2017 Department of Defense – Allied Nations
Technical Corrosion Conference

Paper No. 2017-600147

SENSOR BASED CORROSION CONDITION MONITORING OF COATING SUBSTRATE SYSTEM INFORMED BY FRACTURE MECHANICS, ELECTROCHEMISTRY AND HEAT TRANSFER CONCEPTS

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Keywords: Corrosion, coating failure, condition monitoring, strain gauge

ABSTRACT

This research investigates delamination and blistering as coating failure mechanisms due to corrosive diffusing species, residual and thermal stresses. Several mathematical models to include environmental variables as temperature, humidity ratio, and atmospheric constituents have been developed and reported. During this study, various coating failures have been analysed through a combination of electrochemistry, fracture mechanics, and heat transfer concepts. This approach enabled the development of comprehensive mathematical models for the prediction and prognoses of coating failures applied to high-value assets. The formation of blister and its propagation due to diffusion of corrosive species was investigated. Fracture mechanics concepts were utilised to study the initiation and propagation of a circular blister as an interfacial crack under the coupling effects of compressive and diffusion-induced stresses along with heat transfer due to pressure gradient at the interface of the coating-substrate system. The direction of blister propagation was defined through a mathematical model with blister radius r and radial angle θ as initial defining parameters. Experimental work was conducted to assess the influence of varying temperatures, humidity ratios, and environmental pollutants as SO_2 and salt particles to investigate corrosion failures. Live condition monitoring techniques were developed to assess corrosion rate with respect to large vehicles operation frequencies to study the effects of changing environments. Three years of real time data consisted of 150K data points was acquired for investigating corrosion failures with or without coatings. Both experimental and simulation data was compared to predictive and prognostics models. There is an excellent agreement between experimental and simulation results to be applied for live corrosion condition monitoring of large high-value assets. A sensor based corrosion condition monitoring methodology, informed by experimental and simulation results has been developed and is presented.

INTRODUCTION

Protective coating applied to industrial components, mobile assets and infrastructures are susceptible to mechanical and electrochemical failures. Corrosion and Coating failures within industrial components, infrastructures and large vehicles operating under harsh environmental conditions cause huge financial loss up to 3.1% of GDP for an industrial economy[1]. Live condition monitoring techniques are aimed to reduce the cost through early detection of corrosion and coating failure by changing the scheduled based maintenance to condition-based maintenance. MEMS sensor provides an adequate way to measure the parameters involved in metal and coating deterioration. The diagnostic and prognostic models can be applied on real-time monitored data to assess the structural health. NanoCorr Energy and Modelling (NCEM) research group analysed the surface corrosion on large vehicles and proposed mathematical models for diagnoses and prognoses of coating life. Variable environmental conditions play a major role in material degradation. The useful life of large vehicles can be extended by enhanced and precision condition monitoring techniques. Corrosion and stresses within coating play a major role in coating delamination process. Sensor technology has a wide range of applications in many areas to monitor, control and diagnose the processes. This research investigates corrosion and stress/strain behavior of coating/substrate system by using micro-electromechanical (MEMS) sensors. Micro-linear polarization Resistors (μLPR) and strain gauge sensors were used to investigate the effect of corrosion and stresses. Live condition monitoring techniques were utilised to assess corrosion rate with respect to large vehicles operation frequencies to study the effects of changing environmental conditions. Three years of real time data consisted of 150K data points was acquired for investigating corrosion failures with or without coatings. The strain rate was measured by mounting strain gauge sensor on coating/substrate system in an arm of Wheatstone bridge circuit with a protective coating. Live condition monitoring technique can provide data for critical assessment of coating/substrate system to predict the failures.

EXPERIMENTAL PROCEDURE

The application of corrosion sensor and strain gauge sensor for live condition monitoring system is presented. Stress analysis is done through the principle of strain measurement. Strain gauge sensor has been widely adapted to measure stress/strain in foundations, building and other (mechanical and civil) infrastructures. Whilst, the μLPR concept has been widely utilised to monitor the corrosion problems in aerospace applications, waste water treatment systems, paper manufacturing cooling water systems, civil and mechanical infrastructures where the structure is vulnerable to a corrosive environment. The strain/stress behavior was monitored on coated samples in the accelerated corrosive environment. AISI carbon steel 1010 was used as a substrate with red oxide primer coating [2]. In order to monitor the corrosion rate of vehicles operating under variable environmental conditions, the μLPRs are mounted on turret top. Complete insulation process of live condition monitoring mechanism of the strain gauge and μLPR are discussed in following sections.

Strain Monitoring System

The general purpose strain gage sensors with grid resistance 350.0±0.2 were used to monitor strain on coated samples. Accessories were used to mount strain gauge on the desired area of coated sample as shown in Figure 1. First, the area where the sensor would be installed was conditioned with M-Prep neutralizer by using gauge sponge. The strain gauge was then carefully transferred on a sample by using PCT-2M tape. Strain gauge grid area was wiped by using M- Bond 200 catalyst-C and M-Bond 200 was applied to attach sensor on the coating. The PCT-2M gauge installation tape was removed after two minutes. For bonding, the strain gauge on surface M-Bond 200 was used which does not have any effect on the substrate and coating. After mounting the strain gauge on the sample, solder was used to wire the connections between strain gauge sensor terminals and cable leading to DAC. The mounted strain gauge has shown in Figure 2.

The strain gage sensors were connected to Data Acquisition Conditioner (DAC) which has 8 Hz sampling rate. The DAC has RJ 45 connectors to communicate with strain gauge sensors and powered via USB interface which also connects with base station[3]. It measures the change in strain by measuring the change in resistance through Wheatstone bridge concept which is an electrical circuit used to find unknown electrical resistance by forming a bridge of known resistances. The complete architecture of strain monitoring system is presented in Figure 3. DAC supports quarter, half and full bridge configurations with bridge impedance from 60 to 2000Ω.

Figure 1
Accessories used for strain gauge installation

The following equation represents the relation between measured unknown resistance and strain.

$$G.F = \frac{\Delta R/R_G}{\epsilon} \tag{1}$$

Where $G.F$ is a gauge factor which is defined as relative ratio between mechanical strain and change in electrical resistance, ΔR change in resistance, R_G is the resistance of the un-deformed gauge and ϵ is strain. Two samples were prepared with strain gauge sensors.

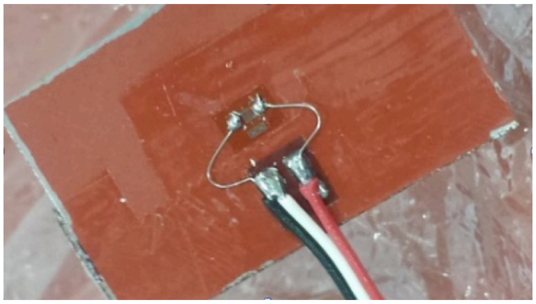

Figure 2
Strain gauge mounted on coating/substrate system

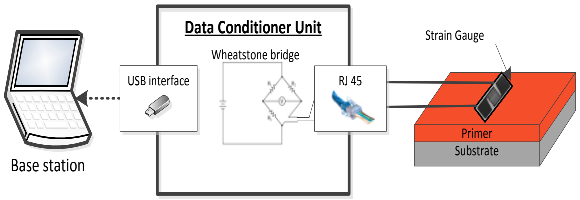

Figure 3
Architecture of strain monitoring system

Corrosion Monitoring System

Large military vehicles exposed to harsh environmental conditions causing concerns for structural health in terms of corrosion and coating failures. Linear polarization resistance (LPR) is the only electrochemical technique being used for real-time monitoring of corrosion rate. The accuracy and precision of LPR in the corrosive environment have been verified using ASTM G85 Annex 5 standard [4]. According to mixed potential theory, the potentials induced at anodic and cathodic sides are equivalent to corrosion potential. The current density between the potential is called corrosion current density [5]. Corrosion current density can be calculated through Stern-Geary equation which can be given as:

$$\mathrm{I_{Corr}} = \frac{\mathrm{B}}{\mathrm{R_p}} \tag{2}$$

In the above equation, I_{Corr} represents corrosion current density which is a ratio between proportionality constant (B) and polarization resistance ($\mathrm{R_p}$). For aluminum alloy widely used in aerospace industry has B = 1000 and structural carbon steel 1010 has B = 3000. Proportionality constant (B) can be determined for any particular material by using anodic and cathodic slopes in Tafel plot [6]. Relation between slops and proportionality constant can be given as:

$$B = \frac{b_a b_c}{\ln(10)\,(b_a + b_c)} \tag{3}$$

Polarization residence ($\mathrm{R_p}$) can be determined by using two and three electrode system. The μLPR sensor is based on the principle of three electrodes system to measure polarization resistance. The rate of corrosion with respect to time at any instant can be computed by modifying Faraday's Law as:

$$CR(t) = \mathrm{I_{Corr}} \left[\frac{w}{A * e * F}\right] = \frac{\mathrm{B}}{\mathrm{R_p}} \left[\frac{w}{A * e * F}\right] \tag{4}$$

F is Faraday's constant, e is the number electrons exchanged during oxidation reaction, A represents corroding electrode's area and w is the atomic weight of metal.

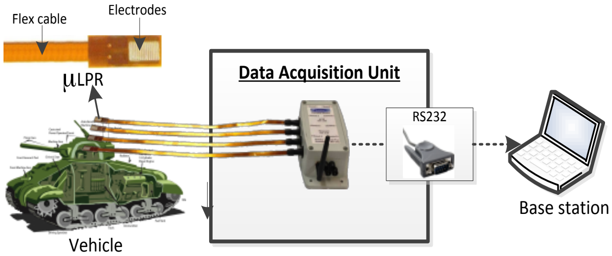

Figure 4
Architecture of corrosion monitoring system

Large military vehicles at the Tank Museum are operating under controlled and uncontrolled environmental conditions. The real-time corrosion monitoring performed on vehicle **A** operating under controlled and vehicle **B** operating under uncontrolled environment is presented in this paper. The sensors were mounted on Turret top, which is the most exposed area of the vehicle to environmental changes. The μLPR has working, reference and counter electrodes as shown in Figure 4. The counter and the reference electrode are made from copper with (ENIG) electroless nickel plating covered with a thin coat of immersion gold to insulate the nickel from oxidation. The working electrode is also fabricated with Electroless nickel immersion gold (ENIG). Electrodes are attached with flex cable which can be installed onto the substrate by using epoxy for corrosion rate measurement. The μLPR sensors were mounted on Turret top and connected to Data acquisition unit (DAQ) which can store the measured values of linear polarization resistance from the sensor. DAQ has a battery life of approximately 5-7 years subjected to temperature conditions and duty cycle. The data stored in DAQ can be transferred to the base station by using RS232, RS-484 or wireless ZigBee protocol. The software installed at base station computes corrosion rate based on linear polarization resistance values retrieved from DAQ.

Condition Based Monitoring System

From the past several years, NCEM research group has been making significant contributions in providing engineering solutions for protection of industrial components, large vehicles operating in harsh environmental conditions and valuable assets [2, 7-20]. Several diagnostic and prognostic mathematical models have been proposed and validated based on multidisciplinary research approach.

Current research is a step advance towards building live condition health monitoring system by incorporating state-of-the-art mathematical model which includes electrochemistry, fracture mechanics, material science and heat transfer concepts. The flow diagram of the proposed condition based monitoring system based on multidisciplinary approach is shown in Figure 5. The application of MEMS sensor is presented in this paper and further investigation in more depth using MEMS sensors will be conducted in future to bridge them with mathematical models for accurate future predictions. Khan-Nazir model has been previously reported which is an efficient and novel approach by fusing diffusion and fracture mechanics concepts to explain the behavior of cathodic delamination process [13, 16]. Primary influential parameters like de-bonding driving force have been modeled as a function of mechanical and chemical properties of the coating-substrate system to expound the nucleation and propagation of coating failures including blistering and micro-cracks [10, 12, 14]. The structural steel used in bridges, industrial components, and other high-value assets are greatly affected by acidic rain which contains a solution of water and sulfur dioxide (SO_2). The mathematical relations to simulate the influence of corrosive product (SO_2) on corrosion mechanism of structural steel with respect to time, wind velocity, inclination angle θ was also presented [2]. NCEM research group has also conducted three years of live corrosion monitoring analysis by using μLPR sensors of historical tanks stationed within The Tank Museum at Bovington, United Kingdom. Three years of real time data consisted of 150K data points was acquired for investigating corrosion failures with or without coatings. For accurate condition based monitoring plan, statistical techniques can be applied to the real-time data which was obtained from sensors and mathematical model for reliable detectability of potential risks of structural deterioration.

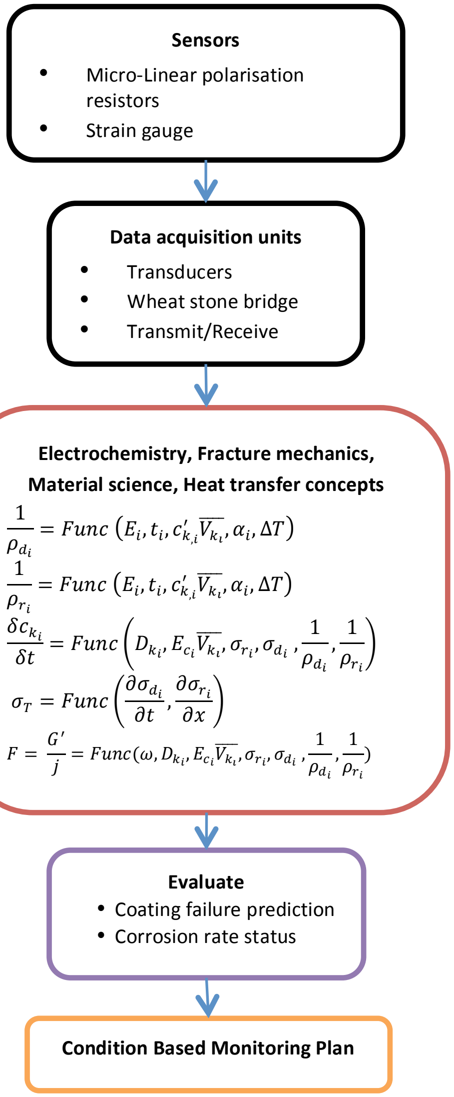

Figure 5
Condition base monitoring system model

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RESULTS AND DISCUSSION

The performance of strain gauge sensor for coated samples was tested under variable temperature conditions. Stress/strain is a major parameter to drive de-bonding driving force of coating/substrate system. The aim of using strain gauge sensor over the coating is to take real time measurement of stress/strain to monitor current condition of coating and to input real-time stress value into the mathematical models which have been designed for coating failures. The samples with incorporated strain sensor were kept inside the environmental chamber with a wire leading to DAC placed outside the chamber. The experimental results acquired from DAC are plotted in Figure 6. The experimental results have shown promising results for utilizing this test configuration for live stress measurement. The effect of Thermal stress was observed by increasing temperature when sample 1 was transported into the chamber where the temperature was slightly higher as compared to the surrounding temperature. The change in temperature induces Thermal stress which can be observed at point A in Figure 6. Thermal stress depends on Elastic modulus, the coefficient of Thermal expansion and change in temperature as: $\sigma_{th} = E\alpha\Delta T$ [21]. The Thermal stress due to change in temperature produced compressive strain/stress which can be seen in embedded plot A in Figure 6. The temperature was kept constant for next 24 hours. During constant temperature, Thermal expansion taking place until it reaches maximum level depending on the magnitude of temperature. After 24 hours, the temperature was increased by $\Delta T = 20$. As a result, The Thermal stress induced at this point was large than observed at point A depending on the rate of change in temperature. After point B, the temperature was kept constant again for the next 24 hours. During this period, the Thermal expansion of coating once again started to gain its maximum level corresponding to magnitude of temperature. After 24 hours, temperature was increased further and at this time the $\Delta T = 30$ which resulted in high Thermal stress as compared to point A and point B. The embedded plots of points A, B and C in Figure 6 which shows the behavior of stress when Thermal stress appears due to increase in temperature. It can also be seen that the high change in temperature resulting in high Thermal stress. The experimental work shows promising results to utilize strain gauge sensor for real time values for prognosis models. Similar kind of experiment was also performed on another sample 2 with strain gauge sensor to ensure repeatability of sensor behavior with same sensing equipment. The experimental results can be seen in Figure 7 which shows similar behavior. As temperature increases, the coating material tends to reach its maximum Thermal expansion level corresponding to magnitude of temperature.

The real-time corrosion monitoring of two different vehicles operating (stationary and mobile) in the various environment have been presented. There were two μLPR sensors mounted on turret top of each large vehicle connected to DAQ. Sensors data were continuously been stored in the memory unit of DAQ and retrieved regularly after few months of time. The vehicle **A** was remained stationary during the course of this stud and was subjected to controlled environment. According to acquired data from vehicle **A** operating in controlled environmental conditions, μLPRs have not shown any data points due to reason that no significant variation in temperature, salinity, and relative humidity had occurred. The results obtained from corrosion monitoring system installed on vehicle **A** is shown in in Figure 8. Whilst, the corrosion was observed in vehicle **B,** which has been in a dual state of operation i.e. both under the controlled and uncontrolled environmental conditions. The results obtained from sensors mounted on turret top of vehicle **B** presented in Figure 9. There were two LPR sensors embedded on each large vehicle. LPR1 has not shown any corrosion rate. So its value remained zero in both conditions (Controlled and uncontrolled environment) as shown in Figure 8 and Figure 9. The corrosion rate was observed on several occasions during activity. The area pointed with the caption as activity in Figure 9 represents the existence of corrosion reactions during activity. There are mainly two types of environmental conditions where large vehicles are operated or stationed. One is under the shed, where the environment is controlled and more likely suitable for the structure of large vehicles. The second environment is outside the shed where large vehicles are also operated or stationed for exhibition activity. The Tank Museum is situated near the coast, therefore in the uncontrolled environment the salt particles present in the atmosphere accumulated over uncovered steel parts. These salt particles are a major factor for the initiation of corrosion. The activity of moving vehicle **B** repeated several times during three years but the corrosion rate is not similar as it kept on decreasing due to the formation of a thin layer of corrosive species over the vehicle surface.

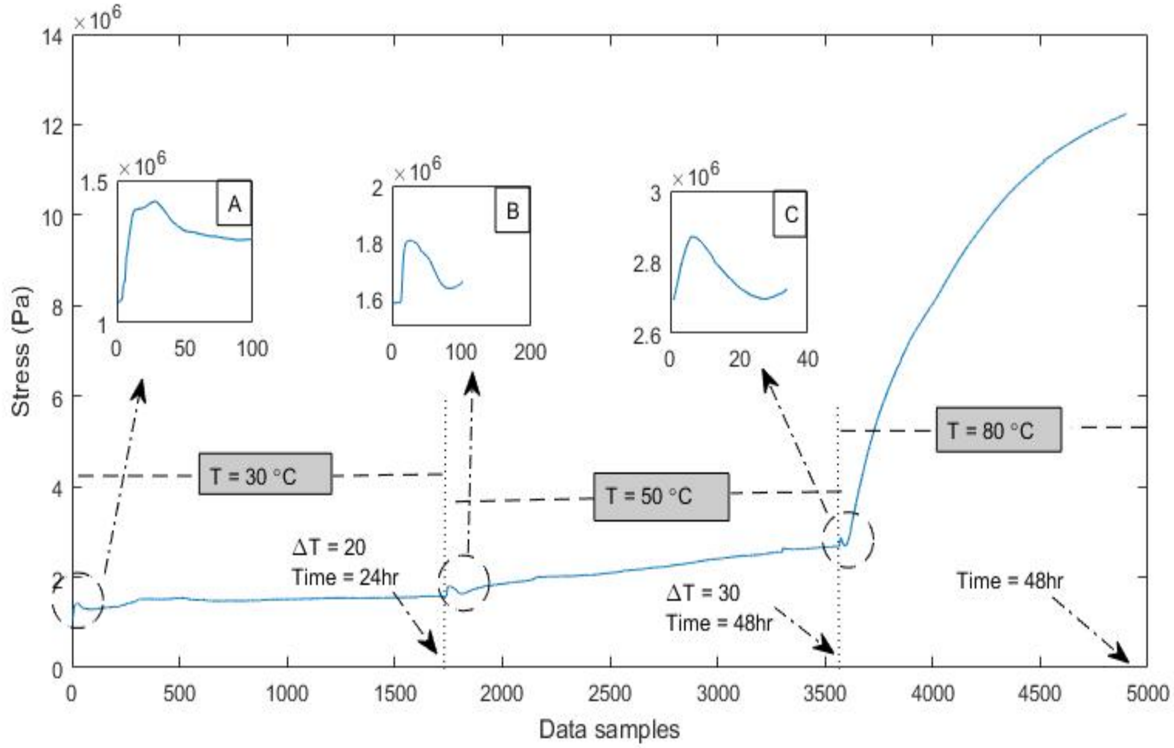

Figure 6
Experimental results acquired from strain gauge monitoring system from sample 1

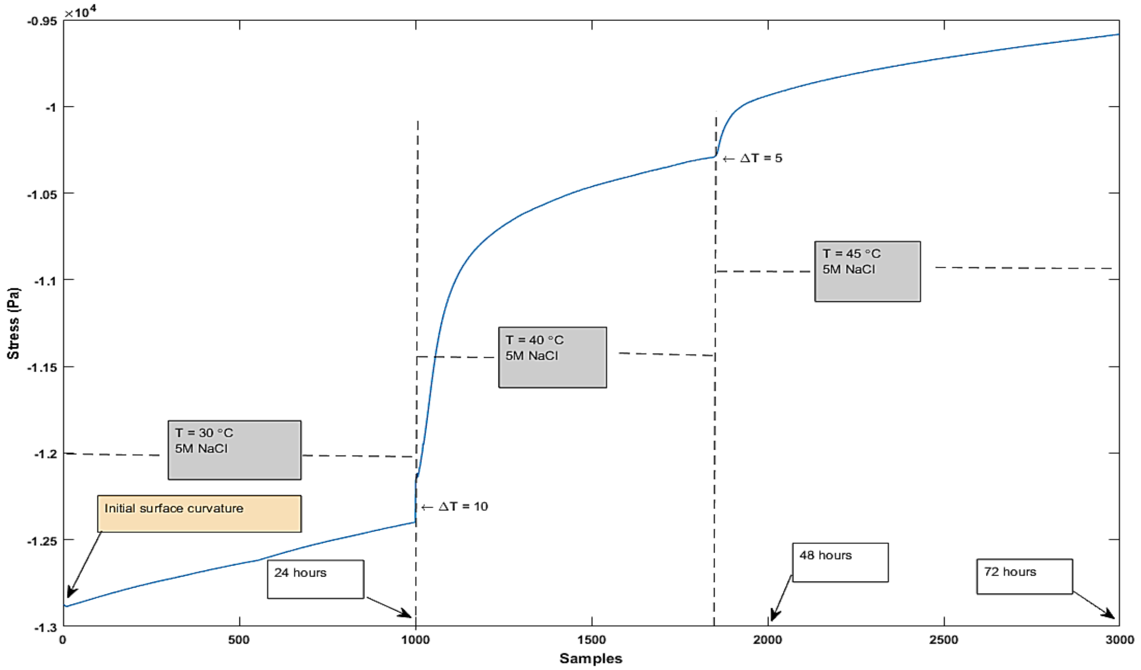

Figure 7
Experimental results acquired from strain gauge monitoring system from sample 2

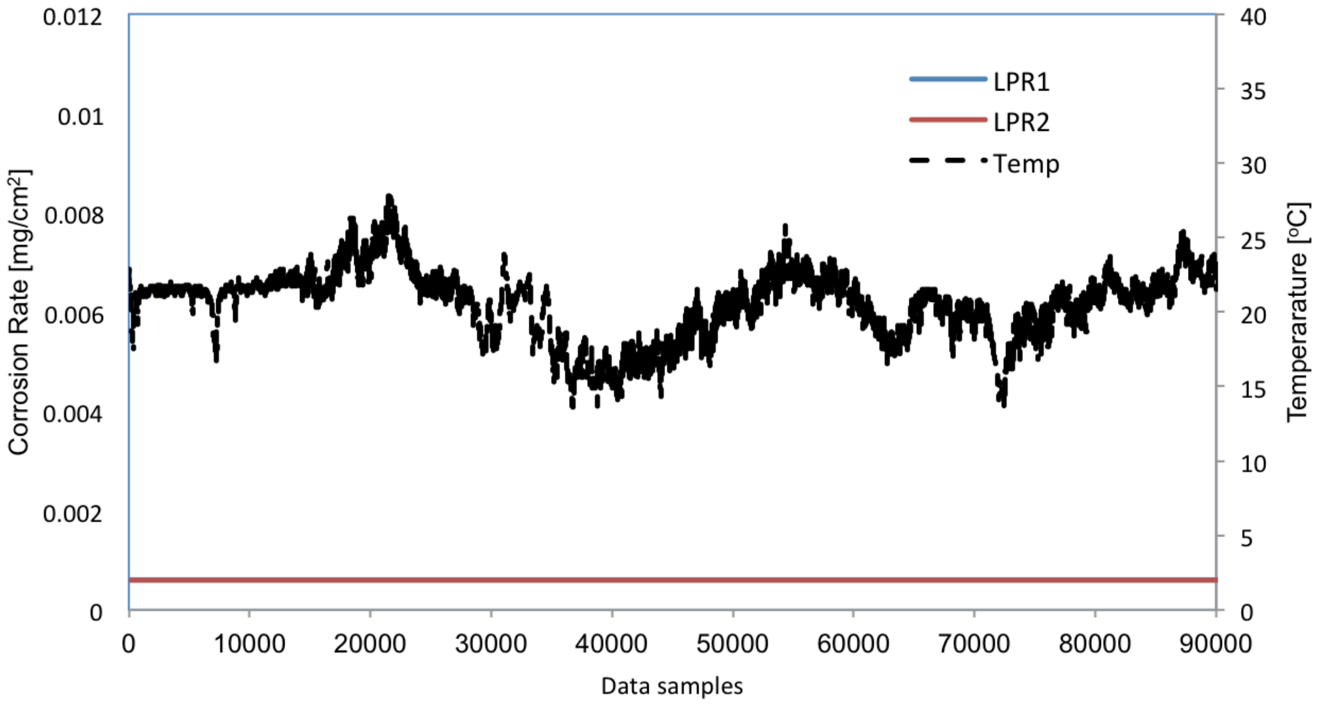

Figure 8
Results obtained from corrosion monitoring system applied on stationary vehicle A

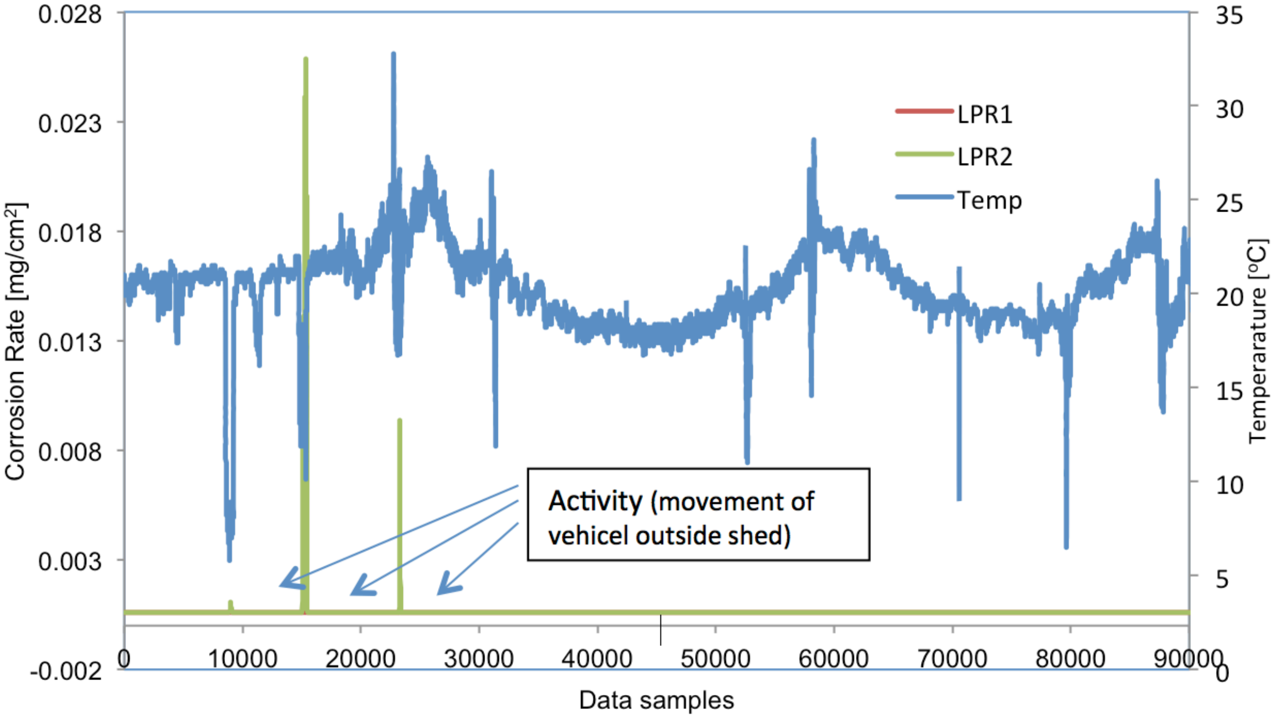

Figure 9
Results obtained from corrosion monitoring system applied on operating vehicle B

CONCLUSION

The real-time corrosion monitoring and stress/strain measurement techniques have been reported in the current research. The data points obtained from both systems have shown promising results for utilization of MEMS for live and remote structural health monitoring system. The strain gauge sensor has shown the values of thermal compressive stress for minor changes in temperature which will provide useful data for coating life assessment. The μLPR sensor with wireless technology embedded within high-value assets can send alert/warning about the initiation of corrosion process to the professionals to take necessary actions which will help in prolonging the useful life of these assets. According to the results obtained from experimentation, the strain gauge sensors and μLPRs will provide an effective way to design state-of-the-art condition based monitoring system.

ACKNOWLEDGEMENT

This research is jointly funded by Defence Science and Technology Laboratory (DSTL), Ministry of Defence (MoD) and Bournemouth University UK. The authors acknowledge their support and contributions.

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