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Electrochemical corrosion failure analysis of large complex engineering structures by using micro-LPR sensors

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ABSTRACT

This paper presents the effects of three major parameters; temperature, relative humidity and hygroscopic salts contaminants on the atmospheric corrosion of large steel structures. The effects of these three parameters have been analysed by using micro-sized LPR sensors to continuously monitor the corrosion rate of a degrading large structure under varying parameters. A long term, three years study was performed by deploying μ LPRs on strategically selected large military vehicles (main battlefield tanks), which are stationed in the Tank Museum at Bovington, UK. These vehicles are operational and are of historic significance with cultural biography, however structural deterioration through corrosion, corrosion fatigue, stress corrosion cracking and mechanical failures are a threat to these vehicles in terms of their conservation. A set of vehicles operational (uncontrolled environment) and non-operational (controlled environment) was selected for comparative analysis in context of corrosion rate. This research is founded on a novel real-time corrosion monitoring technique that enables to better understand the relationship between varying environmental parameters and corrosion rate of large steel-based mobile structures during operation. This research provides a synthesis of real time corrosion data, which has been accumulated over a period of three years. An overview of structural deterioration is presented and derived from a significantly large data, therefore it provides a more reliable and highly accurate assessment of failures due to corrosion.

1. Introduction

The most important factor in atmospheric corrosion is moisture, either in the form of high relative humidity (RH) or condensate on the surface of metal substrate. The maximum amount of moisture the atmosphere can hold increases as the temperature increases [1]. When the atmosphere cannot hold all the moisture, then it condenses forming a thin electrolytic layer on steel substrate. This thin layer along with pre-existing corrosive contaminants deposits on the surface of steel such as hygroscopic salts forming a high alkaline electrolytic solution which accelerates the corrosion rate [2]. While thin film is almost invisible, the corrosive contaminants it contains are known to reach relatively high concentration, especially under operating conditions of structures (such as vehicles) in outdoor open atmosphere and places near to coastal regions.

When steel surfaces become contaminated their surface can be wetted at lower relative humidity therefore, reducing the critical relative humidity of steel. The critical relative humidity of steel is a variable term that depends on the nature of the corroding material, the atmospheric temperature, the atmospheric contaminants and the tendency of surface contaminants to absorb moisture. For example the critical relative humidity of steel is in the region of 60–65% if the surface is contaminated with particles of sodium chloride, or ammonium sulphate, or if the atmosphere contains sulphur dioxide. However in the absence of strong electrolytes the critical relative humidity value of steel remains high such that in some cases, even at 100% relative humidity, the corrosion rate remains fairly low [3].

Lower critical humidity accounts for early initiation of corrosion at low relative humidity values due to high wettability rate of steel [4]. Therefore wettability of steel is an important parameter in deciding the corrosion rate. The wettability is measured in terms of time of wetness (TOW) [4] which is a complex parameter and in addition to critical relative humidity also depends on many other physical parameters such as type of surface, surface roughness, position and orientation of exposed surface and frequency of exposure. Therefore, undoubtedly it can be said that atmospheric corrosion rate of steel is a function of its compositional characteristics, relative humidity, temperature, hygroscopic salts contaminants, critical relative humidity of steel and TOW as shown

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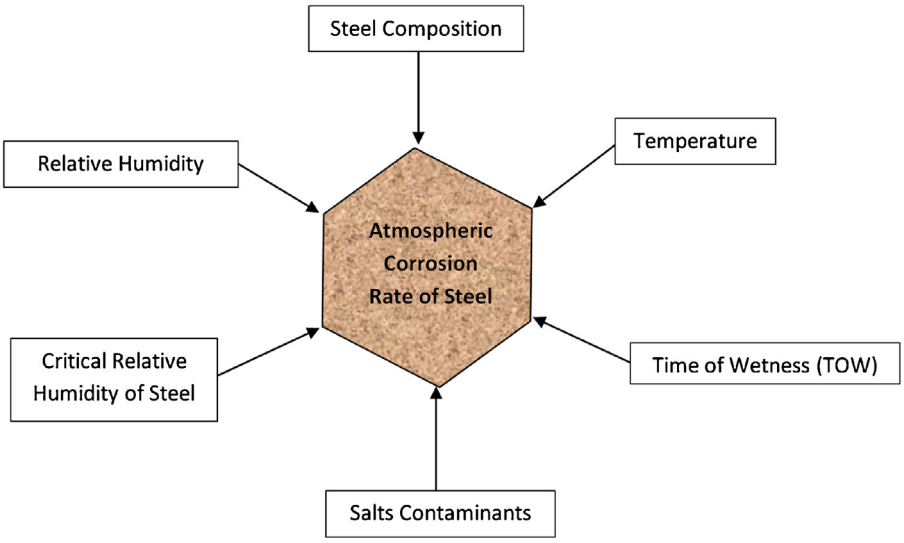

Fig. 1. Figure showing that atmospheric corrosion rate of steel is a function of its compositional characteristics, relative humidity, temperature, hygroscopic salts contaminants, critical relative humidity of steel and TOW.

in Fig. 1. Understanding the comprehensive relationship between corrosion rate and these parameters is of vital importance for controlling the detoriation of steel based large structures. This research is an effort in understanding this complex relationship.

In this paper, the study of the corrosion of large steel structures will revolve around the effects of three major parameters: temperature, relative humidity and contaminants. Although, significant in-situ laboratory analyses of corrosion degradation of steel already exists in literature but continuous real time corrosion monitoring of large steel-based operating structures corresponding to the above changing parameters is still an area which needs further research. This latest approach of continuous corrosion monitoring of structures by using high-tech micro-sized LPR sensors advantages in data/information collection and analysis based on 'when and where needed'. Further it helps in analysing 'not-easily-accessible sites' on complex engineering structures.

Previous investigation of coating failures, i.e. blistering, delamination, micro-cracks and corrosion damage measurement in real time has been reported [5–28]. This research focuses on analysing the corrosion failure of large military vehicles (battle tanks) corresponding to changing relative humidity, temperature and concentration of surface contaminants by using μ LPR sensors. These vehicles consisting of a fleet of three hundred battle tanks are situated at the Tank museum, Bovington UK. The vehicles are of historical importance however corrosion is one of the most significant contributors to the structural damage and material aging of these large vehicles. Therefore, corrosion monitoring technique was utilised to monitor the continuous degradation of vehicles. For this, two set of vehicles (operating and stationary) were selected for a long term experiment, comprising of three years (Aug. 2013 to Aug. 2016) comparative analysis. A comparative study between the results of two set of vehicles was performed to understand the relationship of varying environmental parameters with the corrosion rate under the operational conditions. The experiment helped in understanding the prevailing mechanisms of failures due to corrosion with various types occurring in these vehicles identified.

2. μ LPR

LPR (Linear Polarization Resistance) monitoring is an effective electrochemical method of measuring corrosion. Monitoring the relationship between electrochemical potential and current generated between electrically charged electrodes in a process stream allows the calculation of the corrosion rate. This measurement of the actual corrosion rate allows almost instant feedback to operators [29].

A two or three electrode probe is inserted into the process system, with the electrodes being electrically isolated from each other and the process line. A small potential in the range (in mV's which does not affect the natural corrosion process), is applied between the elements and the resulting current is measured. The polarization resistance is the ratio of the applied potential and the resulting current level. The measured resistance is inversely related to the corrosion rate. The electrical resistance of any conductor is given by: R = V/I. Where R = Effective instantaneous resistance V = Applied voltage and I = Instantaneous current between electrodes. If the electrodes are corroding at a high rate with the metal ions passing easily into solution, a small potential applied between the electrodes will produce a high current, and therefore a low polarization resistance. This corresponds to a high corrosion rate [29].

Recently, Analatom's developed commercially available, μ LPR [30–36] is the micro-scaled small form factor of conventional LPR measurement setup [37,38] which is designed to minimize the volume of an electrochemical corrosion monitoring setup as shown in Fig. 2 (a). μ LPR sensor can be used for corrosion monitoring of variety of steel based industrial applications [36] to aluminium based aerospace applications [31].

μ LPR has dimensions 40 mm x 20 mm x 0.1 mm. The sensor consists of multiple plates made from the material of interest which form the two electrodes (counter and reference). The electrodes are used in conjunction with a potentiostat for conducting LPR measurements. The use of relatively large counter electrode minimizes polarization effects at the counter electrode to ensure that a stable reference potential is maintained throughout the experiments. Potential step-sweeps are performed by applying a series of 30 steps over a range of ±10 mV spanning a period of 2.6 s [39]. μ LPR measures the polarization resistance $R_p(\Omega)$ between the corrosive agents (electrolytic solution) and the steel substrate. The polarization resistance is then used to calculate the corrosion current density '*i*' and subsequently corrosion rate of steel structure [40],

The μ LPR is adhered to the conditioned face of the steel samples with industrial strength epoxy as shown in Fig. 2(b). The sensor array includes at least two interlaced inert electrodes which are manufactured of a noble metal. The noble metal could be Au, Pt