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Crack Detection in Engineering Materials: A Systematic Review Based on Physical Principles

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Abstract

Crack detection in engineering materials has become a prominent research area due to the severe consequences of potential failures in safety-critical systems such as pipelines, railway systems, welded joints, rotating machinery elements, and load-bearing structures. Although significant advancements have been made in nondestructive testing (NDT) methods, there is currently no single method capable of simultaneously meeting the requirements of high detection sensitivity, quantitative crack characterization capability, and applicability under real service conditions. In this study, literature published from 2000 to the present is reviewed using a systematic and method-oriented approach. Unlike conventional reviews, this study classifies existing methods based on the fundamental physical principles underlying the crack detection mechanism rather than the types of sensors used. The investigated approaches are discussed under the categories of Magnetic Flux Leakage (MFL), direct current electromagnetic and motion-induced eddy current techniques, Eddy Current Testing (ECT) and ACFM methods, thermography-assisted electromagnetic approaches, weak magnetic field and Metal Magnetic Memory (MMM) techniques, magneto-optical and visual methods, hybrid EMAT-ultrasonic systems, and optical/data-driven approaches. Each method is comparatively analyzed in terms of material compatibility, sensitivity to crack type, quantitative evaluation capacity, static/dynamic or real field/load/structure applicability, and system complexity. The cross-evaluation demonstrates that high quantitative accuracy, applicability under real field conditions, and low system complexity cannot be simultaneously achieved in most methods. Consequently, crack detection is evolving as a multidisciplinary research area at the intersection of materials science, sensor physics, and data-driven modeling, necessitating the development of holistic and application-specific sensing strategies in the future.

Keywords

Crack Detection, Electromagnetic Non-Destructive Testing (EM-NDT),
Magnetic Flux Leakage (MFL), Metal Magnetic Memory (MMM),
Quantitative Crack Characterization

1. Introduction

Cracks are among the most common and critical types of damage in engineering structures and industrial components. Particularly in safety-critical systems such as pipelines, rails, bridge elements, and welded joints, crack formation can occur as a result of fatigue, overloading, and environmental effects, and can lead to sudden and catastrophic failures if not detected early. Therefore, the early, reliable, and preferably quantitative detection of cracks has become one of the fundamental elements of modern maintenance and integrity management strategies.

Among the conventional nondestructive testing (NDT) methods, magnetic flux leakage (MFL), eddy current testing (ECT), and ultrasonic techniques have been widely used in the industry for many years. While MFL-based systems offer effective solutions, particularly in the in-line inspection of pipelines and the examination of thick-walled ferromagnetic structures [1]-[3], ECT and ACFM approaches play a significant role in the characterization of surface and near-surface cracks [4]-[6]. However, these methods have various limitations, such as detection depth, sensitivity to geometry, operator dependence, and applicability to in-service systems.

In recent years, alternative approaches based on electromagnetic field distortions have developed significantly. Direct current electromagnetic (DC-EM) and motion-induced eddy current techniques offer solutions for determining crack orientation and character, especially in moving ferromagnetic systems [7]-[9]. Similarly, metal magnetic memory (MMM) and weak magnetic field-based methods stand out as complementary approaches in monitoring fatigue cracks and stress concentration zones [10]-[12]. These methods draw attention in terms of enabling non-contact measurement and adaptability to dynamic systems.

For situations where electromagnetic methods are limited, alternative techniques such as induction thermography and magneto-optical imaging also hold a significant place in literature. DC-bias assisted induction thermography and similar configurations have presented promising results in detecting subsurface defects [13]-[15], while magneto-optical imaging systems enable the visual mapping of cracks [16] [17]. Furthermore, EMAT-based ultrasonic approaches and hybrid electromagnetic-ultrasonic systems have developed solutions for the non-contact and in-depth examination of internal defects [18] [19].

More recently, machine learning and data-driven analysis methods have been used in conjunction with electromagnetic and optical measurements to improve crack detection accuracy and develop automated evaluation processes [20]-[22]. However, the increase in methodological diversity has also led to a proliferation of fragmented studies in literature that focus on a specific sensor type or application.

A significant portion of existing review studies focuses on either a specific material type or a single sensor family. Yet the fundamental element determining crack detection performance is not the sensor type used, but rather the physical principle underlying the crack detection mechanism. The fact that the same sensor architecture can be used to observe different physical mechanisms, or that a specific method can be adapted to heterogeneous material groups, necessitates a method-based systematic classification.

In this study, a broad pool of literature published in the field of crack detection is systematically reviewed, and the studies are classified according to the fundamental physical mechanism of the sensing method used. The literature search was conducted across the Web of Science, Scopus, IEEE Xplore, and Google Scholar databases. Keywords such as "crack detection", "electromagnetic NDT", "magnetic flux leakage", "eddy current testing", and "sensor fusion for crack sensing", as well as their various combinations, were employed during the search. The scope of the review was limited to studies published between 2000 and 2025. Only peer-reviewed journal articles published in English and full-text conference proceedings were included in the analysis. Conversely, studies that did not focus on physical mechanisms remained solely at the simulation level, or lacked experimental validation were excluded from the scope of this work. In this study, Magnetic flux leakage-based methods, direct current electromagnetic and motion-induced techniques, eddy current and ACFM approaches, thermography-assisted electromagnetic methods, weak magnetic field-based techniques, magneto-optical and visual methods, as well as hybrid electromagnetic-ultrasonic and data-driven approaches, are discussed under separate headings. To maintain a focused technical depth, this review specifically targets crack-detection methods grounded in electromagnetic and magnetic physical principles. Consequently, purely acoustic or conventional ultrasonic methods (e.g., piezoelectric-based testing) are excluded from the primary analysis, as they rely on mechanical wave propagation rather than electromagnetic interaction. However, "borderline" hybrid techniques, such as Electromagnetic Acoustic Transducers (EMAT) and Thermo-electromagnetic NDT, are intentionally included. These cases are treated based on their sensing interface; for instance, EMAT-based ultrasound is discussed due to its non-contact electromagnetic induction mechanism, which aligns with the core physical focus of this study. Furthermore, while data-driven approaches are addressed, they are evaluated only when applied to the electromagnetic sensing modalities defined within our scope. This explicit boundary ensures a rigorous analysis of methods sharing a common physical foundation while preventing the dilution of technical insights across unrelated NDT families.

Furthermore, the reviewed studies are analyzed through comparative tables in terms of the material type used, sensor structure, crack type, quantitative evaluation capability, and application conditions. In this respect, the presented study aims not only to summarize the methods in the field of crack detection but also to evaluate them from the perspective of method-material-application compatibility, thereby revealing gaps in the literature and future research directions.

2. Method-Oriented Classification of Crack Detection Techniques

Crack detection studies in literature present a more systematic and comparable structure when classified based on the fundamental physical principles underlying the crack detection mechanism, rather than sensor configuration, the type of material investigated, or specific application areas. The fact that the same sensor architecture can be used to observe different physical mechanisms, or that a specific method can be adapted to heterogeneous material groups, necessitates a method-based classification. Accordingly, within the scope of this study, existing approaches are categorized with reference to their methodological foundations, and each technique is examined with an analytical approach within the framework of its own physical mechanism.

The methods investigated are structured under the following main headings in the remainder of the article:

1) Magnetic Flux Leakage (MFL)-based techniques,
2) Direct current (DC) electromagnetic and motion-induced methods,
3) Eddy Current Testing (ECT) and Alternating Current Field Measurement (ACFM) approaches,
4) Thermography-assisted electromagnetic methods,
5) Weak magnetic field and Metal Magnetic Memory (MMM) techniques,
6) Magneto-optical and visual magnetic imaging methods,
7) Hybrid electromagnetic-ultrasonic techniques and modern data-driven approaches.

Furthermore, to ensure a consistent and reproducible comparison, the studies analyzed in this review were categorized based on a predefined rubric. The “Quantitative Evaluation Capability” of each study was evaluated using three distinct labels: “Yes” was assigned to works providing precise numerical sizing (e.g., depth, width, or length) supported by experimental validation; “Partial” was used for studies offering relative numerical trends, signal-based estimations, or results primarily derived from simulations without full geometric reconstruction; and “No” was assigned to studies focusing on qualitative visualization, mapping, or the mere detection of a crack’s presence.

Similarly, “Inspection Conditions” were classified into three operational categories: “Static” conditions involve a stationary specimen during measurement, where sensor movement is intended solely for scanning purposes. "Dynamic" conditions describe systems where the specimen is in continuous motion, such as production line simulations involving wires or tubes. Lastly, "Real-field/Load/Structure" conditions were assigned to studies conducted under actual service environments or active structural stress, such as in-pipe PIG applications or bridges under live loading. These explicit decision rules ensure that the comparative analysis remains transparent and interpretable throughout the study.

2.1. Magnetic Flux Leakage (MFL)-Based Techniques

The Magnetic Flux Leakage (MFL) method is one of the most well-established nondestructive testing (NDT) techniques used for detecting surface and subsurface defects in ferromagnetic materials [23]-[25]. The fundamental physical principle of this method is based on the fact that when a material is magnetized to a level near saturation, geometric discontinuities such as cracks or corrosion create a high-reluctance region for the magnetic flux lines. Due to this reluctance, the magnetic flux deviates outward from the material, creating a "leakage field".

By measuring the gradient of this leakage field through Hall effect sensors, magneto resistive sensors, magneto-optical systems, or induction coils placed immediately above the surface, quantitative data regarding the depth, width, and orientation of the defect are obtained [26]-[28]. MFL has become an industrial standard, particularly in the inspection of pipelines (PIG technology) and the floor inspections of storage tanks, due to its high scanning speed and its nature that does not require surface cleaning [1]-[3] [29]. However, the sensitivity of the method is directly dependent on the magnetic saturation level of the material and the distance of the sensor from the surface (lift-off).

Various variants of MFL methods have been developed in literature. In addition to classical MFL applications, studies aiming at the reconstruction of 3D crack profiles have been reported, utilizing multi-directional and rotary magnetization systems, probes with adjustable magnetization angles, and high-resolution, broadband MFL approaches [30] [31].

Table 1. Evaluation of MFL studies: comparative analysis of crack geometries, quantitative accuracy, and operational constraints.

Ref.	Method Class	Material Type	Crack Type	Quantitative Evaluation Capability	Inspection Conditions
[32]	MFL	Ferromagnetic	Surface	Yes	Static
[33]	MFL	Ferromagnetic	Internal	Partial	Static
[1]	MFL	Ferromagnetic	Internal	Yes	Real field/load/structure
[34]	MFL	Ferromagnetic	Surface	Partial	Static
[29]	MFL	Ferromagnetic	Surface	Partial	Static
[30]	MFL	Ferromagnetic	Surface	Yes	Static
[2]	MFL	Ferromagnetic	Internal	Yes	Real field/load/structure
[23]	MFL	Ferromagnetic	Surface	Yes	Static
[35]	MFL	Ferromagnetic	Internal	Partial	Real field/load/structure

Continued

[31]	MFL	Ferromagnetic	Surface	Partial	Static
[36]	MFL	Ferromagnetic	Surface	Partial	Static
[26]	MFL	Ferromagnetic	Internal	Partial	Real field/load/structure
[37]	MFL	Ferromagnetic	Surface	Partial	Static
[25]	MFL	Ferromagnetic	Surface	No	Static
[3]	MFL	Ferromagnetic	Internal	Yes	Real field/load/structure
[38]	MFL	Ferromagnetic	Surface	No	Static
[39]	MFL	Ferromagnetic	Surface	Partial	Static
[28]	MFL	Ferromagnetic	Surface	Partial	Static

As seen in **Table 1**, the inspection conditions in this method are classified under three main headings: static, dynamic, and real field/load conditions. In static measurements, the specimen remains stationary during the measurement, regardless of whether it is in a laboratory or field environment; the movement of the sensor for scanning purposes does not render the system dynamic. Dynamic measurements, on the other hand, refer to systems where the specimen moves linearly (e.g., rail, wire, strip) or circularly (e.g., bearing, ring) during measurement, typically involving continuous production line simulations. Furthermore, in "real-field and load" conditions, although mobility is not a prerequisite, it is essential that the structure is examined under its actual service conditions (e.g., in-line PIG applications in pipes, bridge elements under load, or active systems under tension).

The reviewed literature is categorized based on the sizing of the crack profile and quantitative evaluation capacities. The studies numbered [1]-[3], which successfully quantify the depth and dimensions of internal defects in pipelines, and the study numbered [30], which reconstructs the 3D crack profile with geometric models, are classified as literature where quantitative measurement is fully achieved. Internal defect analyses [26] [33] [35], which are predominantly based on simulation and provide relative numerical data under complex field conditions, were found to be "partially" sufficient in terms of quantitative evaluation. In contrast, it was concluded that quantitative sizing is absent in the studies numbered [23] [25], and [38], which focus on field analysis, leakage flux mapping, detection of stress zones, and visualization rather than numerical crack measurement.

2.2. Direct Current (DC) Electromagnetic and Motion-Induced Eddy Current Methods

Direct current electromagnetic (DC-EM) and motion-induced eddy current methods are techniques developed specifically for crack detection in moving ferromagnetic systems. In these approaches, the magnetic field is distorted due to the current passing through the conductive material or the relative motion, and cracks are detected through these distortions.

In the literature, DC electromagnetic configurations based on the principles of drag effect and motion-induced eddy current have been reported with the aim of determining crack orientation and orientation-dependent detection characteristics in high-speed ferromagnetic materials [7]-[9] [40]. On the other hand, metal magnetic memory (MMM) and weak magnetic field-based methods have been widely used in studies focusing on monitoring fatigue-induced crack propagation and evaluating damage evolution [10]-[12] [41] [42]. These electromagnetic-based methods provide advantages particularly in continuously moving components such as rails, wire products, pipes, and rolling processes.

The prominent feature of these methods is their ability to provide additional information regarding crack orientation and geometry. However, the design of the systems is relatively complex, and magnetization stability as well as the accurate modeling of motion conditions are of critical importance.

Table 2. Evaluation of DC-EM and motion-induced eddy current methods: comparative analysis of crack geometries, quantitative accuracy, and operational constraints.

Ref.	Method Class	Material Type	Crack Type	Quantitative Evaluation Capability	Inspection Conditions
[7]	DC-EM/Motion-Induced EC	Ferromagnetic	Surface	Partial	Specimen moving (dynamic)/in experimental setup
[8]	DC-EM/Motion-Induced EC	Ferromagnetic	Surface	Partial	Specimen moving (dynamic)/in experimental setup
[40]	DC-EM/Motion-Induced EC	Ferromagnetic	Fatigue*	Partial	Specimen stationary
[9]	DC-EM/Motion-Induced EC	Ferromagnetic	Fatigue	Partial	Specimen moving (dynamic)/in experimental setup
[43]	DC-EM/Motion-Induced EC	Ferromagnetic	Surface	Partial	Specimen moving (dynamic)/in experimental setup

In this method, fatigue cracks were investigated in the context of rolling contact fatigue (RCF), crack propagation dynamics, and damage caused by cyclic loading. It is observed that absolute crack sizing was not performed in the studies focusing on the detection of crack orientation and characterization [7] [9] [40]; and the relationship between the signal and the crack remained relative in the studies where motion-induced eddy currents (EC) were modeled [8] and the high-speed factor was investigated [43]. In this context, the quantitative evaluation capability of these studies is classified as “partial” in the data of **Table 2**. The primary reason for this is that the motion-based methods in question produce relative metrics, such as crack orientation, relative size, and propagation tendency, rather than providing absolute crack depth. Despite these limitations in quantitative measurement, the method provides a unique operational advantage as it eliminates the necessity of stopping the system or the production line during testing. Therefore, the related approach is highly advantageous and functional in industrial applications that require continuous operation, such as rails, wire products, rolling lines, moving sheet/strip systems, and rotating equipment.

2.3. Eddy Current and Alternating Current Field Measurement (ACFM)-Based Techniques

Eddy Current Testing (ECT) and Alternating Current Field Measurement (ACFM)-based methods are widely used for crack detection in both ferromagnetic and non-ferromagnetic materials. In these methods, alternating magnetic fields induce eddy currents within the conductive material, and detection is performed based on the current distortions caused by cracks [6] [40].

In addition to classical ECT applications in the literature, advanced variants such as pulsed eddy current (Pulsed ECT), chirp-excited ECT, multi-frequency ACFM, and RACFM have been developed [4] [5] [44] [45]. These approaches offer advantages particularly in terms of detecting cracks with different orientations and improving the signal-to-noise ratio.

However, the detection depth of eddy current-based methods is limited, and the measurement performance is significantly affected by the lift-off distance. Therefore, the methods generally remain limited to surface and near-surface cracks [46] [47]. Alternating Current Field Measurement (ACFM) is a similar electromagnetic technique used to detect cracks on metal surfaces like ECT, but it is less affected by surface roughness.

Table 3. Evaluation of ECT and ACFM methods: comparative analysis of crack geometries, quantitative accuracy, and operational constraints.

Ref.	Method Class	Material Type	Crack Type	Quantitative Evaluation Capability	Inspection Conditions
[44]	ECT/ACFM	Ferromagnetic	Surface	Partial	Dynamic
[4]	ECT/ACFM	Ferromagnetic	Surface	Yes	Static
[46]	ECT/ACFM	Ferromagnetic	Surface	Partial	Static
[45]	ECT/ACFM	Ferromagnetic	Surface	Partial	Static
[47]	ECT/ACFM	Non-ferromagnetic	Subsurface	Yes	Static
[5]	ECT/ACFM	Ferromagnetic	Subsurface	Yes	Static
[48]	ECT/ACFM	Ferromagnetic	Surface	Yes	Static
[22]	ECT/ACFM	Ferromagnetic	Surface	Partial	Static
[49]	ECT/ACFM	Non-ferromagnetic	Subsurface	Partial	Static
[50]	ECT/ACFM	Ferromagnetic	Surface	Partial	Static
[6]	ECT/ACFM	Ferromagnetic	Surface	Yes	Static

Upon reviewing the relevant literature, it is observed that Eddy Current Testing (ECT) studies are predominantly conducted under static conditions (**Table 3**). In contrast, studies focusing on crack size estimation using the Alternating Current Field Measurement (ACFM) method, as well as reconstruction (inverse problem) analyses aiming to calculate the exact geometry of the internal crack from sensor signals, are classified as fully sufficient ("Yes") in **Table 3** in terms of quantitative evaluation capacity.

On the other hand, applications utilizing pulsed, chirping, or inclined sensor configurations can mostly provide partial ("Partial") quantitative evaluation. Structuring **Table 3** around these four fundamental criteria systematically prevents the investigated dynamic and alternating current-based methods from being confused with Direct Current Electromagnetic (DC-EM) techniques, while also clearly demonstrating their characteristic features that differentiate them from the Magnetic Flux Leakage (MFL) method.

2.4. Thermography-Assisted Electromagnetic Methods

In thermography-assisted electromagnetic methods, Joule heating caused by currents induced in a conductive material under electromagnetic excitation, and the subsequent thermal diffusion, are monitored via infrared (IR) cameras. Cracks and defects cause local distortions in current density and heat flow, creating a distinguishable thermal contrast compared to their surroundings. This approach offers significant advantages, particularly for the non-contact detection of subsurface and hard-to-reach defects.

In the literature, in addition to classical induction thermography, DC-bias assisted induction thermography, AC-DC combined magnetization, eddy current thermography (EC Thermography), and scanning thermographic configurations adapted for moving systems have been developed. The use of a DC magnetic field in conjunction with alternating excitation allows for the control of current distribution in ferromagnetic materials and the enhancement of crack-induced thermal contrast. Within this scope, successful applications aimed at detecting surface and subsurface defects and quantitatively estimating crack depth have been reported [8] [14] [15] [51]-[53].

The prominent advantages of thermography-assisted electromagnetic methods include non-contact measurement, rapid scanning of large areas, and sensitivity to subsurface defects. Conversely, measurement performance depends on the thermal properties of the material, excitation parameters, and environmental conditions. Due to the nature of thermal diffusion, spatial resolution decreases for deep defects, and the interpretation of thermal contrast can become complex. Therefore, the reliability of the method is, in most cases, supported by appropriate excitation strategies and advanced signal processing techniques [15] [52].

Table 4. Evaluation of thermography-assisted EM method: comparative analysis of crack geometries, quantitative accuracy, and operational constraints.

Ref.	Method Class	Material Type	Crack Type	Quantitative Evaluation Capability	Inspection Conditions
[51]	Thermography-Assisted EM	Ferromagnetic	Surface	Partial	Static
[13]	Thermography-Assisted EM	Ferromagnetic	Surface	Yes	Static

Continued

[52]	Thermography-Assisted EM	Ferromagnetic	Subsurface	Partial	Static
[14]	Thermography-Assisted EM	Ferromagnetic	Surface	Yes	Static
[46]	Thermography-Assisted EM	Ferromagnetic	Surface	Partial	Static
[15]	Thermography-Assisted EM	Ferromagnetic	Surface	Yes	Static
[53]	Thermography-Assisted EM	Ferromagnetic	Surface	Partial	Static
[49]	Thermography-Assisted EM	Non-ferromagnetic	Subsurface	Partial	Static

In thermography-assisted electromagnetic methods, the inspection conditions where the specimen is kept in a stationary position throughout the test are defined as a static measurement configuration (**Table 4**). In this setup, data acquisition and surface scanning operations are performed solely through the relative motion of the sensor, and the system is considered static since the investigated material remains stationary.

2.5. Weak Magnetic Field and Metal Magnetic Memory (MMM) Methods

Weak magnetic field and Metal Magnetic Memory (MMM)-based methods are distinguished from other electromagnetic techniques as they do not require external magnetization for crack and damage detection. These approaches are based on the measurement of residual magnetic field distributions formed as a result of stress, plastic deformation, and fatigue effects that ferromagnetic materials are subjected to under service conditions. Crack formation and propagation cause local distortion of the magnetic field, and these distortions can be detected through weak magnetic signals.

In the literature, MMM and weak magnetic field methods have been widely used, particularly for the determination of stress concentration zones, monitoring of fatigue damage, and evaluation of crack propagation. Applications cover large-scale and in-service structures such as pipelines, welded joints, bridge steels, and wire products [10]-[12] [25] [41] [42] [54]-[56].

A significant advantage of MMM methods is that measurements can be performed in service and non-contact. This feature offers substantial potential, especially in terms of maintenance planning and early damage detection in industrial facilities. However, the measured magnetic signals are strongly affected by the magnetic history of the material, environmental magnetic fields, and loading conditions. This situation complicates the interpretation of the signals and limits the quantitative evaluation capability of the methods.

In recent years, studies focusing on topics such as the extraction of quantitative signal features, modeling the effect of loading conditions, and investigating atomic-scale mechanisms have been reported in order to interpret MMM signals more reliably [11] [12] [41] [57]. While these studies contribute to a better understanding of the physical foundations of MMM-based methods, they also reveal the necessity for the standardization of these methods and the enhancement of comparability across different applications.

Table 5. Evaluation of Metal Magnetic Memory (MMM) and weak magnetic methods: comparative analysis of crack geometries, quantitative accuracy, and operational constraints.

Ref.	Method Class	Material Type	Crack Type	Quantitative Evaluation Capability	Inspection Conditions
[54]	Weak Magnetic/MMM	Ferromagnetic	Weld-related	Partial	Static
[55]	Weak Magnetic/MMM	Ferromagnetic	Weld-related	Partial	Static
[10]	Weak Magnetic/MMM	Ferromagnetic	Fatigue	Partial	Static
[41]	Weak Magnetic/MMM	Ferromagnetic	Fatigue	Partial	Static
[58]	Weak Magnetic/MMM	Ferromagnetic	Internal	Partial	Static
[56]	Weak Magnetic/MMM	Ferromagnetic	Fatigue	Partial	Static
[11]	Weak Magnetic/MMM	Ferromagnetic	Fatigue	Partial	Under load/Embedded crack/Service conditions
[42]	Weak Magnetic/MMM	Ferromagnetic	Fatigue	Partial	Static
[57]	Weak Magnetic/MMM	Ferromagnetic	Fatigue	Partial	Static
[12]	Weak Magnetic/MMM	Ferromagnetic	Fatigue	Partial	Static
[59]	Weak Magnetic/MMM	Ferromagnetic	Surface	Partial	Static
[60]	Weak Magnetic/MMM	Ferromagnetic	Weld-related	Partial	Static
[61]	Weak Magnetic/MMM	Ferromagnetic	Weld-related	Partial	Static
[62]	Weak Magnetic/MMM	Ferromagnetic	Fatigue	Partial	Static
[63]	Weak Magnetic/MMM	Ferromagnetic	Surface	Partial	Static
[25]	Weak Magnetic/MMM	Ferromagnetic	Surface	No	Static

Upon examining the fundamental principles of MMM theory and the relevant literature, it is observed that the absolute sizing of structural cracks is not the primary objective of the method (**Table 5**). However, the detection of local stress concentrations, the monitoring of fatigue-induced damage accumulation, and the characterization of the propagation tendencies of existing cracks can be performed highly effectively with this method. This situation ensures that the method maintains its validity and rationale within an analytical framework, despite its quantitative measurement limitations. Indeed, this monitoring mechanism plays a highly critical role in the observation of weld-related cracks occurring in the weld seam or the Heat-Affected Zone (HAZ).

2.6. Magneto-Optical and Visual Magnetic Methods

Magneto-optical and visual magnetic methods are present in the literature as approaches aiming at the direct visualization of magnetic field distortions caused by cracks. In these methods, magnetic field distributions formed on the ferromagnetic material are converted into images through magneto-optical sensors or media based on optical-magnetic interaction. Thus, cracks and defects can be detected intuitively and rapidly without the need for complex signal processing steps.

Magneto-Optical Imaging (MOI)-based methods enable the imaging of surface and near-surface cracks with high spatial resolution by utilizing magneto-optical principles such as the Faraday effect. These approaches have provided effective results, particularly in the visualization of cracks caused by rolling contact fatigue (RCF) in railway systems and large-surface ferromagnetic components [16] [17] [64].

In addition, approaches based on observing magnetic field distortions with the naked eye using optical media or ferrofluid-like visualization techniques have also been reported in the literature. These methods provide advantages for the rapid pre-screening of cracks and educational applications; however, in most cases, they remain limited to qualitative evaluation [38] [65].

The most important advantages of magneto-optical and visual magnetic methods are that they offer non-contact measurement, high intuitiveness, and rapid evaluation capabilities. Conversely, the fact that measurements are generally limited to the surface, the difficulty of quantitative crack characterization, and integration requirements in industrial environments are among the main limitations of these methods. Therefore, in most applications, these approaches are considered as complementary or pre-screening tools rather than independent nondestructive testing methods.

Table 6. Evaluation of Magneto-Optical (MOI) and visual methods: comparative analysis of crack geometries, quantitative accuracy, and operational constraints.

Ref.	Method Class	Material Type	Crack Type	Quantitative Evaluation Capability	Inspection Conditions
[16]	Magneto-Optical/Visual	Ferromagnetic	Surface	No	Static
[66]	Magneto-Optical/Visual	Concrete/Cement-based	Surface	No	Static
[67]	Magneto-Optical/Visual	Ferromagnetic	Surface	Partial	Static
[64]	Magneto-Optical/Visual	Ferromagnetic	Surface	No	Static
[17]	Magneto-Optical/Visual	Ferromagnetic	Fatigue	No	Static
[38]	Magneto-Optical/Visual	Ferromagnetic	Surface	No	Static
[65]	Magneto-Optical/Visual	Ferromagnetic	Surface	No	Static

In magneto-optical and visual magnetic methods, the inspection condition is static, and it has been observed that these methods are predominantly used in literature for visualization, intuitive crack detection, and rapid pre-screening applications (**Table 6**). In contrast, precise quantitative evaluations, such as crack depth in millimeters or numerical crack length, are lacking in the vast majority of existing studies. In particular, it is noteworthy that analytical (inverse problem) approaches aimed at determining the exact geometry and size of the internal crack based on sensor signal data are not sufficiently addressed.

2.7. Hybrid Electromagnetic-Ultrasonic (EMAT-Based) Methods

Electromagnetic-ultrasonic hybrid methods offer a complementary approach to crack detection and characterization by combining the advantages of electromagnetic excitation with the deep penetration capability of ultrasonic waves. The most widely used techniques in this group are systems based on Electromagnetic Acoustic Transducers (EMAT). EMATs provide significant advantages on coated surfaces and in challenging field conditions, thanks to their ability to generate and detect ultrasonic waves in conductive and ferromagnetic materials without contact.

In the literature, guided wave EMAT configurations aimed particularly at detecting internal defects in pipe- and plate-like structures have been reported. These approaches allow for the rapid inspection of large areas thanks to their long-range scanning capability and offer effective results in detecting inner surface cracks [19]. Furthermore, studies focusing on the development of high-energy pulse excitations and special probe designs to strengthen the interaction between electromagnetic excitation and the ultrasonic signal are also present in the literature [68] [69].

Another important branch of hybrid EMAT approaches consists of multi-sensor configurations where electromagnetic methods (e.g., MFL) are used in conjunction with ultrasonic detection. In such systems, near-surface defects are detected using electromagnetic methods, while deeper or internal defects are evaluated via ultrasonic waves. Thus, complementary detection is ensured for defects at different depths [18].

The primary advantages of EMAT-based hybrid methods stand out as non-contact measurement, the ability to operate on high-temperature and coated surfaces, and sensitivity to deep defects. Conversely, relatively low ultrasonic wave generation efficiency, system complexity, and high signal processing requirements are the main limitations of these methods. Therefore, in most applications, EMAT-based approaches are considered hybrid systems used together with electromagnetic or optical methods rather than as standalone solutions.

Table 7. Evaluation of hybrid EMAT and ultrasonic methods: comparative analysis of crack geometries, quantitative accuracy, and operational constraints.

Ref.	Method Class	Material Type	Crack Type	Quantitative Evaluation Capability	Inspection Conditions
[18]	Hybrid EMAT/Ultrasonic	Ferromagnetic	Subsurface	Partial	Static
[19]	Hybrid EMAT/Ultrasonic	Ferromagnetic	Internal	Partial	Static
[68]	Hybrid EMAT/Ultrasonic	Ferromagnetic	Internal	Partial	Static
[69]	Hybrid EMAT/Ultrasonic	Ferromagnetic	Internal	Partial	Static

When the existing literature based on ultrasonic inspection techniques is evaluated, it is understood that the capacity for absolute depth measurement and high-precision geometric sizing of defects is limited in the vast majority of studies.

Additionally, the common feature of all examined experimental approaches is that the testing procedures are conducted entirely under controlled laboratory conditions, and a static measurement principle where the specimen is kept in a stationary position throughout the inspection is adopted (**Table 7**).

2.8. Optical and Data-Driven Approaches

Optical and data-driven approaches are present in the literature as methods that do not directly rely on electromagnetic field measurement for crack detection but rather focus on the analysis of visual information or numerical data patterns. In these methods, cracks are detected and evaluated based on the geometric discontinuities they create on the surface, deformation fields, or image-based characteristics.

Among the optical-based methods, Digital Image Correlation (DIC), high-resolution camera systems, and optical profilometry-based approaches stand out. These techniques offer advantages particularly for the detection of surface cracks and the quantitative measurement of crack opening, length, or displacement fields [20] [37]. However, the fact that measurements are limited to the surface and sensitivity to lighting conditions are among the fundamental constraints of these methods (**Table 8**).

In recent years, studies focusing on the processing of data obtained from optical and electromagnetic measurements using machine learning (ML) and deep learning (DL)-based algorithms have also increased. These approaches enable the automatic identification, classification, and measurement of cracks, making it possible to achieve high accuracy, especially on large datasets [21] [22] [70]. Furthermore, through multi-level classification and feature extraction techniques, it has become possible to differentiate between various types of defects.

However, the success of data-driven approaches largely depends on the quality of the training data, labeling accuracy, and compatibility with application conditions. Variations in material type, surface condition, and imaging conditions can limit the generalizability of the models. Therefore, it is observed in the literature that data-driven methods are considered complementary analysis tools used in conjunction with physics-based methods, rather than standalone nondestructive testing solutions.

To ensure the reliability and reproducibility of data-driven crack detection, studies must adhere to a rigorous validation framework. At a minimum, reporting should include dataset provenance, the labeling procedure, and a clear train/test/validation split strategy to avoid data leakage. Furthermore, robustness checks are essential to evaluate model performance under variations in material properties or surface roughness. A critical challenge in this domain is the "domain-shift" risk, which can be mitigated by integrating physics-informed constraints, such as Maxwell's equations, into the model architecture. Additionally, leveraging synthetic data from high-fidelity simulations for pre-training, followed by fine-tuning on limited experimental datasets, significantly reduces the gap between simulated and service conditions, thereby enhancing the model's transferability across heterogeneous material groups.

Table 8. Evaluation of optical and data-driven methods: comparative analysis of crack geometries, quantitative accuracy, and operational constraints.

Ref.	Method Class	Material Type	Crack Type	Quantitative Evaluation Capability	Inspection Conditions
[20]	Optical/Data-Driven	Ferromagnetic	Surface	Yes	Static
[21]	Optical/Data-Driven	Multi-material	Surface	Partial	Static
[67]	Optical/Data-Driven	Ferromagnetic	Surface	Partial	Static
[70]	Optical/Data-Driven	Ferromagnetic	Surface	Partial	Static
[37]	Optical/Data-Driven	Ferromagnetic	Surface	Partial	Static
[22]	Optical/Data-Driven	Ferromagnetic	Surface	Partial	Static

3. Cross-Analysis and Critical Discussion

In this section, the studies summarized in the tables above are cross-analyzed in terms of method-material compatibility, quantitative evaluation capability, applicability, and practical integration (with respect to inspection conditions). The objective is to reveal the relative strengths and weaknesses of different electromagnetic and related approaches and to evaluate current trends in literature from a critical perspective.

3.1. Method-Material Compatibility

Comparative analysis demonstrates that crack detection methods are largely focused on ferromagnetic materials. In particular, MFL, DC-EM, MMM, and magneto-optical methods have been predominantly utilized in this material group, as magnetic properties are a direct part of the measurement mechanism. In contrast, eddy current (ECT/ACFM) and optical/data-driven approaches offer a more flexible application range for non-ferromagnetic materials and composite structures. This situation indicates that method selection in literature is often dictated by physical suitability; however, as material diversity increases, the need for hybrid and complementary approaches becomes more apparent.

3.2. Comparison in Terms of Quantitative Evaluation Capability

One of the clearest results revealed by the tables is that absolute quantitative crack sizing is possible with only a limited number of methods. MFL and some advanced ECT/ACFM approaches allow for the numerical estimation of crack depth or geometry under appropriate conditions. Thermography-assisted electromagnetic methods, particularly in combination with DC-bias applications, also offer potential for quantitative evaluation within certain depth ranges.

In contrast, MMM and magneto-optical methods are mostly based on relative metrics (the method does not provide the absolute size of the crack in mm; instead, it measures the relative change of a physical quantity associated with the crack). These methods can reliably detect and monitor damage processes such as crack propagation, fatigue damage, or stress concentration. However, in most cases, the determination of crack depth or geometry in terms of absolute numerical values remains limited. This situation indicates that there is still a distinct separation between crack detection and quantitative characterization in literature.

3.3. Static vs. Dynamic Approaches and Applicability (Real Field/Load/Structure)

It is observed that a large majority of the methods have been developed under static conditions. While this provides an advantage for controlled experiments in a laboratory environment, it is limited in terms of direct transfer to real industrial applications. Methods adapted to dynamic conditions, particularly DC-EM and motion-induced eddy current approaches, offer significant potential for moving ferromagnetic components.

Real-field/load/structural applications, on the other hand, are relatively limited and are mostly encountered in MFL and MMM-based studies. This observation indicates that the balance between high sensitivity and field applicability has not yet been fully established in the literature. It is noteworthy that in many methods, laboratory success cannot be sustained to the same extent under field conditions.

3.4. Sensor Complexity and Practical Applicability

Cross-analysis reveals a distinct inverse relationship between the practical applicability of methods and the complexity of sensors and systems. Although EMAT-based hybrid systems and thermography-assisted electromagnetic approaches are technically robust, they offer more complex solutions in terms of system integration and cost.

In contrast, MFL and some optical/visual methods have gained wider industrial acceptance due to their relatively simple hardware. However, this simplicity often comes with limited quantitative information. This situation points to an ongoing search for a balance in the literature between "high accuracy-high complexity" and "high practicality-limited information".

Table 9. Comparative analysis of crack detection methods.

Method Class	Fundamental Physical Mechanism	Typical Material Content	Detection Capability	Quantitative Capability	Static/ Dynamic/ Real-Field-Load-Structure Applicability*	System Complexity	Typical Role in Practice
MFL	Magnetic flux leakage due to geometric discontinuities	Ferromagnetic	High	Medium-High	High	Medium	Industrial inspection and crack sizing in pipelines and large structures

Continued

DC-EM/ Motion-Induced EC	Motion-induced electromagnetic field perturbation	Ferromagnetic	High	Medium (relative metrics)	High	Medium-High	Crack detection and orientation assessment in moving components
ECT/ACFM	Eddy current redistribution under AC excitation	Conductive (ferro & non-ferro)	Medium-High	Medium	Low-Medium	Medium	Surface and near-surface crack characterization
Thermography-Assisted EM	Joule heating and heat diffusion induced by EM fields	Ferromagnetic	Medium-High	Medium	Low	High	Subsurface defect screening and depth trend analysis
Weak Magnetic/MMM	Residual magnetic field caused by stress and plastic deformation	Ferromagnetic	Medium	Low (relative metrics)	Medium-High	Low	Fatigue damage and stress concentration monitoring
Magneto-Optical/Visual	Visualization of magnetic field disturbances	Ferromagnetic	Medium	Low	Low	Low	Rapid screening and qualitative crack visualization
Hybrid EMAT/ Ultrasonic	Ultrasonic wave propagation generated by EM excitation	Ferromagnetic	Medium-High	Medium	Low-Medium	High	Internal and subsurface defect detection
Optical/ Data-Driven	Image-based or data-driven pattern recognition	Material-independent	Medium	Medium	Low	Medium	Automated crack detection and assessment support

Note: * The relevant metric was established to demonstrate the adaptation capacity of the investigated methods under different environmental and operational constraints. Within the context of the classification criteria, methods whose practical application is restricted solely to stationary (static) laboratory conditions are evaluated in the "Low" category. Methods that can be integrated into dynamic processes or demonstrate flexibility under semi-field conditions are defined with a "Medium" rating. On the other hand, methods with applicability competence to be directly implemented in both dynamic systems containing moving components and real-field, active loading, and operational structural conditions are distinguished by being included in the "High" classification.

The combined comparison presented in **Table 9** clearly demonstrates that the performance of crack detection methods cannot be evaluated on a single axis. There are distinct trade-offs between the detection capability, numerical characterization potential, and the static/dynamic or real field/load/structural applicability of the methods. For instance, while MFL and DC-EM-based approaches stand out in terms of high detection power and real-field/load/structural applicability, the numerical characterization capabilities of these methods remain limited in most cases by certain assumptions and relative metrics. In contrast, ECT/ACFM and some thermography-assisted electromagnetic methods can provide more detailed numerical information under controlled conditions. However, their adaptation to dynamic or real field/structural environments proves to be relatively more challenging.

Weak magnetic field and magneto-optical approaches play a significant complementary role in monitoring processes such as crack propagation, fatigue damage, and stress concentration, yet they remain limited in determining absolute crack dimensions. Similarly, although hybrid EMAT and optical/data-driven methods offer robust solutions for specific defect types, they are far from being a general-purpose solution due to system complexity and their sensitivity to application conditions. These findings indicate that research on crack detection in literature does not converge around a single optimal method; instead, it requires a multi-criteria method selection specific to the application scenario.

Overall, the synthesis in Table 9 reveals that crack detection gains significance not only through detection sensitivity but also by establishing a balance between numerical data generation, operational applicability, and system complexity. This situation suggests that it is inevitable for future research to lean towards holistic and flexible sensing strategies that combine different physical principles, rather than merely pushing the boundaries of individual methods.

3.5. Technical Challenges and Mitigation Strategies in Practical Deployment

To bridge the gap between laboratory success and field reliability, the inherent physical limitations of each method class must be addressed. For MFL and DC-EM techniques, the primary constraint is magnetization history and material-dependent magnetic non-linearity, which can obscure small crack signals. Mitigation involves the use of saturation-level excitation and advanced differential sensor configurations to suppress background noise. In ECT/ACFM applications, lift-off sensitivity remains the dominant error source, often leading to false positives or misinterpreted crack depths. This is typically mitigated by employing multi-frequency excitation or lift-off compensation algorithms that decouple distance-induced signals from defect-induced impedance changes.

For thermography-aided electromagnetic methods, the rapid thermal diffusion in high-conductivity materials limits the detectable depth of sub-surface cracks. This constraint is addressed by using high-power pulse excitation or lock-in signal processing to enhance the signal-to-noise ratio in deeper layers. In motion-induced and dynamic sensing, motion effects (velocity-induced currents) introduce complex electromagnetic drag forces that distort the primary sensing field. Implementing real-time velocity compensation models or high-speed sampling synchronized with displacement is essential for maintaining interpretability during high-speed inspections. Finally, the interpretability of weak magnetic fields and magneto-optic methods is often hindered by ambient magnetic noise, requiring robust magnetic shielding or gradiometric sensor arrays to ensure successful transfer to noisy industrial service conditions.

3.6. General Evaluation and Gaps in Literature

The literature reviewed in this study clearly demonstrates that although numerous methods for crack detection have been developed, no single method can satisfy all requirements simultaneously. High quantitative accuracy, real field/load/structural applicability, and system simplicity emerge as objectives that are generally in conflict with one another.

Electromagnetic, magneto-optical, and hybrid methods, in particular, stand out in the literature. However, the performance of these methods varies significantly depending on material properties, crack geometry, and measurement conditions. This situation reveals that crack detection is not merely a measurement problem; it is an interdisciplinary research field situated at the intersection of materials science, physics, and sensor engineering.

In this context, the prominent gaps in literature can be summarized as follows:

1) Insufficient quantitative modeling of physical interaction mechanisms.

2) The inability to transfer the high sensitivity achieved under laboratory conditions to real field/load/structural conditions with the same degree of success.

3) The limited availability of standardized performance metrics for the comparison of different methods.

4. Conclusion

Studies on crack detection in engineering materials are being continuously advanced by hundreds of technical papers published worldwide each year. A significant portion of these studies focuses on expanding the boundaries of sensor technologies by centering on the material-method-sensor interaction rather than solely on the detection methods used. It is observed in the literature that not only have measurement parameters been improved for crack detection, but numerous approaches based on different physical principles have also been developed. Especially in electromagnetic, magneto-optical, and hybrid methods, a deeper understanding of the crack-material interaction necessitates physics-based modeling and multi-scale analysis, moving beyond classical engineering approaches. In this context, it is noteworthy that advancements in material properties and developments in sensor designs have become a mutually reinforcing process, where new sensor concepts are often built upon the gains achieved in material physics. The literature reviewed clearly demonstrates that crack detection has evolved from being merely a measurement problem into a multidisciplinary research field situated at the intersection of materials science, physics, and sensor engineering.

5. Recommendations for Future Work

Research on crack detection in engineering materials is increasingly moving away from being a mere engineering problem focused solely on improving detection accuracy. Instead, it is evolving into an interdisciplinary research field that requires an understanding of the multiscale and multiphysical nature of material behavior. Current literature indicates that sensors and measurement approaches used in crack detection have evolved largely in tandem with advancements in material properties and the physical modeling of these properties. In this context, future studies are expected to focus not only on developing new sensor geometries or algorithms but also on physics-based approaches that explain the crack–material–field interaction at a more fundamental level.

In the coming period, it is anticipated that crack detection systems will be shaped around solutions aimed at establishing a balance between absolute quantitative characterization, applicability, and system complexity. Toward this goal, it is likely that hybrid sensor concepts—where electromagnetic, thermal, mechanical, and optical information are evaluated together—as well as data-driven approaches supported by physics-based models, will become more prevalent. However, for such developments to be sustainable and comparable, the necessity for defining measurement metrics, standardizing experimental conditions, and addressing inter-method performance benchmarks in a more systematic manner is clearly evident.

Broadly speaking, the future of the crack detection field is seen to be built upon holistic and flexible sensing strategies adapted to material types, damage mechanisms, and application conditions, rather than a single superior method. This approach positions crack detection not just as a non-destructive testing problem, but as a field of discovery where materials science and sensor physics advance together.

1) In future studies, integrating the physical mechanisms behind electromagnetic and thermal measurements with machine learning and data-driven models will play a critical role both in advancing quantitative crack characterization and in producing generalizable solutions across different materials.

2) The transformation of methods offering high sensitivity in laboratory environments into sensor architectures that can operate reliably under moving and real-service conditions will be one of the fundamental factors determining the industrial applicability of crack detection technologies.

3) For the fair comparison of different methods in terms of detection, quantitative characterization, and applicability, it appears inevitable for the field to mature by establishing more systematic and standardized definitions for measurement metrics and experimental conditions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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