thickness are analyzed, highlighting the influence of these parameters on the detection process. The study concludes that this non-destructive testing (NDT) method holds the potential for identifying defects in specimens of varying characteristics, providing valuable insights for quality control and structural integrity assessment.

Keywords: Non-destructive testing; Eddy Current; Inductive heating; Sensors; Cracks

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Introduction

Non-Destructive Testing (NDT) plays a pivotal role in the broader landscape of engineering, industry, and safety. It serves as a crucial foundation for ensuring the reliability, efficiency, and safety of materials and structures across various sectors [1]. In a rapidly evolving world, where technology advances at an unprecedented pace and industries demand higher levels of performance, NDT stands as a vital tool that addresses critical challenges and contributes to the overall success of multiple domains.

In the greater context of engineering, NDT serves as a linchpin for quality assurance. It allows engineers to assess the integrity of components without causing damage, which is particularly essential in industries where safety and reliability are paramount [2]. By detecting flaws and defects in materials early, NDT helps prevent potential failures and accidents that could have far-reaching consequences. Beyond safety, NDT aligns closely with cost-effectiveness and sustainability [3]. It enables industries to optimize their maintenance and repair efforts, thereby reducing downtime and avoiding costly unscheduled shutdowns [4]. By extending the lifespan of components through proper monitoring and assessment, NDT contributes to the efficient utilization of resources and maximizes the return on investment for assets [5]. The applications of NDT span a wide spectrum of industries. From aerospace, where the inspection of critical aircraft components ensures the safety of air travel, to the oil and gas sector, where the integrity of pipelines and facilities directly impacts environmental and operational safety, NDT is a common thread that weaves through various industrial landscapes. In manufacturing, it ensures the quality of products, while in civil engineering, it maintains the structural health of essential infrastructure [6]. The mechanisms of NDT techniques demonstrate their adaptability and effectiveness across diverse materials and component geometries. The selection of the appropriate NDT method depends on specific requirements, highlighting the precision and customization that can be achieved. Each technique addresses different inspection needs and has its advantages and limitations, providing a rich toolkit for engineers to choose from [7]. As technology continues to advance, NDT will remain at the forefront of ensuring the integrity and safety of engineering assets worldwide. It will adapt to new materials, emerging industries, and evolving challenges, making it an ever-evolving and indispensable discipline. NDT's ability to seamlessly integrate with broader engineering goals and its role in mitigating risks while optimizing resource utilization firmly positions it as a cornerstone of modern engineering practices [8].

NDT finds diverse utilization across a broad spectrum of scenarios, including Aerospace and Flight Industry [9,10], Oil and Gas Sector [11,12], Manufacturing [13], Infrastructure Evaluation [14], Power Generation Systems [15], Automotive and Transportation [16], Medical Devices Production [17], and Electronics and Semiconductor Sector [18].

The historical journey of NDT highlights the innovative spirit of human ingenuity. From ancient civilizations using fundamental techniques to modern scientists and engineers harnessing the power of ultrasonic waves and X-rays, the trajectory of NDT demonstrates our relentless pursuit of knowledge and tools to better understand the properties of materials. This pursuit is not just a matter of curiosity; it underpins the design, manufacturing, and maintenance of the infrastructure that supports our way of life. Several contributions have been made in this area in the literature, which collectively classify the methodologies of NDT into a comprehensive framework, ranging from ultrasonic testing and radiography to eddy current inspection.

Regarding infrared thermography, Khodayar et al. [19] studied the evolving landscape of NDT in the context of rapid technological advancements and changing societal needs. In recent years, infrared thermography has gained prominence as an effective and reliable technique to tackle complex NDT challenges. While turn-key infrared thermography NDT systems are now available, the authors raise the question of "What is next?" in the field of infrared thermography NDT. Their analysis suggests that future developments in infrared thermography NDT will encompass various areas, including acquisition, stimulation, processing, and an expanding array of applications. These developments are driven by the continuous emergence of new technologies and materials, each with unique inspection requirements. In another study, Qu et al. [20] studied the landscape of NDT techniques, with a particular focus on the rapid development of infrared thermography as a promising NDT method. In contrast to traditional NDT methods, infrared thermography stands out as a relatively new and evolving technique that has gained significant traction in recent years. The core technologies underpinning infrared thermography involve thermal excitation and infrared image processing. This paper provides a comprehensive review of several key infrared thermography non-destructive testing techniques. The authors conduct an in-depth analysis and comparison of these techniques, considering factors such as detection principles, technical characteristics, and data processing methods. Through this analysis, the paper sheds light on the evolution of infrared thermography as a non-destructive testing technique, highlighting its significant growth and potential applications. Furthermore, the authors summarize the current applications of infrared thermography and outline the anticipated development trends in this field.

In regards to Eddy Current testing, AbdAlla et al. [21] conducted a thorough investigation into the realm of eddy current testing, a technique of paramount importance across various industries, including material coating, nuclear, and oil and gas. Despite its widespread use, the technique requires continuous attention to the intricacies of probe structure and its practical application. This paper offers a comprehensive overview of the eddy current testing technique, with a particular focus on the design factors that influence the accuracy of crack detection through this

method. The initial segment of the paper delves into the evolution of different types of eddy current testing probes, shedding light on their respective advantages and disadvantages. Additionally, it provides an insightful review of prior research endeavors that have explored various aspects, including the testing samples, probe structures, and factors contributing to eddy current signals. The subsequent section of the paper delves deeply into the phenomenon known as the lift-off effect, emphasizing the critical need to ensure precise defect measurements while optimizing the design of eddy current testing probes. This discussion underscores the importance of meticulous probe design to achieve accurate and reliable results. In another study, Koyama et al. [22] conducted a comprehensive exploration into the utilization of an eddy current testing (ECT) method for the inspection and detection of impact damage in carbon fiber-reinforced composites (CFRP). ECT, a non-destructive testing (NDT) technique, leverages electric induction for its evaluation. While ECT has gained widespread recognition for its efficacy in detecting cracks and corrosion in metals and assessing their electric conductivity, its application in the context of CFRP posed unique challenges. The distinguishing feature of CFRP lies in the carbon fiber's lower electric conductivity compared to metals. Moreover, from the perspective of the eddy current probe, CFRP appears as an inhomogeneous conductive material, characterized by the bundling and layering of conductive fibers. This starkly contrasts with the homogeneity of metal samples, making the application of ECT to CFRP a complex endeavor. The research highlighted several critical issues that needed to be addressed for the successful implementation of the ECT method in CFRP inspection. These challenges encompassed the judicious selection of test frequency, the design of the probe, and the intricacies of signal processing. By systematically tackling these hurdles, the study aimed to unlock the full potential of ECT as a valuable tool for the detection of impact damage in CFRP, offering insights that could significantly benefit the NDT community working with composite materials.
Discovering new feasible NDT techniques is of paramount importance for a multitude of reasons. One of the key benefits lies in the potential for improved sensitivity. Novel methods often possess the capability to detect smaller defects, discontinuities, or anomalies that might elude existing techniques. This heightened sensitivity significantly enhances the reliability of inspections, reducing the chances of overlooking critical issues that could compromise safety or product quality. Furthermore, the adaptability of new NDT techniques to changing materials, manufacturing processes, and component designs is crucial. Industries frequently encounter evolving challenges, such as the use of advanced materials, complex geometries, or unique structural arrangements. Developing innovative NDT methods tailored to address these specific challenges expands the applicability of NDT across a broader range of industries and scenarios, ensuring that inspections remain relevant and effective. In summary, the quest for new feasible NDT techniques represents a continuous pursuit driven by the ever-evolving nature of materials, technology, and industry needs. These innovative techniques have far-reaching benefits, enhancing accuracy, efficiency, safety, sustainability, competitiveness, and the ability to tackle emerging challenges.

Methodology

In our research study, we devised a comprehensive methodology to investigate the feasibility of a combination of NDT techniques, specifically the eddy current method and infrared thermography to investigate hidden crack defects. For this purpose, we simulated and analyzed the results entirely within the COMSOL Multiphysics software tool, for obtaining thermal data. Our methodology consisted of the following essential steps:

- Sample Design: We initiated the study by designing a representative circular sheet, serving as a model for a material with a known thickness.
- Crack Introduction: To simulate crack defects, we strategically created a cylindrical void within the sheet with known height and diameter. This artificial crack was introduced to mimic real-world scenarios where structural integrity may be compromised.
- Sheet Redesign: Following the introduction of the crack, we proceeded to redesign another sheet, overlaying it onto the original sheet to enclose the defect. This step was crucial for simulating situations where crack detection and evaluation are vital.
- Coil and Current: On one side of the sample, we positioned a coil. By passing an electric current through this coil, we induced a magnetic field within the material. Consequently, this magnetic field generated eddy currents within the plane of the sample. This coil gives a heat flux to the side of the sample.
- Finite Element Analysis: To simulate the temperature distribution resulting from the eddy currents, we employed the FEM within COMSOL Multiphysics. This enabled us to calculate and visualize the temperature contours across the sample surface.
- Analysis of Temperature Contours: Notably, due to the presence of crack defects, the temperature distribution on the sheet exhibited non-uniform patterns in areas corresponding to the locations of the defects. These non-uniform temperature variations served as indicators of potential defects within the material.
- Results Discussion: Subsequently, we engaged in a comprehensive discussion of the results obtained through our simulation-based analysis. Our analysis delved into the relationship between the observed

temperature contours and the presence of crack defects, providing valuable insights into the effectiveness of our NDT approach, without the need for practical thermographic camera use.

In summary, we developed a comprehensive methodology to explore the feasibility of employing a combination of NDT techniques, specifically the eddy current method and infrared thermography, for the detection of hidden crack defects. To achieve this, we conducted simulations and analysis exclusively within the COMSOL Multiphysics software tool to obtain thermal data. Our methodology encompassed several crucial steps, starting with the design of a representative circular sheet to model a material with a known thickness. We then strategically introduced a cylindrical void, simulating crack defects to mirror real-world structural integrity challenges. The subsequent redesign of the sheet encapsulated the defect, akin to scenarios requiring accurate crack detection and evaluation. By positioning a coil and inducing eddy currents within the sample, we generated heat flux. Utilizing finite element analysis, we simulated the resulting temperature distribution across the sample's surface. Notably, the presence of crack defects manifested as non-uniform temperature variations within the sheet, serving as indicators of potential defects. Through comprehensive result discussions, we gained valuable insights into the effectiveness of our NDT approach.

Results and discussion

The interaction between the specimen and the electromagnetic stimulation is examined using an axisymmetric magnetothermal model, solved through the finite element method (FEM). The primary objective of this study is to identify potential defects by carefully crack radius, crack depth, and sheet thickness as key parameters.

The structure of the analyzed system is depicted in Figure (1). A current-carrying coil makes a magnetic field, causing Eddy Current in the specimen. This Eddy Current heats the specimen. The temperature distribution would bring the possibility of detecting the hidden cracks in the specimen. This study aims to analyze the feasibility of this technique to detect cracks in various depths and lengths as well as the material and thickness of the specimen. Thus, the heat flux is assumed as a constant 800 W/m^2. The crack is designed with underlying voids at the center of the specimen. On the opposite side of the specimen, we analyzed the temperature distribution.

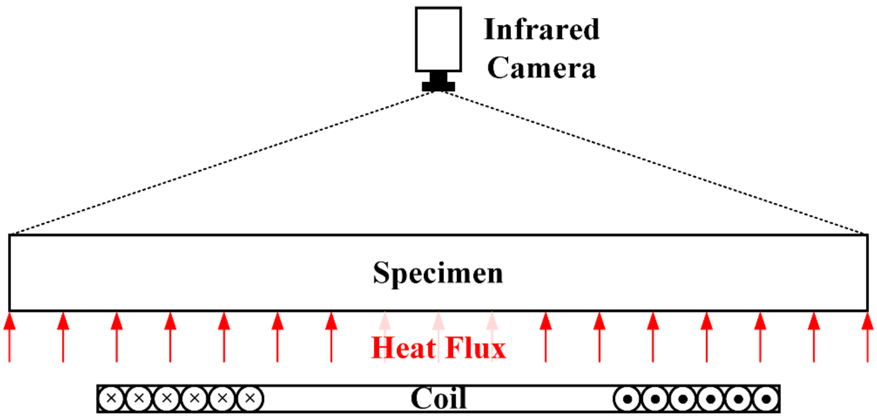


Figure (1) The structure of the analyzed system.

Before any result presentation, it is needed to conduct a mesh independence analysis. This analysis verifies the validation of the results. The purpose of mesh independence analysis is to determine the appropriate level of mesh refinement required to obtain reliable and accurate results without unnecessary computational costs.

Figure (2) shows the results of mesh independence analysis. The error is estimated to be lower than 1E-6, even without refinement. Thus, we ensured that the results of FEM do not depend on the mesh.

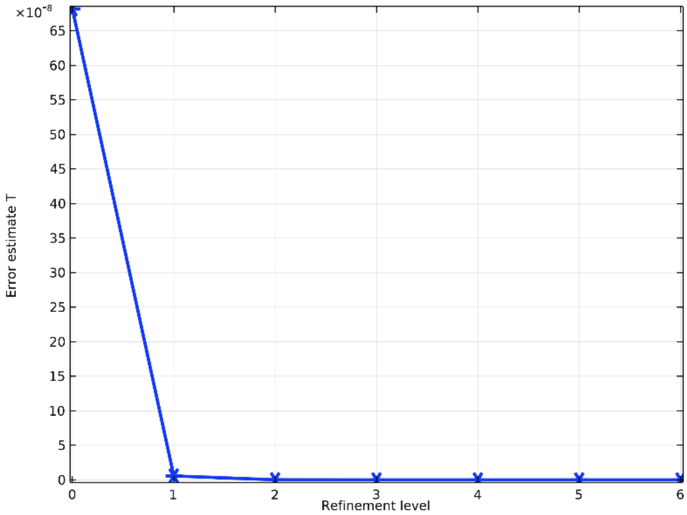
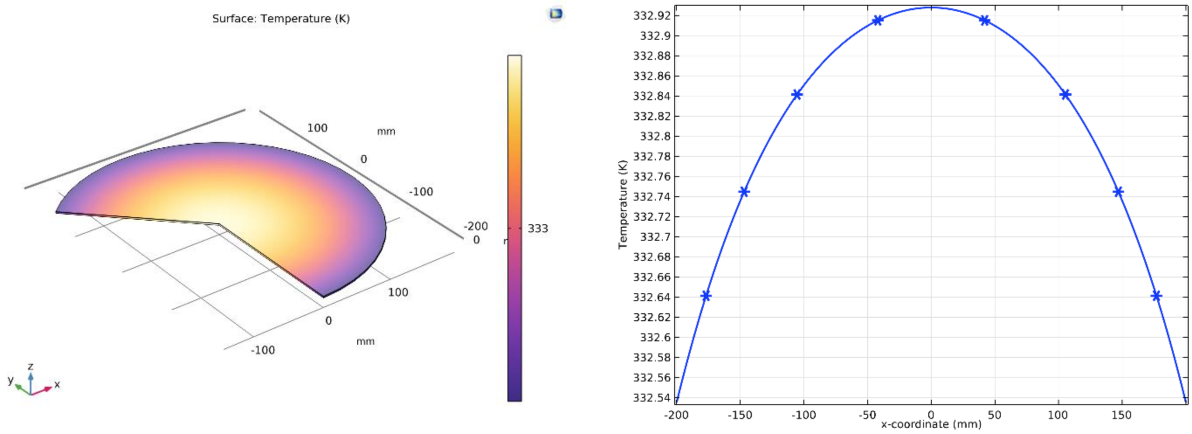


Figure (2) Mesh independency analysis.

In this study, the 2D-axisymmetric environment is used. The temperature of the surface where the heat flux is not applied is measured to analyze the detection feasibility. Figure (3.a) illustrates the temperature distribution of a specimen without any cracks. It should be noted that this plate is 2 mm thick and the material is assumed to be iron. Figure (3.b) depicts the plot of the temperature distribution for the surface of the sample without cracks. Here, the results show that as we go from the outside to the center of the sample, the surface temperature increases. In other words, the hottest point is the center of the sample. This temperature is equal to 332.93 K.

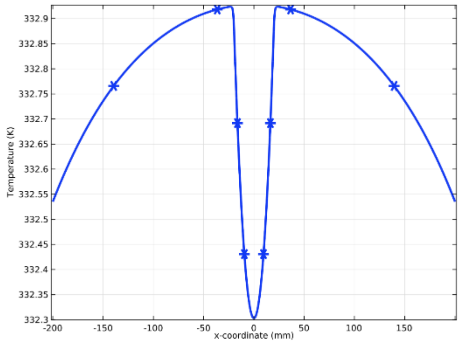


(a) **(b)**

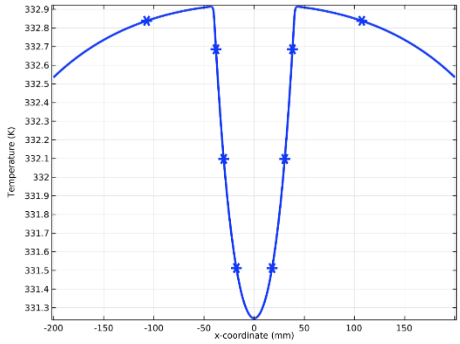
Figure (3) Temperature distribution of a specimen without crack

Crack radius

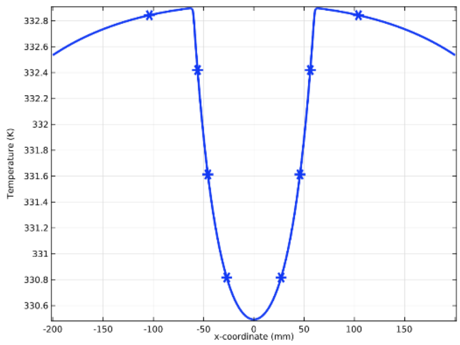
In this part, a hidden crack-like void is designed in the center of the specimen. The crack depth is designed to be 0.5 mm. The temperature analysis is conducted for 20, 40, 60, 80, 100, and 120 mm of crack radius. Figure (4) depicts the temperature distribution in different crack radii.



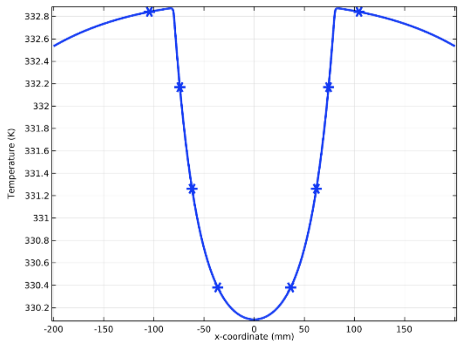
(a) Crack radius 20 mm



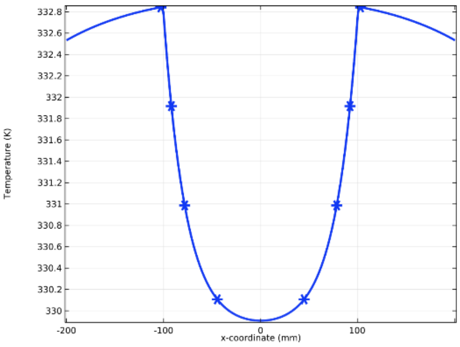
(b) Crack radius 40 mm



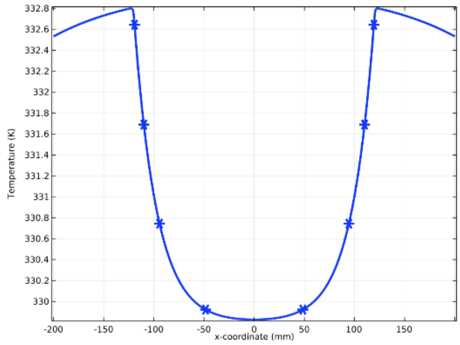
(c) Crack radius 60 mm



(d) Crack radius 80 mm



(e) Crack radius 100 mm



(f) Crack radius 120 mm

Figure (4) Temperature distribution in different crack radii.

In all cases, the temperature increases from the outside to the inside as in the sample without cracks; with the difference that a sharp temperature drop is seen in the crack region. As the crack gets bigger, this temperature drop has happened in a bigger area. Therefore, the maximum temperature decreases with the increase of the crack radius. Table (1) shows the maximum temperature and maximum temperature gradient magnitude in various crack radii.

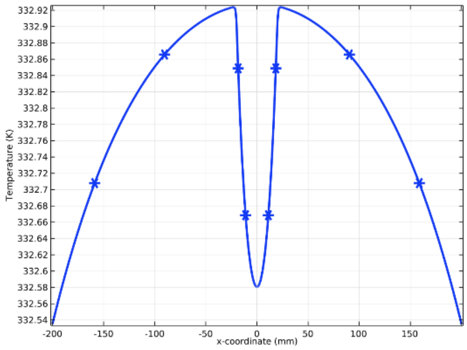
Table (1) Maximum temperature and maximum temperature gradient magnitude in various crack radii.

No.	Crack radius (mm)	Maximum temperature (K)	Maximum temperature gradient magnitude (K/m)
1	20	332.92	58.546
2	40	332.91	93.837
3	60	332.90	110.11
4	80	332.87	117.57
5	100	332.84	121.34
6	120	332.80	123.41
7	Without crack	332.93	7.3096

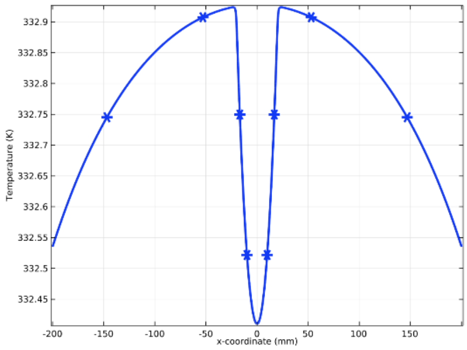
The maximum temperature in cracks with a smaller radius is close to the case without cracks. As the crack gets bigger, the difference between the maximum temperature and the maximum temperature in the state without cracks increases; Although this difference order of magnitude is 0.1. The most important thing to diagnose the failure is the location where this maximum temperature occurs. The maximum temperature occurs at the edge of the crack, which can also provide the possibility of estimating the crack location. Temperature gradient can be a suitable parameter to detect the presence of cracks in the sample. In case of no crack, the maximum temperature gradient is equal to 7.3096 K/m, while it is 58.546 K/m in a 20 mm crack and 123.41 in a 120 mm crack. This parameter can be a promising variable in NDT.

Crack depth

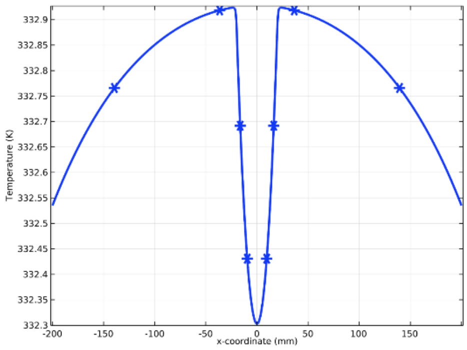
In this part, an investigation is conducted to analyze the temperature distribution of the sample with various crack depths, including 0.1, 0.3, 0.5, and 0.7 mm. The crack radius is assumed to be 20 mm. Figure 5 illustrates the temperature distribution in different crack depths.



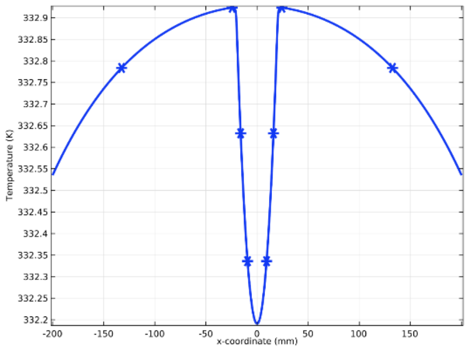
(a) Crack depth 0.1 mm



(b) Crack depth 0.3 mm



(c) Crack depth 0.5 mm



(d) Crack depth 0.7 mm

Figure (5) Temperature distribution in different crack depths.

As mentioned earlier, the maximum temperature occurs at the crack edge. Thus, in this study, the maximum temperature has all happened in a specific area. Therefore, the maximum temperature in all cases is the same and equal to 332.92 K. The minimum temperature shows its effect at different depths. In other words, the greater the depth, the cooler the plate is in the crack region. Table (2) shows the minimum temperature and maximum temperature gradient magnitude in various crack depths.

Table (2) Minimum temperature and maximum temperature gradient magnitude in various crack depths.

No.	Crack depth (mm)	Minimum temperature (K)	Maximum temperature gradient magnitude (K/m)
1	0.1	332.54	35.650
2	0.3	332.41	49.251
3	0.5	332.30	58.546
4	0.7	332.19	72.881
5	Without crack	332.54	7.3096

The minimum temperature decreases with increasing crack depth. In other words, the greater the depth, the cooler the areas where there are cracks; Although the order of magnitude of the changes is 0.1. As before, the maximum temperature gradient shows great changes with the change in crack depth. The maximum temperature gradient in the crack with a depth of 0.1 mm is 35.650 K/m and in the crack with a depth of 0.7 mm it is 72.881 K/m. While it was equal to 7.3096 in the state without crack.

Sheet Thickness

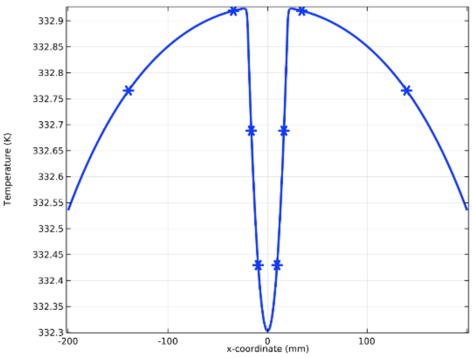
In the present study, we investigated the thickness of the sheet and we have drawn the temperature distribution in sheets of different thicknesses to verify whether this method can be applied to sheets of different thicknesses or not. For this purpose, we have designed a crack with a radius of 40 mm and a depth of 0.5 mm in an iron sheet with different thicknesses, including 2, 4, 6, 8, 10, and 12 mm, and we have performed thermal analysis for each of them. Figure (6) shows the temperature distribution in different sheet thicknesses.

As can be seen in the pictures, the temperature changes in different areas decrease with increasing thickness, making this NDT more difficult. Evaluation of thicker samples requires more energy to produce more heat flux because the previous heating flux has not been able to heat the sample enough for the temperature difference to be felt. Table (3) illustrates the maximum temperature and maximum temperature gradient magnitude in various sheet thicknesses.

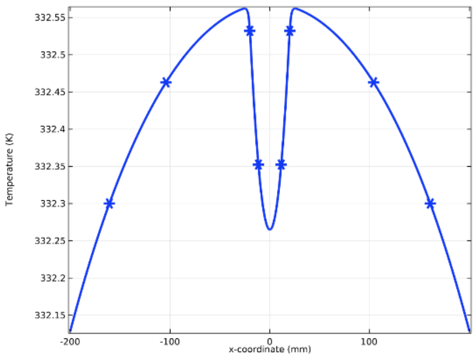
Table (3) Maximum temperature and maximum temperature gradient magnitude in various sheet thicknesses.

No.	Sheet thickness (mm)	Maximum temperature (K)	Maximum temperature gradient magnitude (K/m)
1	2	332.92	58.546
2	4	332.56	25.446
3	6	332.19	15.947
4	8	331.82	11.672
5	10	331.45	9.3637
6	12	331.09	7.9315

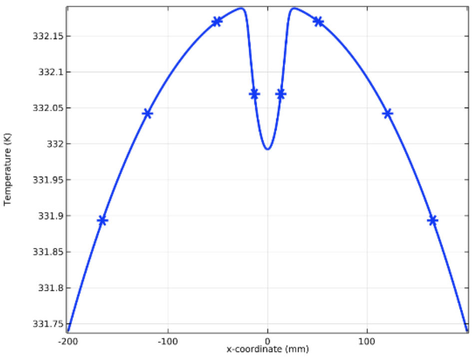
The maximum surface temperature decreases with increasing thickness of the plate. This is due to the conduction heat transfer in the whole plate, which distributes the energy in the whole plate by increasing the volume. The maximum temperature gradient also becomes smaller and smaller with increasing thickness, because the temperature difference is smaller and smaller.



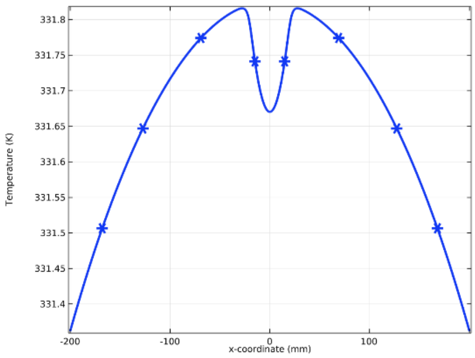
(b) Sheet thickness 2 mm



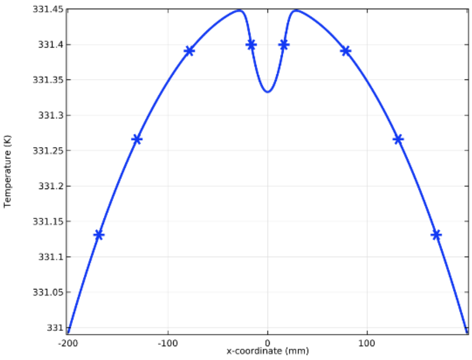
(c) Sheet thickness 4 mm



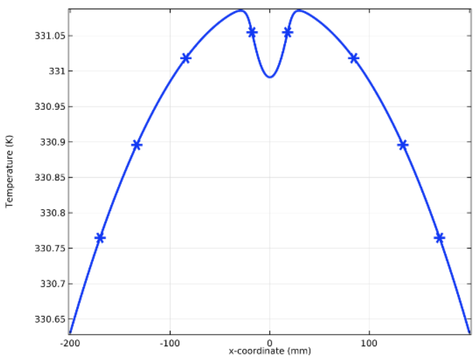
(d) Sheet thickness 6 mm



(e) Sheet thickness 8 mm



(f) Sheet thickness 10 mm



(a) Sheet thickness 12 mm

Figure (6) Temperature distribution in different sheet thicknesses.

Conclusion

In this study, we have investigated the effectiveness of an axisymmetric magnetothermal model solved through the finite element method (FEM) for detecting hidden cracks in specimens. Our findings reveal the following key insights:

- Mesh Independency Analysis: Mesh independency analysis was conducted to ensure the reliability of our FEM results. The results demonstrate that the simulation outcomes remain consistent even with variations in mesh density, confirming the robustness of our computational approach.
- Temperature Analysis: Temperature distributions in specimens without cracks showed a gradual increase from the outside to the center, with the hottest point occurring at the center. This characteristic temperature distribution forms a baseline for detecting cracks within the specimen.
- Crack Radius: Increasing the crack radius resulted in a more significant temperature drop within the crack region. The maximum temperature decreased as the crack radius increased, while the temperature gradient

magnitude increased substantially. These observations suggest that crack size can be estimated based on the location and magnitude of temperature variations.

- Crack Depth: Varying the crack depth affected the minimum temperature within the crack region, with deeper cracks causing cooler areas. The maximum temperature remained consistent across different crack depths. The temperature gradient magnitude increased with deeper cracks, providing a potential indicator for crack depth estimation.
- Sheet Thickness: Specimens with varying sheet thicknesses displayed diminishing temperature changes across different areas with increasing thickness. This finding indicates that detecting cracks in thicker specimens may require higher energy input for sufficient temperature differences to be discernible.

In conclusion, our study demonstrates the potential of the axisymmetric magnetothermal model and FEM for non-destructive testing (NDT) to detect cracks in specimens with varying characteristics. The maximum temperature and temperature gradient emerge as promising parameters for crack detection, with the ability to estimate crack size and depth. This research contributes valuable insights for quality control and structural integrity assessment in various applications.

The research presented in this article lays the groundwork for further advancements and applications in the field of NDT using the axisymmetric magnetothermal model and FEM. Prospects in this area encompass several promising directions for research and development:

- Optimization of Experimental Setup: Future studies can focus on optimizing the experimental setup, including coil design, magnetic field strength, and measurement techniques. Fine-tuning these parameters can enhance the sensitivity and accuracy of crack detection, making the technique more practical for real-world applications.
- Machine Learning Integration: Incorporating machine learning algorithms into the crack detection process holds significant potential. By training models on a diverse dataset of temperature profiles, machine learning can improve the efficiency and reliability of crack identification, even in complex scenarios.
- Material Characterization: Extending the scope of this research to include a wider range of materials and alloys will broaden the applicability of the technique. Investigating how material properties influence temperature distributions and crack detection will be invaluable for industries such as aerospace, automotive, and construction.
- Automation and Robotics: Integrating the developed crack detection technique into automated systems or robotics can enable real-time monitoring and inspection of large structures, pipelines, and critical infrastructure. This automation could significantly reduce inspection time and increase safety.
- Multi-Modal Inspection: Combining the magnetothermal technique with other NDT methods, such as ultrasound, X-ray, or thermography, can create a powerful multi-modal inspection approach. This synergistic approach can improve the accuracy of defect detection and characterization.
- Field Applications: Transitioning from laboratory experiments to real-world field applications is a crucial step. Conducting tests on actual components and structures, such as bridges, pipelines, and aircraft components, will validate the technique's practicality and reliability.
- Cost-Effective Solutions: Exploring cost-effective implementations of the magnetothermal model for industries with budget constraints is essential. Developing affordable sensor systems and software solutions can democratize the use of this technology across various sectors.
- Standardization and Certification: Establishing industry standards and certification procedures for the magnetothermal crack detection method will promote its adoption and integration into quality control and safety protocols.
- Environmental Considerations: Investigating the environmental impact of the magnetothermal testing method, including energy consumption and waste generation, will be essential as industries strive for sustainability and eco-friendly practices.
- Interdisciplinary Collaboration: Collaboration between researchers from various disciplines, including materials science, electromagnetics, and robotics, will foster innovative approaches and cross-pollination of ideas, accelerating advancements in non-destructive testing.

In summary, the prospects for the axisymmetric magnetothermal model and FEM-based crack detection technique are promising and multifaceted. Continued research and development in these areas hold the potential to revolutionize quality control, safety assessment, and structural integrity maintenance across a wide range of industries.

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