

Review Article

Nondestructive Testing for Corrosion Evaluation of Metal under Coating

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The use of steel has grown rapidly over the past decades. However, corrosion under coating detection still presents challenges for nondestructive testing (NDT) techniques. One of such challenges is the lift-off introduced by complex structures. Inaccessibility due to structure leads corrosion to be undetected, which can lead to catastrophic failure. Furthermore, lift-off effects reduce the sensitivities. The limitations of existing NDT techniques heighten the need for novel approaches to the characterization of corrosion. This paper begins with a discussion of the challenges associated with corrosion detection of metal under coating. Secondly, reviews are given of the most NDT methods used for the detection of corrosion under coating. The different techniques based on nondestructive testing methods such as ultrasonic, acoustic, electromagnetic, radiographic, and thermographic have been detailed out. This review presents the significance and advantages provided by the emerging NDT techniques. In the end, the trends and identified problems are summarized.

1. Introduction

Nondestructive testing (NDT) refers to the implementation of the defect detection of material, which at the same time does not affect the material's future performance. Corrosion is the deterioration in material properties due to interaction with the environment [1] and materials which corrode including metals and alloys, nonmetals, woods, ceramics, plastics, and composites [2]. For many applications, the preferred metal is still mild steel with its virtues of relatively low cost, mechanical strength, and ease of fabrication. The fact that it corrodes easily is the main drawback, which means that it rapidly loses strength which readily leads to structural failure. Therefore, steel or other metal structures such as vessels are typically coated to control corrosion. The purpose of coating is to prevent corrosion from occurring by inserting a barrier between the environment and the metal surface. Although coating provides a high level of protection against corrosion, the metal is still prone to corrosion. This form of corrosion occurs on steel under coating, and it is very difficult to detect due to the cor-

rosion being concealed by the coating layer. The development of undetected corrosion can lead to serious failure. Serious consequences include the risk to the safety of persons, damage to the environment, and economic impacts.

Undetected corrosion may develop beneath coating which can lead to failure without curb. When steel is in contact with water and oxygen, it is likely to corrode. In order to improve the efficiency of examination, various NDT methods have been adopted to detect corrosion under coating without removing [3–5], each of which has different capabilities. These NDT techniques are then used to target problem areas where further inspection is needed.

In order to improve the reliability of coated metal, NDT approaches are used to investigate the existence of corrosion. The overall structure of this paper include the following: Section 2 of this paper will present the challenges posed by CUI. Section 3 reviews the development of nondestructive techniques with case studies. Then, the comparison and discussion have been provided in Section 4. Trends are in Section 5. Finally, the conclusions are outlined.

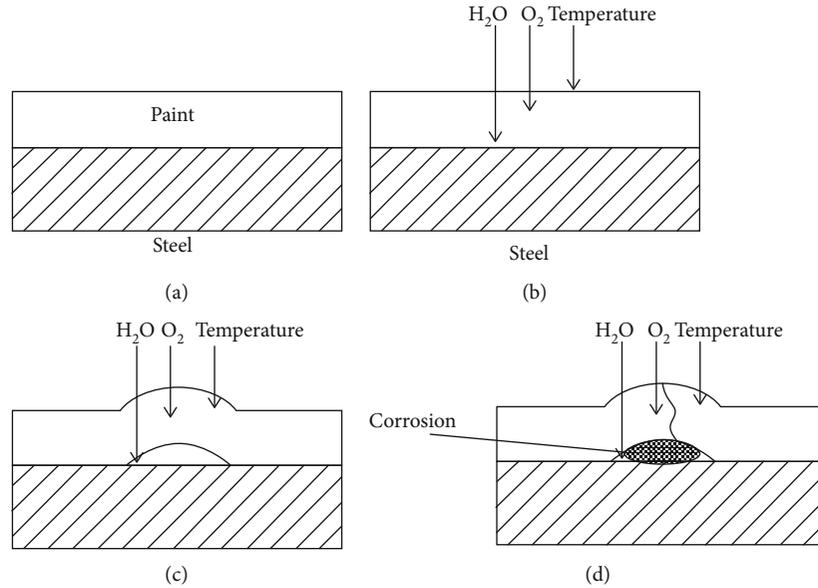
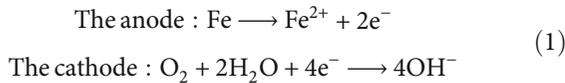


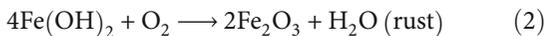
FIGURE 1: The mechanism of corrosion formation.

2. Challenges Posed by Corrosion under Coating

Unfortunately, metals are susceptible to corrosion. The occurrence of reactions among the metal surface, oxygen and water will result in the loss of electrons and the transformation of metal atoms into metal ions. Examples of the mechanisms of corrosion are [1]:



Corrosion is formed by the interaction of positively charged Fe^{2+} ions with negatively charged OH^{-} ions, as in $\text{Fe}^{2+} + 2\text{OH}^{-} \longrightarrow \text{Fe}(\text{OH})_2$. The hydroxide is insoluble and separates from the electrolyte. A more familiar name for $\text{Fe}(\text{OH})_2$ is a rust, white-green precipitate. With further access to oxygen, $\text{Fe}(\text{OH})_2$ oxidizes to ferric hydroxide $\text{Fe}(\text{OH})_3$, which in turn converts to Fe_2O_3 (reddish-brown rust) and H_2O :



Different types of corrosion, such as Fe_3O_4 (black magnetite), $\gamma\text{-Fe}_2\text{O}_3$ (brown rust), and $\gamma(\text{FeOOH})$ (yellow rust), are observed depending on the nature of the interaction in the environment, and the general mechanism of corrosion formation is shown in Figure 1. Metal can be affected by corrosion in many different ways, depending on the nature of corrosion and the prevalence of specific environmental conditions.

Various techniques such as electrochemical impedance spectroscopy [6, 7] can be used to determine the condition of the metal and determine the level/severity of any corrosion. Challenges of NDT for detection under coating are diverse. Along with the usual challenges of accurately detecting and quantifying corrosion, the task is made more difficult

due to the large distance between the sensor and the metal surface introduced by the inaccessible coating layer. This distance is known as the lift-off. The immediate effect of a large lift-off is the reduction in sensitivity to small changes accompanying corrosion, such as variation in thickness or loss of mass. Meanwhile, the thickness of the coatings may be different, resulting in variations in lift-off leading to lift-off effects. This lift-off effect will cause errors in detection.

In addition, the challenges associated with the characterization of metal corrosion require an understanding of the microstructural and physical changes occurring prior to corrosion initiation and growth. In most cases of corrosion, changes in the intrinsic material properties are dominant in the early stages. Physical damages such as defects will be observable when the accumulation of these changes exceeds a critical limit. Therefore, there is no universal method for the detection of corrosion under coating because the behaviour of corrosion is affected by the mix of these diverse factors.

To detect corrosion on the metal surface under coating, NDT is a powerful tool. In the next section, the state-of-the-art NDT techniques for detecting corrosion in metal are reviewed. The advantages and disadvantages of each method are summarized, followed by the challenges for the evaluation and monitoring of metal underlying coating.

3. State-Of-The-Art NDT Techniques

Several NDT techniques have been applied for corrosion detection, and each has certain advantages and disadvantages. For example, eddy current-based techniques have been used for corrosion inspection, where a relatively small probe is employed and no physical contact with the specimen is needed [8]. However, these methods can only be used to detect corrosion on the surface or near-surface. Furthermore, they are sensitive not only to variations in conductivity and

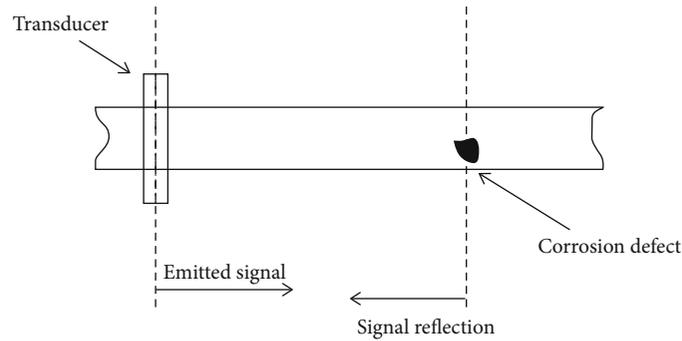


FIGURE 2: Ultrasonic testing for corrosion detection [10].

magnetic permeability of the specimen, but also to lift-off variations.

3.1. Ultrasonic Testing (UT). Ultrasonic testing is based on generating and detecting mechanical waves or vibrations within samples under test. These samples are not limited to solids. A majority of ultrasonic techniques adopt 1 MHz to 100 MHz as operating frequencies. The term ultrasonic refers to those sound frequencies beyond human hearing restrictions. The traveling speed of ultrasonic waves in a material is dependent on the material's density and elastic modulus. Therefore, ultrasonic methods are very suitable for the characterizing properties of materials. Furthermore, changes in material properties will strongly reflect ultrasonic waves at the boundaries. Thus, ultrasonic methods are often used for the measurement of thickness and corrosion monitoring [9].

Although UT has the capability to detect corrosion, these methods suffer from a difficulty in distinguishing between reflections from surface/near-surface corrosion and reflections from multiple material surfaces. Another disadvantage is that they require coupling media such as water or gel to acoustically couple pulses from the transducer to the material. This makes traditional UT unsuitable for certain situations due to the requirements for surface preparation. Much work has been done in recent years to develop noncontact ultrasonic techniques for defect characterization without requiring surface preparation. Air-coupled techniques include adaptations of traditional piezoelectric transducers [10], which are more suitable for most inspection conditions. However, an appropriate angle for the introduction of the ultrasound into samples to be inspected is a strict requirement. As shown in Figure 2, an experimental set to measure corrosion through guided acoustic waves in pipe has been reported. Guided acoustic waves are emitted by a ring transducer which run through the pipe. When a corrosion is encountered by waves on the pipe walls, they are reflected and returned to transducer.

Electromagnetic acoustic transducers (EMATs) have also been developed, in which electromagnetic noncontact transducers are used to generate and receive acoustic signals, although this does mean that EMATs are limited to electrically conductive materials. A modified variational mode decomposition (VMD) linked wavelet method is proposed by Si et al. [11] for EMAT denoising with a large lift-off

detection condition. High-frequency narrowband noise in EMAT signals can be suppressed too. By using an ultrasonic B-scan method, short-time Fourier transform (STFT) is used by Le et al. to analyze the ultrasonic signal for pitting corrosion detection in a multilayer structure [12].

Nowadays, developments in the field of ultrasonic techniques has led to phased array ultrasonics in instruments which can be portable [13]. The precise tailoring of ultrasonic waves is introduced into the sample by using the phased firing of ultrasonic arrays in one transducer. To and Dang [14] used a phased array ultrasonic probe for the detection and sizing of stress corrosion cracks in fuel tank. This method employs a single phased array probe with focal laws for two kinds of sectorial scans (S-scans) separately based on transverse and longitudinal wave velocities. The transverse wave S-scan with an angle beam transverse wave method is used for the detection of stress corrosion cracks. The longitudinal wave S-scan uses a multiple beam method to determine the size of stress corrosion cracks.

3.2. Laser Ultrasonic. Given recent advances in laser ultrasonic techniques, lasers can be used to generate and detect ultrasonic waves [15]. This noncontact technique has been used for the measurement of material thickness, flaw detection, and materials characterization. A laser ultrasonic system is composed of a laser ultrasonic generator and an interferometric sensor.

Liu et al. [16] employed laser ultrasonics for the detection and locating of internal corrosion in hollow metallic components. 125 MHz piezoelectric transducers and broad band laser-ultrasonic are adopted to generate ultrasonic waves which will interact with corrosion, and then changes in generated wave-modes are examined using time-frequency analysis techniques. In a laser-ultrasonic method, as shown in Figure 3, laser beams are generated and detected at the front side where reflection mode is utilized. A pulsed Nd:YAG laser is used to generate ultrasound. A laser ultrasonic receiver (TEMPO) is used to detect the reflected ultrasound. A time-varying analog voltage is produced by the detector which is proportional to the instantaneous displacement at ultrasonic frequencies.

The geometric images of corrosion can be provided by scanning the samples for corrosion identification. The limitation of this technique is that access to the surface of the

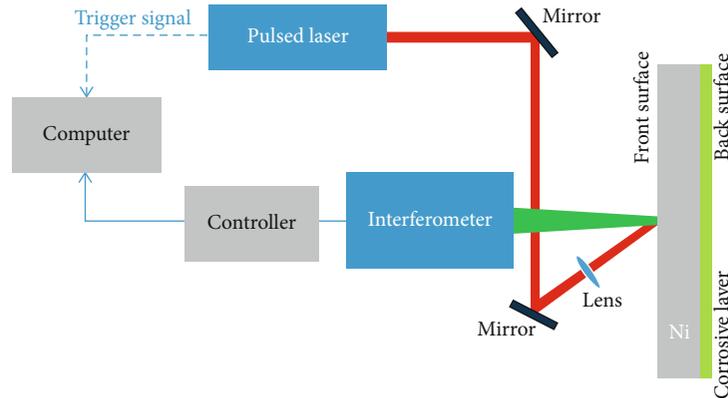


FIGURE 3: Schematic for laser-ultrasonic corrosion detection [16].

sample under test is required. Furthermore, this technique is sensitive to surface-breaking defects, and thus, its scope is limited.

3.2.1. Acoustic Emission (AE). AE is defined as strain energy suddenly released within or on the surface of a material, which generates a transient elastic wave. Therefore, the dynamic process associated with the degradation of a structure can be detected by AE. When an external stimulus, such as a change in pressure, load, or temperature, is applied to a structure, an energy released causes localized sources to form stress waves, and these waves then propagate to the surface, where sensors are used to record them.

In the majority of studies, AE techniques have been used to detect pitting corrosion. Zhang et al. [17] evaluated acoustic emission waveform for stress corrosion cracking monitoring in 304 stainless steel. As shown in Figure 4, the AE signals were collected by a mounted wideband AE sensor (Physical Acoustics Co.), and then through a preamplifier, an acquisition device was used to capture the AE signals. Wu and Byeon [18] used an AE technique to monitor progression of pitting corrosion in austenitic stainless steels. They confirmed that AE can be applied in fundamental research on pitting corrosion because it offers many potential advantages over other techniques. Zaki et al. [19] demonstrated the effectiveness of AE in the corrosion detection of concrete structures at an early stage.

The AE technique can be used to detect corrosion occurring in real time giving it an advantage over other NDT method. Unfortunately, AE systems can only be used for qualitative testing. Additional NDT methods are required to obtain quantitative results in regard to the size and depth of corrosion. Furthermore, environment noise affects the AE signals received. Therefore, the use of signal discrimination and noise reduction techniques is essential during real-world applications.

3.3. Eddy Current (EC). Eddy current technique is one of the most effective methods for the detection and characterization of surface defects and corrosion in conductive samples. This technique is based on holding a conducting coil with alternating currents close to the sample. A primary magnetic field is established in an axial direction around the coil. This elec-

trical current then creates its own secondary magnetic field, which is opposite in direction at all times and opposes the coil's magnetic field in accordance with Lenz's Law, as illustrated in Figure 5 [20]. The interaction between the magnetic field generated by the coil and the magnetic field generated by eddy currents is then examined with sensors or coils.

EC methods can be very effective and have been adopted to detect the presence of corrosion on the surface of metal samples. Thus, EC methods are the most common NDT methods which have become extremely portable and relatively inexpensive. Raude et al. employed advanced eddy current array technology for stress corrosion cracking inspection [21]. However, conventional EC techniques have difficulties detecting and quantifying small metal loss due to corrosion in multilayer structures. This is because the ability of EC techniques to detect subsurface defects is largely determined by the skin effect phenomenon. Most of the current flow occurs on the surface of a conductor due to the skin effect, exponentially decaying with increasing depth.

The development of EC technology has led to the introduction of the pulsed eddy current (PEC). This is a natural evolution of EC method and has been developed to improve penetration depth. With conventional EC methods, a fixed frequency sinusoidal current is used to generate eddy currents on the surface of a conductor. However, in PEC, the shape of the excitation current is a square pulse or step function. Looking at the Fourier transform of a step function, it is clear that it contains a continuum of frequency components compared to just one for sinusoidal EC. Because penetration depth is dependent on operating frequency, the PEC response signal will contain information from multiple depths, which is thus equivalent to multiple-frequency EC. The detection capabilities of PEC have been demonstrated in corrosion characterization [22]. PEC can be automated, and it has the advantages of greater penetration, the ability to locate corrosion, and only moderate cost.

Grosso et al. [23] have presented the results of a method based on a multifrequency eddy current along with signal processing to characterize iron oxide in a petrochemical storage tank. The thicknesses of the individual layers of the lap joint have been mapped with this technique. The result shows that corrosion can be quantified with an error of less than 5% for different corrosion thickness. Furthermore, recent developments

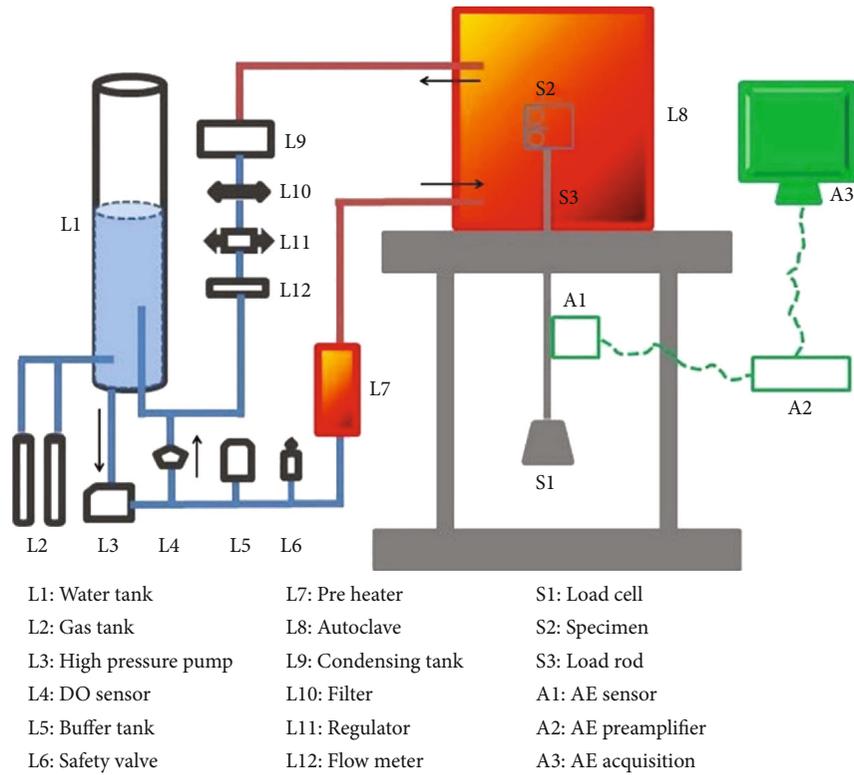


FIGURE 4: Experimental setup of in situ AE corrosion monitoring system [17].

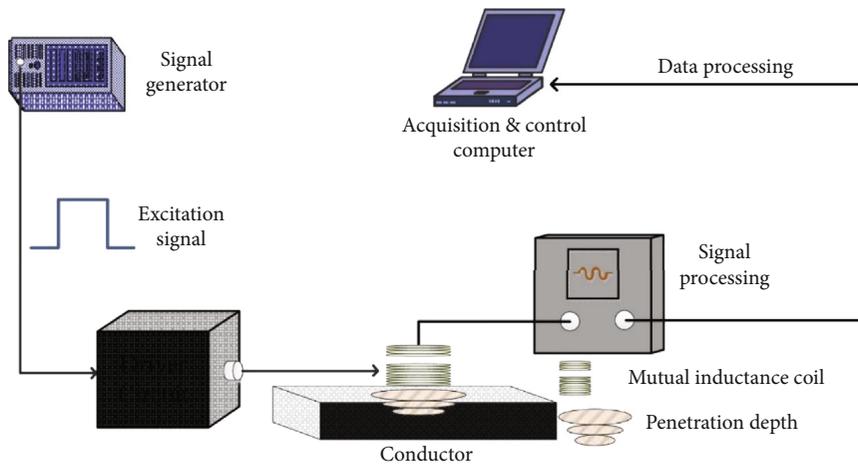


FIGURE 5: Schematic for eddy current corrosion detection [20].

in eddy current technology have led to multichannel portable instruments which allow the faster inspection of larger areas. Meanwhile, new magnetic sensors have been developed to replace coils [24], such as giant magneto resistive (GMR) sensors. Bailey et al. have investigated GMR sensor array to characterize corrosion of pipes under coating [25]. Rifai et al. have reviewed and described the implementation of GMR sensors in detail [26]. However, EC-based methods are limited to electrically conducting materials. Furthermore, these methods are very sensitive to lift-off effects, and the surface of the material must be accessible.

3.4. Magnetic Flux Leakage (MFL). MFL is a derivative of magnetic particle inspection (MPI). It is based on measuring the leakage of magnetic flux caused by the presence of corrosion. In practice, magnetisation is provided by a permanent magnet or an electromagnet by DC, AC, or pulsed excitation. The difference between MPI and MFL is that the latter measures flux leakage using magnetic field sensors such as Hall devices or magneto-resistive sensors. The inspection system is mainly composed of magnetic signal sensor, computer, serial port server, and three-axis transmission device, as shown in Figure 6 [27]. Qu et al. proposed a spontaneous

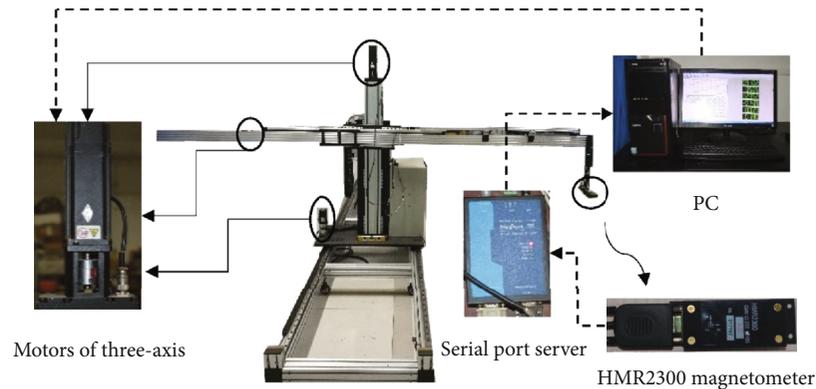


FIGURE 6: Schematic for magnetic flux leakage (MFL) inspection [27].

magnetic flux leakage (SMFL) method for the corrosion width predicting of cables. Three-axis transmission device can provide three mutually perpendicular scanning paths which are driven by three motors. The current position of the magnetic sensor is recorded. The Honeywell HMR2300 magnetic sensor is used to collect three-dimensional magnetic flux leakage signal. It is a giant magnetoresistance sensor with a range of ± 2 gauss. The resolution is about 70 micro-gauss. Thus, the data acquired can be processed using computer-based analysis, signal processing, and quantitative assessment. However, MFL is only appropriate for the characterization of corrosion in ferromagnetic-material.

MFL techniques are popular in the inspection of pipelines. Azizzadeh and Safizadeh [28] employed an adaptive filter and a wavelet-based denoising technique for pipeline inspection. Xia et al. [29] used a high-resolution self-magnetic flux leakage (SMFL) to generate magnetic fields to quantitative measure corrosion. With three growth models (logistic model, exponential model, and linear model) and magnetic dipole model, leakage and mass loss can also be detected with SMFL. The precise location of corrosion can also be provided. Ege and Kuramik [30] adopted MFL with KMZ51 AMR sensors to examine the speed variable for corrosion detection in metal pipelines. Both penetrating depth and detecting sensitivity have been improved due to the abundant components of the speed variable signal.

3.5. Microwave NDT (MNDT). Microwave frequency range is between 300 MHz and 300 GHz. Unlike ultrasound signals, dielectric coating materials can be easily penetrated by microwave signals without suffering from high attenuation and then internal structures of materials can interact with these microwave signals. These microwave signals would then totally reflect at the metal surface. Therefore, these signals travel twice through the areas of corrosion and defects, which increases the possibility of detecting them under coating. With the measurement of transmitted or reflected microwave signals, microwave NDT techniques examine magnitude or phase in inspecting the specimen. Furthermore, reflection and transmission properties are influenced by lift-off and the frequency of operation during inspection. The experimental setup for microwave NDT has been

depicted in Figure 7 [31]. A waveguide probe is placed above sample under test with a specified lift-off. A vector network analyzer is used to provide excitation signals and to obtain the reflected signals' frequency spectrum information. A PC is used to control the vector network analyzer and acquire measurement data transmitted to the PC through GPIB (General Purpose Interface Bus). An X-Y scanner was connected to a controller through a parallel port and controlled by PC. A MATLAB program is used to make the X-Y scanner and vector network analyzer working collaboratively during measurement.

Zoughi [32] employed 3D microwave camera to detect steel corrosion on concrete up to 500 mm. Kharkovsky and Zoughi [33] gave an overview of microwave- and millimetre wave-based NDT&E methods. A wide range of applications was discussed, which included detecting corrosion and the precursors of pitting in insulated structures backed by aluminium and steel. Adhvaryu et al. [34] demonstrated 2.4 GHz apertured EBG-based microwave patch antenna for steel rebar corrosion characterization in civil structures, and good resolution has been achieved at about 14 mm depth. Far-field and near-field microwave NDT approaches detect corrosion through the magnitude and phase variation of the reflection coefficient [35, 36]. From the standpoint of high resolution, signal interpretation, and insensitivity to relative position between sample and antenna, a far-field mode is preferable; but it requires large-aperture antennas to achieve good spatial resolution. In most situations, the use of large antennas is generally impractical and inconvenient. Moreover, near-field mode can be performed indoors, eliminating influences due to weather, electromagnetic interference, etc. Near-field microwave imaging techniques with open-ended rectangular waveguide are commonly used for NDT fields. For producing image, a microwave synthetic aperture radar (SAR) is scanned over sample under test, and the measured reflected signals are used to form a 2D intensity raster image [37]. Mukherjee et al. [38] used a split-ring resonator (SRR) sensor for composite imaging with super resolution capability. The difference between the phase and magnitude of reflected signals was used to produce high-resolution image for pit dimension evaluation. Qaddoumi et al. [39] demonstrated an open-ended rectangular waveguide sensor

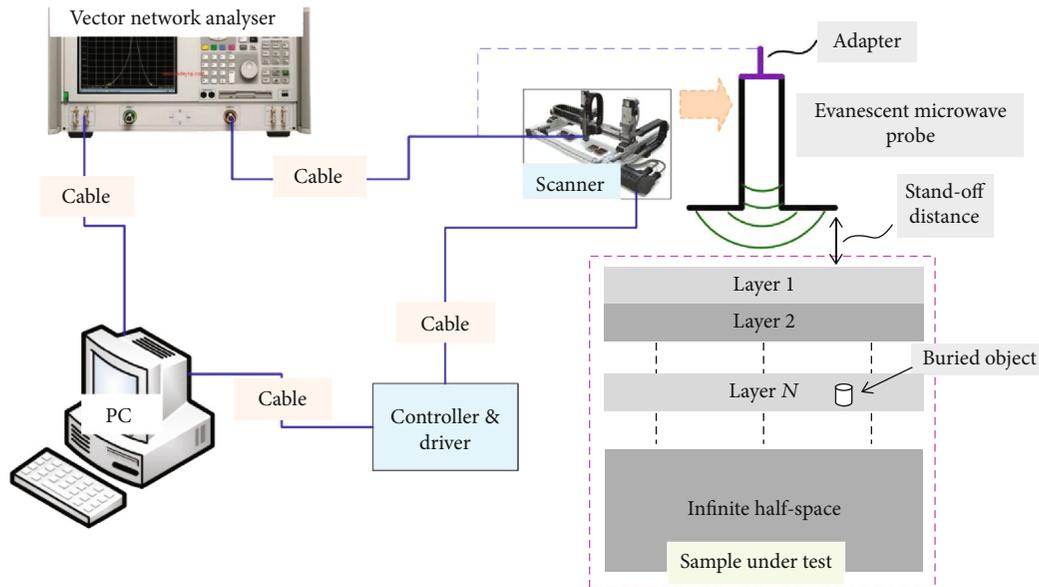


FIGURE 7: Schematic for microwave NDT [31].

operating in the near-field at a frequency of 24 GHz for defect detection and classification in nonceramic insulators. Defects were detected and classified by using a novel artificial neural network.

For corrosion detection under coating, the use of microwave NDT can be extended to the detection of water in the coating layer, since water is a cause of corrosion [40]. Meanwhile, samples with coating-related corrosion can be created to determine whether or not blisters, delamination, and other coating defects can be distinguished with microwave NDT [41]. These different types of defects may look similar when analyzing the features of microwave signal. Therefore, new features are required as well as looking into how the responses in coating to corrosion change over time, such as if blisters may appear as sudden sharp changes compared to defects on metal. For the microwave scanning process over large areas, compressive sensing could also be adopted to reduce scanning time [42]. A future work will also involve looking into methods to obtain quantitative information about conditions under the surface of steel, such as variations in physical parameters. This can be achieved by correlation using advanced feature extraction methods [43]. Zhang and others proposed a K-band sweep frequency microwave imaging system with a waveguide aperture [44]. Figures 8(a) and 8(b) show the images of coated samples with 1- and 6-month corruptions, respectively. Images were obtained using the averaged magnitude of the reflection coefficient.

However, microwaves cannot efficiently penetrate through conductive materials, which means that only surface corrosion can be sensed and it is difficult to detect subsurface one.

3.6. Terahertz (THz) Technology. THz refers to electromagnetic waves with frequencies ranging from 0.1 THz to 10 THz. Wavelengths of THz radiation are between the microwave and infrared spectra which are approximately from 0.03 mm to 3 mm. A THz wave with known wavelength is

used to illuminate a sample during inspection. This THz wave is examined at or near the radiation source after interaction with the sample under test. The inner structure of the sample is determined by analyzing changes in the THz signal, because the dielectric characteristics of the sample or a discontinuity will affect the THz signal. Figure 9 illustrates a typical THz system for detection of defects in SOFI (Spray on Foam Insulation) layers for space shuttle, and researches have shown that THz-based NDT can provide an effective evaluation for shuttle fuel tank under insulation materials. THz-based imaging has been chosen by NASA which will be used for future launch inspection.

Since the mid-1980s, THz-based methods have made important advances. THz wave has a better penetration through most dry, nonmetallic materials such as foams, ceramics, glass, resins, coating, rubber, and composite materials [45]. Therefore, these methods have been applied in the NDT&E fields and can be divided into continuous THz and pulse THz methods. THz-based NDT has unique advantages in detecting inner defects in nonmetallic materials compared to other NDT techniques. The THz wave can penetrate non-transparent materials and evaluate inner defects. Moreover, THz-based NDT has been used to inspect insulated materials. The ability of THz-based imaging for corrosion under coating has been studied by the U.S. Army Research Laboratory and NASA. Corrosion under coating leads nominally smooth surfaces to become rough and irregular, and erosion can be detected by THz-based imaging [46].

Tu et al. demonstrated a THz-based system for manned spacecraft imaging, in which a high-speed time domain is employed for nondestructive evaluation [47]. Moreover, many studies have been shown that signal processing methods can be adopted for THz-based NDT. You et al. adopted a two-dimensional continuous wavelet transform approach to extract defect information from responses, which overcomes the limitations of traditional indirect methods, where reflection signals from a metal base are used

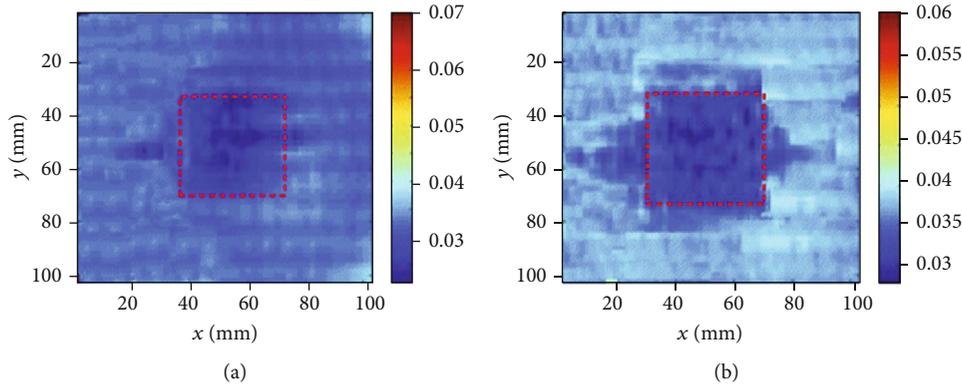


FIGURE 8: Images formed by the averaged magnitude of the reflection coefficient for (a) 1-month and (b) 6-month corrosions [44].

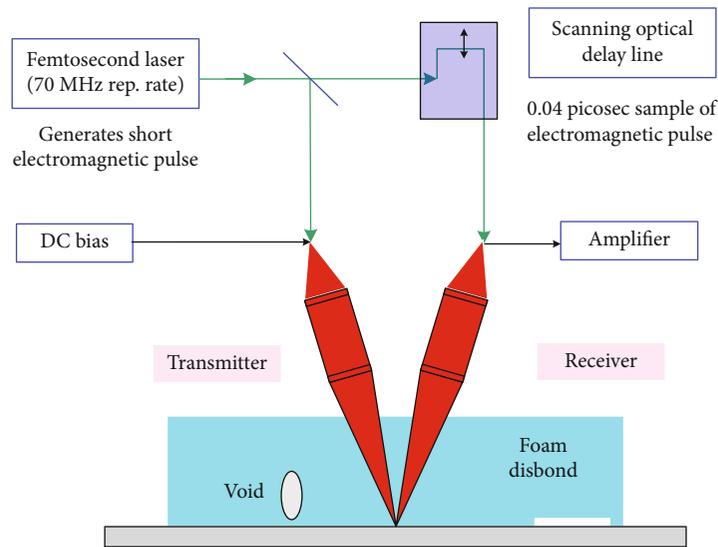


FIGURE 9: A reflected pulse THz system used for corrosion detection.

for further analysis [48]. Cao et al. adopted reflected terahertz pulse echoes to infer four layers of coatings on metallic substrates [49]. However, the THz wave cannot penetrate metallic material, which limits the scope of its application. Furthermore, THz-based methods have disadvantages of high costs and strong water absorption.

3.7. Thermography Testing. Thermography testing measure thermal variance for a characterized sample which undergoes a response to a stimulus. Improvements in IR cameras have led to more advanced forms of thermography. The advantages of thermography are that it is real time and noncontact and a large area can be inspected in a short time. With an IR camera, a thermal image is produced by infrared light which is invisible to the human eye and which is emitted from objects due to their thermal condition. Infrared thermography detection is based on differences in temperature conditions. There are two types of thermography: active and passive [50]. Active thermography (AT) is defined as the application of a stimulus to heat up the target to allow a wide range of its characteristic to be determined. These obtained characteristics can be defects or corrosion. Passive thermog-

raphy (PT) is defined as measuring temperature differences among target material, surrounding materials, and ambient temperature conditions. Normally, active thermography-based methods are the most commonly used. Sfarra et al. [51] employed an infrared thermography for the cellular structure detection in honeycomb structures. Maierhofer et al. [52] studied the use of infrared thermography for voids and cellular hollow testing. One drawback of the IR method is the high cost of quality thermal cameras, but recent developments have led them to become significantly less expensive.

3.8. Radiograph Methods. Radiograph is one of the most common NDT methods and is based on differences in the attenuation of penetrating radiation in materials depending on radiation energy and material density and thickness. Different thicknesses and types of materials give different attenuation coefficients, and variations in transmitted radiation intensity are caused by corrosion. Therefore, the value of radiographs for detecting defects, corrosion, and welds in metals has been proven [53]. For the investigation of corrosion in coated mild steel, as shown in Figure 10, an X-ray tube

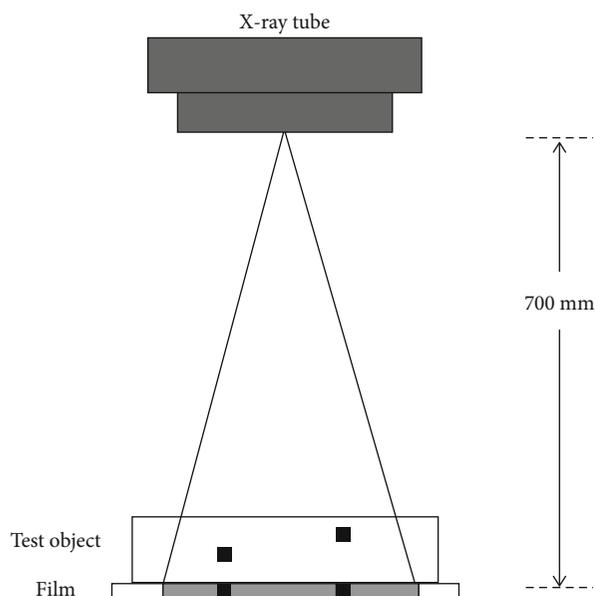


FIGURE 10: Schematic of radiography setup for concealed corrosion detection [54].

has been used with a 160 kV generator and $1.5 \text{ mm} \times 1.5 \text{ mm}$ focal spot [54]. The voltage and current of tube are set to 150 kV and 10.7 mA. For mapping corroded areas in 11 mm thick specimens, exposure time is set to 190 s. Film is AGFA D7. During the radiographic examination, single wall single image technique is used to obtain the concealed corrosion. The film are kept intact with the sample under test. To minimize distortion (due to beam divergence) and geometric unsharpness, the distance between the film and X-ray source is set to 700 mm. The radiographic image sensitivity of 2% is achieved using the appropriate image quality indicator. By using the film digitizer Model Array 2905, radiographs are digitized with 50-micron resolution.

There are several different radiographic techniques, including profile radiography, digital radiography, flash radiography, and real-time radiography [55]. These techniques are based on the use of either gamma rays or X-rays to image the profile of a structure or to provide information about the thickness of an inner structure. In many cases, discontinuities in insulated metals are readily detected. Radiography is still widely used in spite of its expense and the fact that ionising radiation poses health and safety risks. Recent developments in digital radiography have helped to eliminate the use of film, thus reducing costs. Stannard et al. adopted synchrotron X-ray tomography for corrosion fatigue crack analyses [56]. Barlow et al. used X-ray microprobe for corrosion characterization at the buried polymer-steel interface [57].

Apart from the above issues, however, there are several notable limitations on the use of radiography. For example, it is not suitable for the detection of surface corrosion and it is also not possible to extract quantitative information for the estimation of corrosion's depth.

3.9. Eddy Current Pulsed Thermography (ECPT). The configuration of an ECPT system is shown in Figure 11. ECPT involves an application of a high-frequency electromagnetic

wave (typically 50 kHz–500 kHz) at a high current around 256 A to 380 A to the material under inspection for a short period of typically 20 ms–1 s [59, 60]. Induced eddy currents are forced to divert when they encounter a discontinuity, which leads to increases and decreases in the density of the eddy current in that area. Areas with increased density of the eddy current are exhibiting higher levels of Joule (Ohmic) heating, and thus, corrosion can be obtained from sequenced thermograms during the heating and cooling periods. It consists of an induction heating system which induces eddy currents in the sample under inspection and generates a heat; the generated heat is recorded by an IR camera to form digital data; then, these digital data will be displayed on a monitor and stored in PC.

He et al. [61, 62] reported an application of ECPT for the detection of corrosion blisters in mild steel under coating. At 50 and 200 ms, Figures 12(a) and 12(b) show thermograms of a coated sample with 3-month corrosion, respectively. The shape of corrosion can be seen in Figure 12(a). A wide range of defects can be considered based on interactions between the distribution of eddy current density and heat conduction. The corrosion blister areas were easily detected using sequenced thermograms from an IR camera during the experimental study. Yang et al. used electromagnetic induction thermography for coating imaging and nondestructive visualization evaluation on coated mild steel [63]. The complex influence of parameter variation on temperature has been eliminated by using phase analysis, and the corrosion height can be estimated. However, ECPT has the disadvantages of a limited ability to be used to inspect conductive material, and furthermore, the heat inducing equipment is very bulky.

3.10. Microwave Thermography (MWT). As shown in Figure 13, basic principles and types of MWT have been reviewed by Zhang et al. [64]. MWT exhibits a great potential including fast heating, high resolution, fast inspection and high sensitivity, no contact requirement, and better detectability for the inner defect.

Foudazi and others proposed the microwave thermography for corroded reinforced steel bar detection and characterization [65]. They employed a $14 \times 24 \text{ cm}^2$ horn antenna to illuminate steel bars with 50 W of microwave signal for 10s. Because of the relatively low thermal conductivity of corroded steel, heat dissipates quickly in uncorroded steel. Moreover, these temperature differences between the corroded areas indicated that different amounts of corrosion absorb different amounts of microwave energy. With a preliminary simulation and experimental study of the microwave thermography for corrosion detection in steel bars, it demonstrated that a higher excitation microwave frequency will lead to a higher temperature. Pieper and others demonstrated the active microwave thermography for large areas corrosion inspection on reinforcing steel bars for cement-based structures [66]. During an experimental study, two steel (AISI 1008) bars (each with a length of 150 mm and a radius of 4.8 mm) were measured which have been parallel embedded in a concrete block ($170 \times 150 \times 50 \text{ mm}^3$). One of them was light corroded along half of its length, the other was significantly corroded on the order of 1–4 mm of its

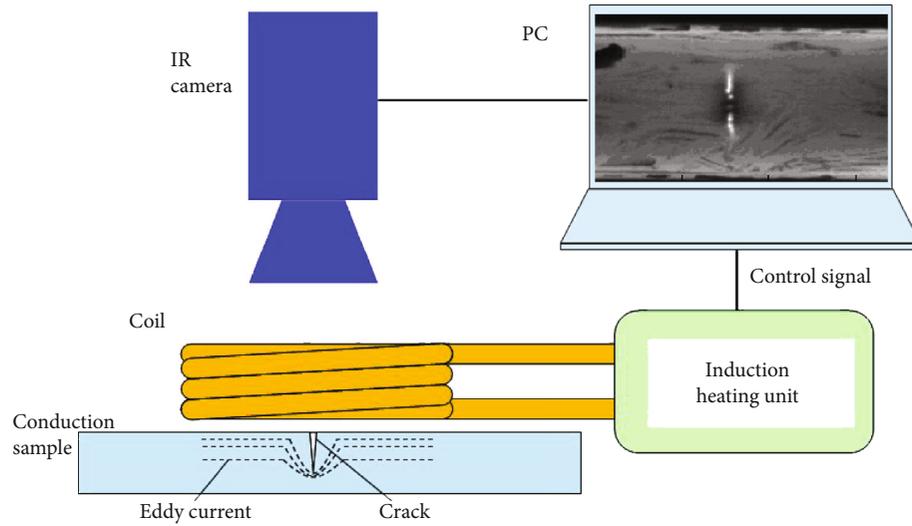


FIGURE 11: A basic configuration of ECPT system [58].

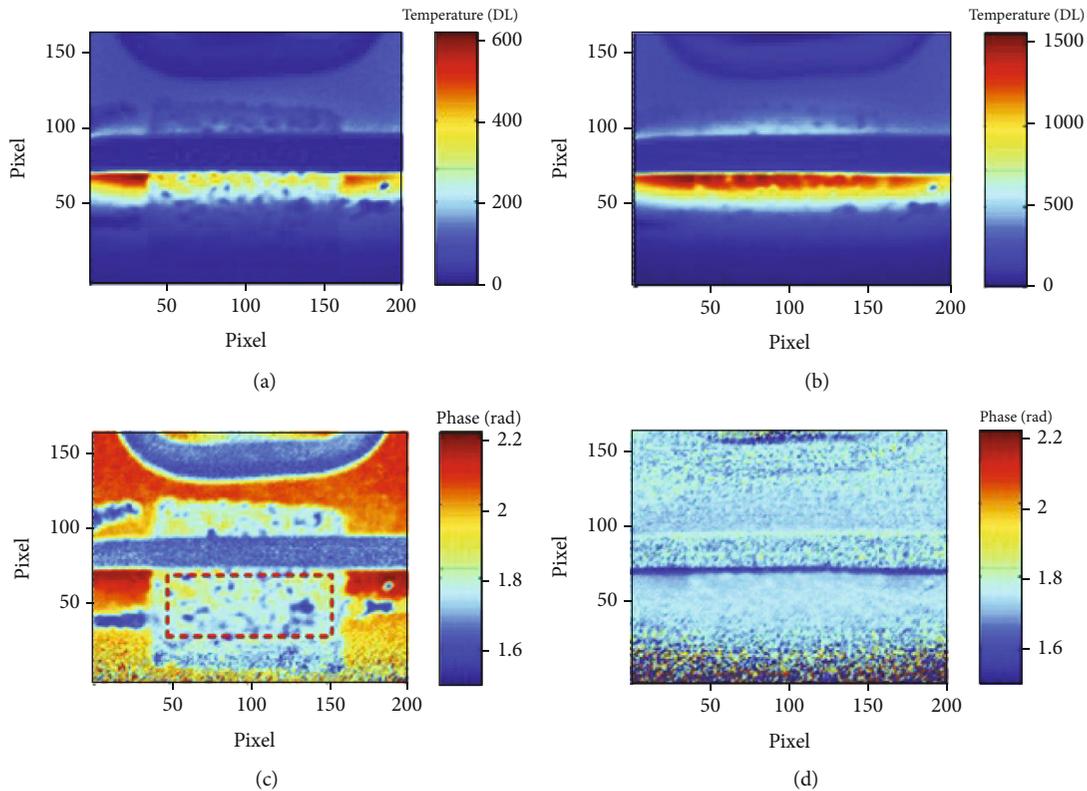


FIGURE 12: Thermal images of a coated sample with 3-month corrosion at (a) 50 and (b) 200 ms. Phase images of a coated sample with 3-month corrosion at (c) 4 and (d) 10 Hz [61].

length. The sample was heated for 5 sec by a microwave oven operating at 2.45 GHz. Keo and others presented a microwave thermography to detect steel in reinforced concrete wall [67]. During an experimental study, a commercial magnetron operating at 2.45 GHz was associated with a pyramidal horn antenna to illuminate a maximum 800 W microwave energy. The thermograms were recorded at 1 image per sec by using the ALTAIR software with a computer. The maxi-

imum temperature areas correspond to the presence of steel reinforcements in the specimen.

4. Discussion

Nine NDT techniques have been discussed. A comparison of these technologies is provided in Table 1, giving an overview

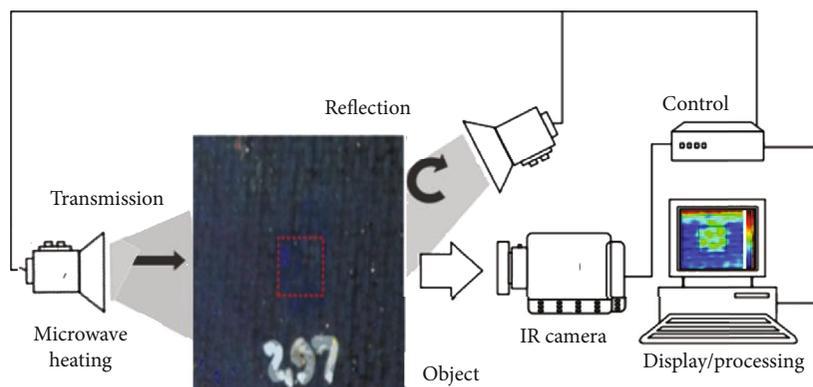


FIGURE 13: MWT setup for corrosion detection.

TABLE 1: Advantages and limitations of NDT technologies for corrosion characterization.

NDT technologies	Advantages	Limitations
Ultrasonic	Fast; inspect large area; penetrate deeply in materials; excellent for corrosion detection; can be automated.	Requires coupling material and contacting with surface; reference standards are required; surface needs to be smooth.
Radiography	Broad range of materials and thicknesses can be inspected; inspection film can be recorded.	Requires a minimum intensity difference; radiation safety requires precautions; expensive; requires to access both sides of the structure.
MFL	Portable; inexpensive; sensitive to surface and near-surface flaws and corrosion.	Bulk size; limited to ferromagnetic materials; requires postinspection and surface preparation.
EC	Quick to perform; moderate cost; no probe contact required.	Limited to materials with electrically conducting; penetration depth is limited; surface must be accessible and smooth.
PEC	Penetrating deeper without altering the coating; noncontact.	Limited inspection area; inability to detect localized corrosion.
Thermography testing (including ECPT)	Good for surface corrosion; high sensitivity; remote sensing; fast; inspect large area.	Expensive; requires heating and cooling of the system; reference standards required; poor resolution on thick sections.
THz	Noncontact; good resolution; inspect coating layer properties; real-time; one-side manner; high sensitivity.	Expensive; complex wave interactions; sensitive to environments (moisture, etc.).
MWT	Very sensitive; quick to perform; time dependent data is available; can detect nonvisible damaged areas.	Expensive; complex data analysis for quantification; localized detection requires knowledge of damaged area.

of each method and identifying the advantages and limitations of current techniques.

Corrosion effects are a complex combination of multiple factors, including variations in conductivity, permeability, and permittivity and changes in thickness. The probability of corrosion detection is affected by these factors. There is no universally applicable method for corrosion detection, due to the complex combination of these different factors. Therefore, none of the NDT techniques discussed above can address all the challenges of detecting corrosion under coating, since coating layers induce a large lift-off between sensors and the inspected surface.

Selection of an NDT technique requires consideration of more than the detection capabilities. The application, portability

of equipment, inspection schedule, inspection area, types of materials, accessibility, costs, and expected corrosion types are also important. Some techniques provide good quantitative information but perform poorly when coating is introduced. Therefore, new methods are required to monitor corrosion which can be used for long-term operation and minimal volume and at lower cost and risk.

5. Trends

5.1. New Principles and Methods. A future work with the RFID and microwave NDT system will be geared towards improvements in handling other challenges related to

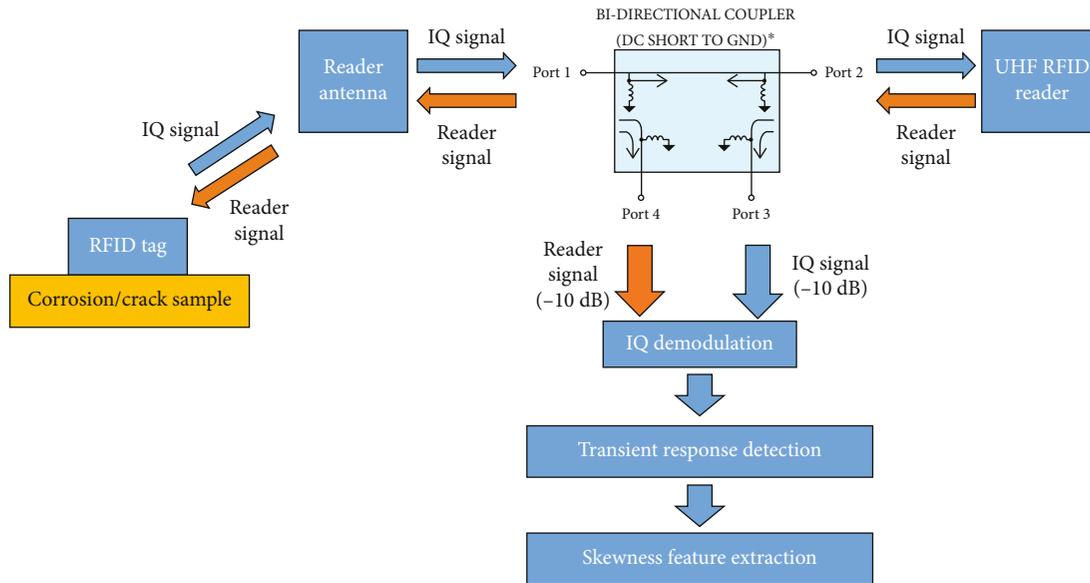


FIGURE 14: RFID-based sensing system diagram for corrosion detection [71].

insulated materials. These improvements will also be important steps towards commercial feasibility.

The inability of the RFID system to monitor large areas limits its potential field of application. Solving this problem requires the redesign of the tag unit [68, 69]. Additionally, the inability of the RFID sensing system to handle large lift-off requires investigations into whether or not carefully placed ferrite material near the tags will improve reading range. New tags employ circular three arm (CTA) element; a parasitic element has been added into the centre of CTA to improve the reliability [70].

As shown in Figure 14, an RFID-based sensing platform comprises RFID reader and tag [71]. The communication between the reader and tag is an asymmetric bidirectional link: the direct link and the reverse link. In the direct link, the reader emitted the power to power up the tag. Then, in the reverse link, the tag modulates backscattering signal and reflects the waves. During measurement, the tag acted as a sensor; the tagged object and the nearby environment can be exploited clearly with characterization of tag antenna's radiation. The power-based parameters have been investigated for stress and defect sensing. In addition to signal strengths and phases, IQ signal in RFID systems is investigated to improve sensitivity and robustness for corrosion sensing which contains high order information.

HF passive RFID-based monitoring networks can be formed by combining passive RFID tag with SAW (surface acoustic wave) [72]. With cost-efficient and lower power consumption, RFID-based approaches may represent a revolutionary solution for the condition and intelligent structural health monitoring of railways, in-service nuclear power plants, and aerospace applications [73]. Zhang and others [74] employed a UHF RFID antenna for structure health monitoring. Zhao and others employed a T-shape antenna UHF RFID to increase the gain of the miniaturized antenna and the sensitivity [75]. As well as cost-effective passive RFID tags with low power consumption, other sensors could easily

be connected for multiple-purpose sensing. In addition, new features of RFID tags based on advanced signal processing can be used for human body temperature and other measurements.

For corrosion detection under insulation, the use of microwave NDT can be extended to the detection of water in the insulation layer, since water is a cause of corrosion [40]. Meanwhile, samples with insulation related corrosion can be created to determine whether or not blisters, delamination, and other insulation defects can be distinguished with microwave NDT [39]. These different types of defects may look similar when analyzing the features of microwave signal. Therefore, new features are required as well as looking into how the responses in insulation to corrosion change over time, such as if blisters may appear as sudden sharp changes compared to defects on metal. For the microwave scanning process over large areas, compressive sensing could also be adopted to reduce scanning time [42].

5.2. Signal Processing Algorithms. A future work will also involve looking into methods to obtain quantitative information about conditions under the surface of steel, such as variations in physical parameters. This can be achieved by correlation using advanced feature extraction methods [76]. To extract useful features from the captured thermal images, more advanced signal processing algorithms have been used. With suitable signal processing algorithms, the inspection results can be significantly improved in size and depth identification, subsurface corrosion detection, emissivity variation reduction, and corrosion dimension quantification. Therefore, more advanced signal processing algorithms are needed to further improve the sensitivity and quantification ability of NDT system.

5.3. Combination of SHM and NDT. Structural integrity monitoring (SHM) systems for steel under coating can provide continuous real-time data directly to a central

control/monitoring room often located at a significant distance, unlike NDT (often scheduled inspection); thus, it can help identify corroded areas and plan condition-based structural repairs [77]. In [78], structural integrity monitoring of corroded steel marine structures with the use of NDE and SHM approach was presented. First of all, NDT systems for manufacturing quality control and for on-site inspection have been presented. However, the authors thought that the use of NDT was not simple for industry practices on the maintenance of marine steel structures. For that purpose, SHM techniques have to be considered.

5.4. Intelligent Inspection System. The efficiency of corrosion detection system can be improved by exploring an intelligent inspection system with artificial intelligence. As various types of corrosion can be acquired during material measurement, the treatment for different types of corrosion is different. Take uniform corrosion for example, this is characterized by the entirety of the surface area considered corroding at the same (or a similar) rate [79]. Uniform corrosion (or general corrosion) is relatively easily measured and predicted. This type of corrosion causes the loss of metal thickness and weight. This corrosion is the most typical corrosion during manufacturing which needs to identify to improve the manufacturing quality of the coating. Therefore, it is important to classify the corrosion type with an intelligent inspection system. As computers are becoming more and more powerful, artificial intelligence methods can be used to reduce inspection time and improve the reliability. For example, neural networks, artificial neural networks, the classic computer vision techniques, and the deep learning approach have been used for corrosion detection [80].

5.5. Implementation of Unmanned Systems. For a large sample under test, the measurement system needs to be placed in a mobile robot or a vehicle. Pixel physical size calibration has been combined with an unmanned aerial vehicle (UAV) to solve the difficulty of manually detecting the surface of the quay crane [81]. The inspection time for a large material can be significantly reduced. The whole inspection can be performed autonomously. With autonomous robots, corrosion detection can be arranged horizontally and vertically. The safety and efficiency of the NDT system can be significantly improved. However, lightweight equipment and advanced detection algorithms are also required in order to provide the automatic inspection ability.

6. Conclusion

The challenges posed by the development of corrosion under coating are inaccessibility (very difficult or impossible to reach) and lift-off effects caused by the variation of the coating layer. Lift-off effects can cause errors in the detection and measurement of corrosion. Moreover, thick coating layers result in a large lift-off, which leads to a reduction in sensitivity. In addition, the challenges associated with the characterization of corroded metal require an understanding of microstructural and physical changes prior to the initiation and growth of corrosion. In most cases of corrosion, changes

in the intrinsic material properties are dominant in the early stages. Physical damages, such as defects, occur when corrosion has exceeded a critical limit. Furthermore, their concealed nature results in the accumulation of such changes for long periods of time, leading to the critical limit being exceeded, and potentially catastrophic failures will become more likely.

An extensive literature survey in this paper has been followed by a discussion of NDT techniques using ultrasonic, acoustic, electromagnetic, radiographic, thermographic methods for the detection of corrosion. It has been shown that the majority of techniques are limited when it comes to the online in situ monitoring of corrosion under coating, primarily due to the thick coating layer. Solutions to overcome this problem typically involve either applying much higher output power using bulky, expensive equipment or using inspection holes in the coating layer to send signals along the length of an insulated structure. Compare with traditional NDT methods, such as UT, EC, and PEC, microwave NDT provides a wider range of advantages, including non-contact nature and high sensitivity and resolution. However, the cost of microwave NDT systems is relatively high and therefore limits their applications. Therefore, RFID-based methods are made fast and affordable to extend microwave NDT applications in corrosion detection, which requires new approaches to obtaining many details of RFID architectures. To address challenges from corrosion under coating, the following issues is needed to investigate: new principles and methods, signal processing algorithms, combination of SHM and NDT, intelligent inspection system, and implementation of unmanned systems.

Abbreviations

AE:	Acoustic emission
EC:	Eddy current
ECPT:	Eddy current pulsed thermography
EM:	Electromagnetic
EMATs:	Electromagnetic acoustic transducers
GMR:	Giant magneto resistance
IR:	Infrared
MFL:	Magnetic flux leakage
MNDT:	Microwave NDT
MWT:	Microwave thermography
NDT:	Nondestructive testing
PEC:	Pulsed eddy current
THz:	Terahertz
UT:	Ultrasonic testing.

Data Availability

The data supporting this systematic review are from previously reported studies and datasets, which have been cited.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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