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Through coating imaging and nondestructive visualization evaluation of early marine corrosion using electromagnetic induction thermography

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ABSTRACT

Early marine corrosion especially under coating is difficult to be detected, sized and predicted. This work proposed through coating imaging (TCI) based on high frequency electromagnetic induction, thermal wave propagation and infrared temperature field measurement. The proposed method is called electromagnetic induction pulsed phase thermography (EMIPPT), whose advantages include being nondestructive, non-contact, fast speed, large-area, high resolution and visualization. By phase analysis, the complex influence of parameter variation on temperature can be eliminated and then relative variation of corrosion height can be characterized. The mild steel (S275) samples providing coated real marine atmosphere corrosion with exposure from 1, 3 and 6 months were tested. The experimental results illustrate that EMIPPT has greater potential for in-service corrosion detection, sizing and monitoring than laser profilometry, pulsed eddy current, and microwave waveguide.

1. Introduction

Steel components are widely used in shipping, coastal, harbor, offshore and marine structures. Because of the hostile environment, corrosion frequently occurs in steel components. More seriously, corrosion could give rise to holes and wall thinning and then result in operational and safety problems. In real applications, paint coatings are normally used to prevent corrosion(Tu et al., 2016). Even so, corrosion still occurs under the coatings due to the intrinsic coating imperfections and water invasion (Heyer et al., 2013; Traverso and Canepa, 2014). The most serious problem is that the corrosion under coating in the in-service structures is difficult to be detected, sized and predicted using current inspection techniques. Therefore, there is a pressing need to accurately detect and evaluate corrosion under coating using non-destructive testing (NDT), structural health monitoring (SHM) or other sensing techniques (Dong and Frangopol, 2015; Kim et al., 2008).

The simplest corrosion tests are based on mass loss. These tests provide the most accurate results and the corrosion rate can be calculated from the measured mass loss. But in practice these mass loss tests consist of preparing metallic coupons, cleaning them before testing, weighing them before exposure, exposing them to the corrosion media, post-test removal of visible corrosion products, and reweighting (Malumbela et al., 2009). Therefore, the process of mass loss tests is very long (several years) and cannot provide real-time measurement (Hou and Liang, 2004). What's worse, the mass loss methods are destructives. The corrosion (coated or not) can be also evaluated via physical-based characterization methods including laser profilometry or microscopy. These methods have higher spatial resolution. However, these methods are time-consuming and unsuitable for in-service inspection.

Corrosion can lead to the chemical process of steel thus some chemistry based methods including Electrochemical impedance spectroscopy (EIS), canning Kelvin probe, half-cell potential (HCP), etc., are used in corrosion inspection and monitoring. Electrochemical impedance spectroscopy (EIS) is a electrochemical technique, which can be used to test corrosion rate (Nishikata et al., 1995) and to investigate the protecting properties of coating for metal (Bonora et al., 1996). Firstly, the electrochemical tests provide a real-time measurement of the metallic corrosion rate. Secondly, they can provide time-corrosion rate data on a single coupon. Thirdly, they are rapid to perform. Most of works using this technique to investigate atmospheric corrosion is focused on the corrosion behavior and mechanisms. However, EIS cannot be attributed to certain points on the examined surface but instead represents an

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average response of the intact coating containing defects(Grundmeier et al., 2000). In addition, EIS tests require high levels of technical expertise for data analysis (Salvago et al., 1998). What's more, EIS analysis is limited to cases in which the three electrodes used (working, reference and counter) are in contact with an electrolyte. This is not the case of atmospheric corrosion of the focus of the present work. It is known that characterizing coatings using EIS in an aqueous environment can give directional information about the coating performance in atmospheric conditions. However, in the case of atmospheric corrosion, EIS cannot be a 'real-time' measurement. Scanning Kelvin probe (SKP) is a non-destructive technique for measuring the surface distribution of the Volta potential with a high spatial resolution of a few tens of micrometers. The SKP technique allows in situ studies of the localized corrosion processes under atmospheric weathering conditions, on metal surfaces, or underneath organic coatings (Nazarov et al., 2012). Characterization of the micro-droplets zone in initial marine atmospheric corrosion was performed by a scanning Kelvin probe and the scanning vibrating electrode technique (SVET) (Wang et al., 2016).

Industrial non-destructive testing (NDT) techniques are also used in corrosion detection. Ultrasonic testing has been used for corrosion monitoring (Groysman, 2009). But, it suffers from a difficulty to distinguish between reflections from surface and near-surface corrosion and reflections from multiple material surfaces. Magnetic flux leakage (MFL) is very popular for corrosion inspection in pipelines. The location of the corrosion can be provided. But its magnets can't keep away from the components' surface. Moreover, MFL cannot be collapsible to pass internal restrictions due to their large bulky magnets (Sophian et al., 2006). Residual magnetization with progress of corrosion of iron could be detected using a magnetometer, such as Giant magneto-resistive (GMR) (Gallo and Popovics, 2012) and Superconducting interference device (SQUID) (Yashiro et al., 2008). Eddy current methods have been investigated and used in corrosion detection and monitoring (Davoust et al., 2010). A pulsed eddy current (PEC) system has been used to characterize atmospheric corrosion on steel samples. Considering the conductivity and permeability variation in the corrosion layer or the actual rust region, two time-domain features, each representing the conductivity and permeability, were extracted and used to characterize corrosion (He et al., 2012). High frequency electromagnetic methods including Radio frequency identification (RFID) (Alamin et al., 2012) and Microwave waveguide (Qaddoumi and Zoughi, 1996; Zhang et al., 2013) were also used to detect corrosion under coating. However, these sonic and electromagnetic NDT methods require scanning mechanism to obtain the image of corrosion, which is time-consuming. Radiographic methods provide images of corrosion through variations in the density of metallic components. But specialized technicians following relevant safety standards are needed for these measurements (Paik, 2006).

Besides NDT, SHM for corrosion monitoring has also been actively studied. The current SHM techniques for corrosion monitoring mainly include acoustic emission (AE), fiber Bragg grating (FBG), among others. AE technique, based on the rapid release of energy within a material generating a transient elastic wave propagation, was used for monitoring corrosion under insulation (Cho et al., 2011) and pitting corrosion (Fregonese et al., 2001). However, it is very difficult to achieve visualization inspection or to obtain the image of corrosion using these SHM methods.

Infrared (IR) thermography, which can inspect large areas in a short time and safely, has demonstrated ability to detect corrosion under paint without paint removal (Marinetti and Vavilov, 2010; Matzkanin and Yolken, 2008). J. S. Han and J. H. Park used pulsed thermography (PT) to detect the corrosion on the ruptured nlistering area, blister and filiform corrosion under organic coatings (Han and Park, 2004). M. Jönsson et al. used pulsed thermography to detect the blister filament corrosion and made a comparision with the surface profile measurements (Jönsson et al., 2010). As an improved technology of PT, pulsed phase thermography (PPT) was originally developed in 1996 by Maldague et al.(Maldague and Marinetti, 1996). A great deal of work to perform qualitative and quantitative analysis in PPT has shown that non-uniform heating and surface emissivity variations have a negligible impact on phase. A. Schonberger used pulsed phase thermography to detect propagation of corrosion under organic coatings and the results have shown that the corrosion progress can be monitored by the PPT fast and reliably (Schönberger et al., 2012). The phase image shows less perturbation and the highest contrast but the phase range varies with influences such as the thickness and thermal properties of the paint.

Electromagnetic induction or eddy current excited thermography is an emerging NDT technique, which combines multi-physics processes including eddy current heating, thermal conduction and infrared imaging, thus has the advantages of fast, large area, high resolution, high sensitivity and imaging (Bai et al., 2014; Cheng et al., 2014; Gao et al., 2017). Recently, eddy current thermography develops toward intelligence for automatic diagnosing and monitoring defects (Gao et al., 2016a). B. Gao et al. bridged the gap between the physics world and mathematical modeling world in field of eddy current excited thermography. He generated physics-mathematical modeling and mining route in the spatial-, time-, frequency-, and sparse-pattern domains. This is a significant step towards realizing the deeper insight in automatic defect identification (Gao et al., 2016b). S. Baek proposed a novel integrated system of electromagnetic heat induction and IR thermography for nondestructive detection of steel corrosion in reinforced concrete (RC) structures (Baek et al., 2012). However, the phase analysis has not been carried out in these works. Y. He et al. reported an investigation with eddy current pulsed thermography (ECPT) for detecting corrosion blister in mild steel. Experimental studies showed that the blister and ruptured corrosion blister area can be easily monitored using conventional thermograms (He et al., 2014). The preliminary phase analysis was carried out but not been deeply investigated. This work proposed electromagnetic induction pulsed phase thermography (EMIPPT) for detection, sizing and monitoring of early corrosion under coating in six months. EMIPPT consists of through coating heating (TCH) based on high frequency electromagnetic induction and through coating imaging (TCI) through thermal wave propagation and data analysis based on Fourier analysis. In previous works, we have done some researches about electromagnetic induction pulsed phase thermography (EMIPPT). In (He et al., 2013), we proposed for the first time electromagnetic induction pulsed phase thermography for subsurface defects in steel based on surface heating and heat conduction from surface to inside; In (He and Yang, 2015), we used electromagnetic induction pulsed phase thermography for delamination detection in carbon fiber reinforced plastics (CFRP) based on the volumetric heating and heat conduction from inside to surface; In this paper, we used electromagnetic induction pulsed phase thermography for detection of real marine corrosion under coating based on the volumetric heating of corrosion and heat conduction from corrosion to coating. Because the detection objects are totally different, the heating style and heat conduction of these works are also different.

The advantages of proposed EMIPPT include but not limited to: 1) contrary to optical thermography which heats the surface of coating and characterization methods are mainly built on heat conduction from coating to steel and reverse reflection, EMIPPT heats the corrosion directly through coating and characterization methods are mainly built on heat conduction from steel to coating; 2) better than ECPT, they can reduce the non-uniform heating effect and lateral blurring effect (He et al., 2013), and then enlarge inspection area and improve the defect detectability; 3) unlike ultrasonics and AE, it doesn't require the couplant and is total non-contact and far field; 4) comparing with electromagnetic methods such as eddy current, MFL and RFID, it doesn't require the scanning mechanism and is high speed; 5) comparing with pulsed eddy current (hundreds of Hz) and microwave waveguide (18–26.5 GHz, 16.67–11.11 mm), the infrared optical imaging (1.5–5 μm) has a higher spatial resolution; and 6) it doesn't have any radiation like radiographic methods.

The rest of the paper is organized as follows. Firstly, the fundamental theory of EMIPPT for corrosion detection under coating is addressed in