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Metal defects sizing and detection under thick coating using microwave NDT

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ABSTRACT

An experimental study to evaluate shapes and sizes of defect under thick coating by microwaves NDT is demonstrated. Specially fabricated thick fire protect coated steel panels with embedded defects are inspected using an X-band (8.2–12.4 GHz) open-ended rectangular waveguide. The fundamental idea behind using this probe is presented along with several experimental results to validate this method for defect detection under coating. The reflected signal related to the phase and magnitude of the reflection coefficient at the waveguide aperture is used to create images of these coated samples under test. These images indicate the ability of microwaves for identifying and sizing defects under thick coating layer. Linear sweep technique is used here to obtain multiple frequency spectrum variances. Principle Component Analysis (PCA) algorithms have been employed to enhance the resolution of our proposed method. A series of performance comparison with PCA algorithms are also provided to extract the defect features from thick coating layer influence. To evaluate the proposed technique, steel with known defect and five coated steel plates with unknown defect under different coating thickness are measured. Results indicate that the defect detection capability has been enhanced with the suitable use of signal processing methods.

1. Introduction

Metal surface defect detection is very important in many industry areas (such as aircraft fuselage, nuclear power plant steam generator tubing and steel bridges etc.). Currently, there are several prominent non-destructive testing and evaluation (NDT & E) techniques for detecting surface defects on metals. Acoustic emission testing [1–3], eddy current [4,5], pulsed eddy current testing [6–9], eddy current thermography [10–12], ultrasonic testing [13,14], radiographic testing [15,16] and magnetic flux leakage testing [17–19] are examples of these techniques. Eddy current is widely using for surface defect detection. It can examine large areas very quickly and do not require use of coupling liquids. However, they have some crucial limitations: Eddy current and pulsed eddy current based NDT methods limited to be used in electrically conducting materials; the surface must be accessible and cannot detect defects with large lift-off (e.g. thick coating). Ultrasonic inspection is limited by high attenuation in the material while absorption for X-rays is too low for defects (harmful electromagnetic radiation). For the magnetic flux leakage, it can be used only for alloy and ferromagnetic materials.

With developments in materials science, lighter, stronger, and more durable dielectric materials are replacing or coating with metals in many applications. These materials require alternative testing approaches since traditional NDT methods may not be able to inspect them [20–22]. This is partly due to the relatively thick nature of these materials, attenuation and scattering caused by the various layers, low electrical conductivity associated with the layers, and thin planar anomalies that commonly appear in these structures. On the other hand, microwave NDT techniques are well suited for testing these structures since microwaves have a low absorption in dielectric materials, but they still strongly interacting to respond to structures and defects under these materials. In some situations (such as high temperature application), microwave NDT techniques may be the unique solution. For materials $\epsilon''/\epsilon' < 0.1$, penetration depth of microwave δ_d which depends on the operation frequency and the complex permittivity $\epsilon = \epsilon' + i\epsilon''$:

$$\delta_d = \frac{\lambda\sqrt{\epsilon'}}{2\epsilon''} \quad (1)$$

where λ is the wavelength and it depends on the operation frequency [23]. The penetration depth is calculated according to Eq. (1), which shows how it depends on the dielectric properties of the material. The penetration depth is used to denote the depth at which the power density has decreased to $(1/e)^2$ of its initial value at the surface.

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Materials with higher loss factor ϵ'' (imaginary part of the complex permittivity) show faster microwave energy absorption.

In the last two decades, researchers have shown interest in microwave NDT methods, because of the certain advantages of these methods such as remote detection, detection of filled and covered defects, estimating the physical dimension and orientation of the defects, and ease of operation [24–28]. Near-field open-ended waveguide microwave NDT technique appears to be one of the most promising techniques in detecting the presence or absence of a certain layer within layered structures [29]. With this method, the metal surface is scanned by an open-ended waveguide while its standing-wave characteristics are monitored. The defect detection and sizing with this method is prepared by analysing the overall reflection coefficient of the incident electric field at different defect positions beneath the open-ended waveguide aperture. This rectangular waveguide method must use a relatively high frequency in order to detect smaller defects, and this is because of the rectangular waveguide to detect only use primary molding [30,31]. Furthermore, in other applications, optimization of the measurement parameters, such as the frequency of operation, has shown measurement sensitivity to thickness variations in the range of a few micro-meters at frequencies in the X-band frequency range [32]. From signal processing point of view, many works have been already performed for spectral estimation and image reconstruction including but not limited to Fourier-based, correlation based, and super-resolution methods [33,34]. In the literature, spectral estimation or image reconstruction for samples under test has been limited to interpolation [35] in Fourier-based methods [36] and Inverse Fast Fourier Transform (IFFT) [37]. In addition, these methods only manually or use some criteria to select specific frequency band for analysis of defect, therefore, it lacks of deeply mining the informative from the whole band.

This paper presents the design and experimental testing of an open-ended waveguide operating in the X-band (8.2–12.4 GHz) for detecting defects on metal under thick coating layer. The sample under test is illuminated with electromagnetic waves. Then, a part of this incident wave will be absorbed in the coating layer, and another part will be transmitted and propagated through the coating layer. When it reached the metal layer, it will be total reflected. These forward and backward traveling waves inside the coating layer can be formulated by enforcing the appropriate boundary conditions at the air-coating and coating-conductor boundaries. The characteristics of the recorded reflected signal are utilized for detection and sizing of defects for the specimen under test. The reflection coefficient (which is the ratio of the reflected and transmitted waves) [27] from the waveguide aperture is monitored and recorded by a vector network analyser (VNA). Then this measurement data is used to produce imaging of sample under test. A C-scan system is designed for good sensitivity, penetration depth, and spatial resolution for defects evaluation under different coating thickness. A series of measurements was conducted to test the performance of this system.

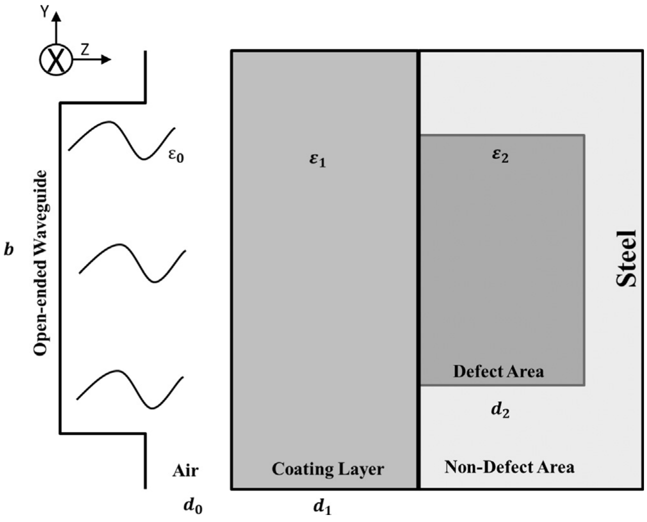

Fig. 1. Electromagnetic wave reflection and transmission for coated metal under test.

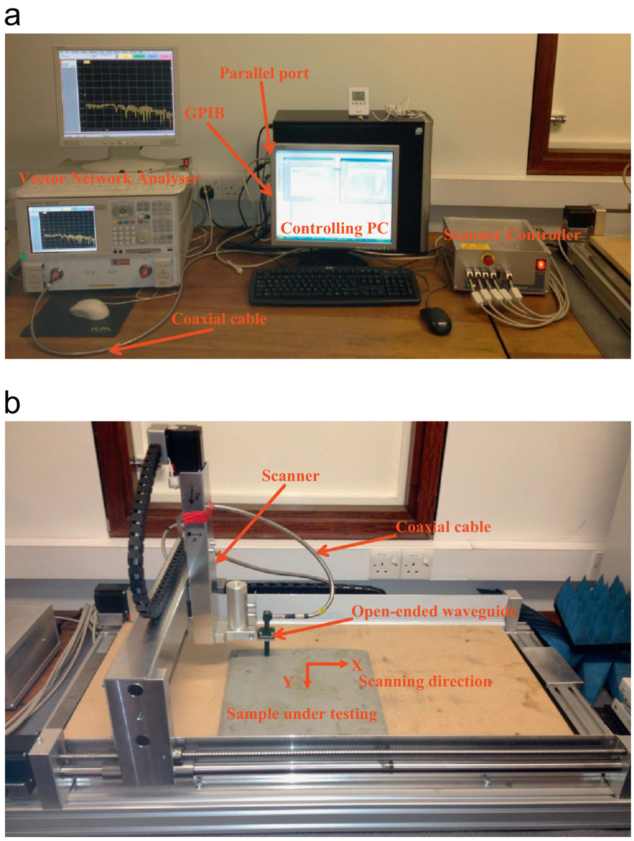

Fig. 2. Open-ended waveguide microwave NDT system experiment setup. (a) Controlling and signal processing platform and (b) Scanning platform.

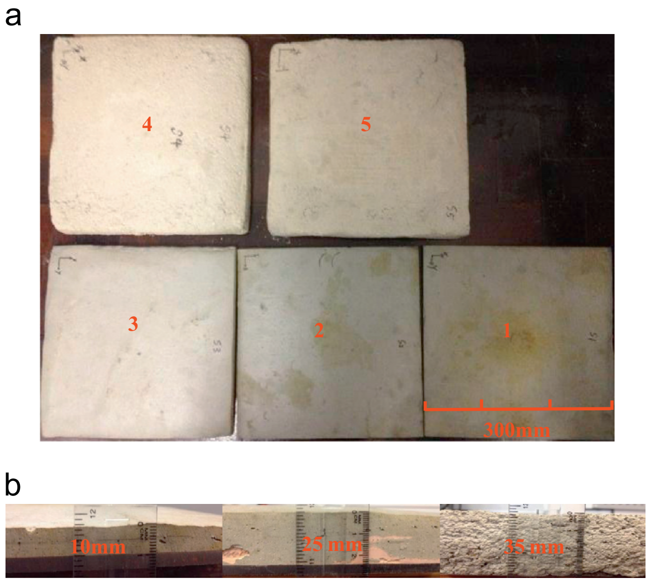

Fig. 3. Schematic of steel samples under test. (a) Coated steel samples for testing and (b) Coating layer thickness.