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Development of a Wireless Corrosion Monitoring Sensor for Land Vehicles

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ABSTRACT

Corrosion of structures and mobile equipment is a concern for all nations as it affects through-life costs, safety, and availability. Historically, corrosion monitoring has relied on visual inspections which hinder its detection in inaccessible areas, and by the time the corrosion damage is caught, requires potentially extensive and expensive repairs. The development of a low-cost and simple to operate corrosion monitoring system that would both aid in early detection and provide cumulative damage information would greatly improve the maintenance efforts. Most currently available corrosion monitoring systems require either powered sensors or a physical connection to the sensors to obtain measurements, which makes the sensor design and the measurement complicated and expensive. In this study, a cost-effective wireless corrosion monitoring system based on radio frequency identification technology (RFID) was developed. A sacrificial metallic coating was applied to the surface of RFID tags to partially block the communication between the tag and the reader. As the coating corroded, the signal was restored. By establishing a correlation between the corrosion rate of the metal object and the sensor communication performance, it will be possible to wirelessly monitor the cumulative corrosion damage.

Key words: corrosion monitoring, wireless sensor, Radio Frequency Identification (RFID), electromagnetic interference, composite coating

INTRODUCTION

Corrosion is a wide-spread problem in stationary structures such as buildings and bridges, and mobile equipment including vehicles, marine vessels, and aircraft. Considerable effort and expense have been expended on developing corrosion control and mitigation methods.[1-3] A number of corrosion monitoring technologies have been developed based on various theories and principles, and many have already been implemented in real world practices. However, most of these sensors require continuous physical connections to readers or data loggers, or a power source, which limits their use for long-term monitoring in remote locations. Wireless sensors are emerging as an attractive alternative to the conventional wired sensors.[4-9]

Radio Frequency Identification (RFID) based sensing has appeared as a promising technology in a number of applications in recent years. An RFID system is typically comprised of tags, a reader, and a host computer which manages the information. While there are many designs of RFID systems, there are two primary types of tags: active, which have a local power source (e.g. battery, solar, etc.); and passive, which do not have an integral power source, and are energized by the reader via electromagnetic coupling during interrogation. The RFID tags do not require constant connection to the reader, and a single reader can be used to interrogate multiple tags either simultaneously, or separately. RFID tags do however, have a limited read range, which requires that the tags and reader be in close proximity; the tag-reader distance depends on the tag type and frequency range. In the present work, we use passive ultra-high frequency (UHF) tags.

There have been many approaches to capitalizing on the wireless nature of RFID tags for corrosion sensors, including incorporating elements in the tags which, when damaged by corrosion, would either cut off communication between the tag and reader,[9] or would result in a shift in the readable bandwidth.[6] Dante and Friedersdorf [8] took a different approach. The signal between the tag and the reader was initially blocked with a sacrificial metallic coating such as aluminum or copper, which, when damaged through corrosion, would eventually restore communication. Some of the problems encountered in this work included the high corrosion resistance of the coating material, which was not ideal for corrosion monitoring, and difficulties associated with applying the thin coating to the tags.

The present work employs and builds upon the shielding concept developed by Dante and Friedersdorf [8] by using carbon steel foils and steel filled composite coatings to act as an electromagnetic interference (EMI) shielding material. The advantage of steel foils and composite coatings are twofold: first, the ease of application and second, the ability to tailor the conductivity of the composite paints through changes in the amount of additives. The objective of this work was to demonstrate the feasibility of using either a steel foil that would completely block the signal, or a conductive composite paint that will attenuate, but not completely block the RFID signal, both of which would act as a corrodible shield on an RFID tag.

Shielding theory

The signal between the reader and tag can be partially or completely blocked by the application of a conductive coating to the tag, which acts as an EMI shielding layer. The shielding effectiveness is the sum of the losses due to reflection off the front plane, absorption, and reflections of various surfaces and interfaces within the shield. The losses due to multiple reflections can be ignored, since they are usually only significant at low frequencies below about 20 kHz, and when the thickness of the EMI layer is thinner than the skin depth, which in the present work was calculated to be on the order of 6 μm.[10-13] In the present study, the following expression was used to calculate the shielding effectiveness (E_s) of a metallic foil and a theoretical conductive composite paint:[11,13-15]

$$E_s = 168.2 + 10\log_{10}\left(\frac{\sigma_r}{\mu_r f}\right) + 131.4\times10^{-6}\, t\sqrt{\mu_r \sigma_r f} \quad (1)$$

where σ_r is the relative conductivity of the shielding material (as compared to copper), f is the frequency in Hz, μ_r is the material's relative permeability, and t is the thickness of the shielding layer in μm. The first two terms on the right-hand side represent the loss by reflection, while the third term is the loss due to absorption. From this equation, it can be shown that at the UHF range of 902-928 MHz, in order to have a positive shielding value, a material with μ_r=1 and thickness t=10 μm should have a conductivity of at least 0.813 $S \cdot m^{-1}$. When considering a metallic foil where typical conductivities are in the range of $10^6 – 10^7$ $S \cdot m^{-1}$, the reflection term dominates, rendering the thickness inconsequential; the calculated shielding effectiveness is in excess of 60 dB, indicating that the signal is more than 99.9999% blocked [E_s=10log($Power_{out}$/$Power_{in}$)], even at thicknesses below 1 μm. Although discontinuities would develop due to corrosion damage, thereby allowing the signal to be partially restored, ultra-thin foils would not be sufficiently robust for the intended use. Conversely, He *et al.*[15] showed that for a theoretical steel-filled conductive composite with a volume fraction of 50% steel particles with an average particle size of 100 μm dispersed in an epoxy resin, the conductivity would be about 1500 $S \cdot m^{-1}$ using a model developed by Mamunya et al.,[16] and an interrogation frequency at the lower end of the UHF frequency range (902 MHz), a layer 110 μm thick would have a shielding effectiveness of 34.7 dB, or 99.97% of the signal would be blocked. Changes in the thickness of the theoretical composite coating of ±100 μm would only change the attenuation by about ±2 dB.

EXPERIMENTAL METHOD

Tags and Reader

The RFID tags used in the present work were 150×18×3 mm rectangular GAO RFID Fastenable Mount-on Metal† UHF (902–928 MHz) tags (Figure 1). These tags are made of laminated polycarbonate and ABS plastics with a built-in metal backplane, and are designed to be attached to a metallic surface with little or no interference of the signals. An Impinj Speedway Revolution R220† reader and associated control software were used to communicate with the tags. This reader had the capability for communication with tags over a range of power levels; in the present work, the transmitted power range was 10 to 30 dBm with a maximum receive sensitivity of -82 dBm.

Figure 1: RFID tags, showing (a) edge profile, (b) top surface of tag, (c) bottom surface of tag with built-in metal backplane, and (d) top surface of tag with plastic casing removed.

Various read metrics were evaluated, and the metric of read rate (reads/sec) at a given transmitted power (dBm) was found to be the best. Tags were read at a constant distance of 75 cm, and orientation

† Trade name.

of 0° relative to the reader antenna over a range of transmitted power. Further details on the performance of the uncoated tags are provided by He *et al*.[14]

Tag Coating

Two different coatings were selected to attenuate the signal between the reader and the tags: 1) plain carbon steel (UNS G10080) shim stock with thicknesses ranging from 25 μm to 300 μm, which was cut to the size of the tags and adhered to the large flat surface using double-sided tape, and 2) a composite coating comprised UNS G43400 steel powder with a nominal spherical particle size of <20 μm dispersed in Sherwin-Williams Opex[†] acrylic resin. In the present work, 75 wt% steel powder was added to the acrylic resin, in the as-supplied state without any additional cleaning or processing. The steel powder was selected based on three criteria:

(i) readily available commercially;
(ii) ability to provide an EMI shielding effect
(iii) ability to readily corrode in corrosive environments.

The resin was selected because it was supplied as a lacquer integrated with a binder and could be readily applied using conventional spray devices. In addition, the acrylic was reported to have low UV sensitivity and good weather resistance, and is thus suitable for the current application. The composite coating was prepared by mechanically mixing the steel powder with the acrylic resin. It was applied to the top surface of the RFID tags using a high volume low pressure spray gun, at thicknesses ranging from 180 to 1100 μm.

Corrosion Tests

The coated tags were subjected to accelerated corrosion tests based on SAE[(1)] J2334[17] with minor variations in the temperatures. The exposures were conducted in an automated cyclic corrosion test chamber. A salt solution of water and 0.5 wt% NaCl, 0.1 wt% $CaCl_2$ and 0.075 wt% $NaHCO_3$ was used as the corrosive medium. The 24-hour corrosion cycle consisted of three stages:

(i) humid stage: 50°C and 100% humidity for 6 hours
(ii) salt fog stage with fog at ambient conditions for 15 minutes
(iii) dry stage: 50°C and 50% humidity for 17 hours 45 minutes

The tags with the steel shim stock coating were subjected to 24 cycles, while those with the composite coatings were subjected to an additional 36 cycles, for a total of 60 24-hour cycles. Mild steel (UNS G10100) witness coupons were also subjected to 60 24-hour cycles, and the mass loss of the coupons was evaluated in accordance with ASTM[(2)] G1.[18] The RFID tag readings and the coupon masses were recorded at 12-cycle intervals.

RESULTS AND DISCUSSION

Shielding effectiveness of coatings

Prior to corrosion testing, the coated tags were evaluated using the metric of read rate at different transmitted powers to establish a baseline reading. As anticipated, the signal between the tag and reader was completely blocked at all powers up to the maximum of 30 dBm when the thinnest steel shim stock (25 μm) was bonded to the surface of the tags. The composite coating, on the other hand, did not fully attenuate the signal at the higher powers even at the thickest thickness tested (1100 μm),

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(1) SAE International (SAE), 400 Commonwealth Drive, Warrendale, PA 15096-0001
(2) ASTM International (ASTM), 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959

allowing some signal to be transmitted. Figure 2 shows the effects of the thickness of the composite coating on the read rate at various powers. Included in Figure 2 are the results from an uncoated tag, to demonstrate the attenuation with a thin coating at very low powers.

In an early part of this research, it was demonstrated that the shielding effectiveness of the composite coating generally increased with an increase in both thickness and metal powder content, as indicated by a decrease in read rate at a given power level. We found that at a higher metal content of 80 wt%, and a thickness of 1.5 mm, the signal at 30 dBm was not completely blocked.[15] The conductivity of the composite coating with 80 wt% steel powder was measured using a four-probe resistivity measurement system and found to be <1.0 $S \cdot m^{-1}$,[15] which is about 6 orders of magnitude lower than solid steel. In the 75 wt% composite coating, the volume fraction of steel within the coating was only about 30%, meaning that there was likely weak connectivity between the steel particles, resulting in a low conductivity composite coating. The conductivity of the composite paint can be readily manipulated through variations in the ratios of the steel powder to acrylic resins, and additions ranging from 50 to 90 wt% were investigated, and documented elsewhere.[15] However, the larger additions of the steel powder were difficult to disperse in the acrylic resin, and to apply to the surface of the tags. Composite coatings with 90 wt% steel powder were found to delaminate from the tag after only 12 corrosion cycles, and thus were not studied further.

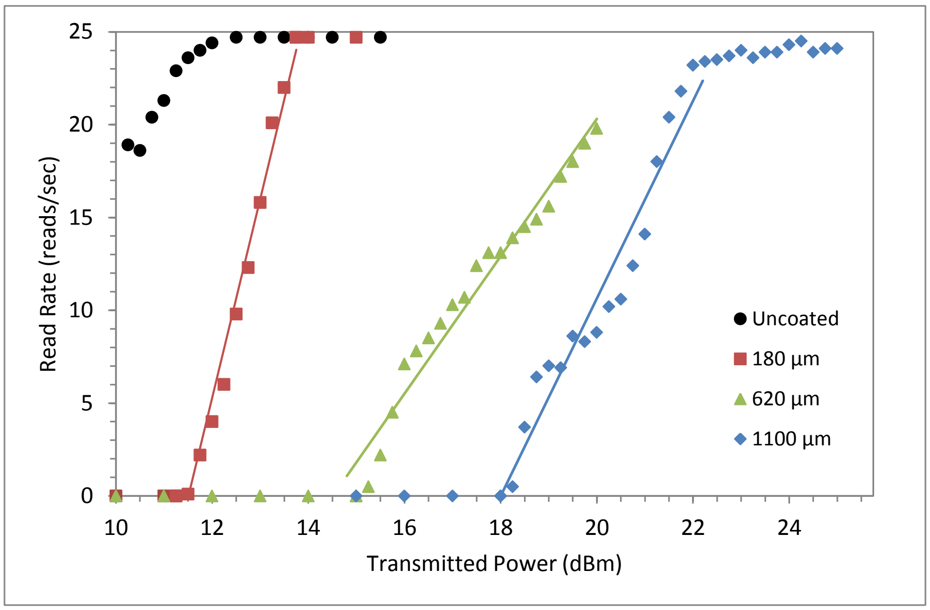

Figure 2: Read rate vs. transmitted power for RFID tags coated with 0, 180, 620, 1100 µm thick 75 wt% steel/acrylic resin composite coatings. (0 corrosion cycles, linear trend-lines added for emphasis)

Corrosion testing results

Figure 3a shows the read rates of the tags with the 25 µm steel shim stock following 12 and 24 24-hour corrosion cycles. After 12 cycles, the only powers investigated were 15, 20, 25, and 30 dBm. It is clear that the shim stock was sufficiently damaged such that the tag was readable at 15 dBm, even though the read rate was only about 5 reads/sec. When the power was increased to 20 dBm, the read rate was close to the maximum rate of 24.7 reads/sec. After an additional 12 cycles (24 in total), the tag was readable at the lowest power of 10 dBm.

As shown in Figure 3b, all tags coated with shim stock were readable after 24 corrosion cycles, and the minimum powers at which the tags were readable varied according to the shim stock thickness. The tag with the 300 µm shim stock was only readable at powers of 27.5 dBm and above, and the maximum read rate was not achieved at the highest read power of 30 dBm. While the shim stock coating does demonstrate the concept of an RFID based corrosion monitoring device, there were two issues noted: first, the signal was completely blocked when the tag was initially covered, meaning that it would be impossible to establish a baseline reading or to determine if the tag was functioning properly before sufficient corrosion damage had occurred; and second, rapid decay occurred in the shielding properties with only 24 cycles. While the thicker coatings of the tags would have a slower decay, and thus a longer useable life, there would still be an issue of establishing a baseline when they are freshly coated. SEM examination of the 25 µm coating following 24 cycles indicated that the steel shim stock coating had been nearly completely converted to a friable and flaky surface oxide. The other shim stock thicknesses investigated were mostly continuous, but had considerable conversion of the iron metal to lower conductivity iron oxides. This development of a delicate flaky surface oxide also limits the usefulness of the tags coated with the steel shim stock, as they would potentially lack the robustness required for the application of monitoring vehicle corrosion. Further analysis of the corroded shim stock coatings on the tags were reported by He *et al*.[14]

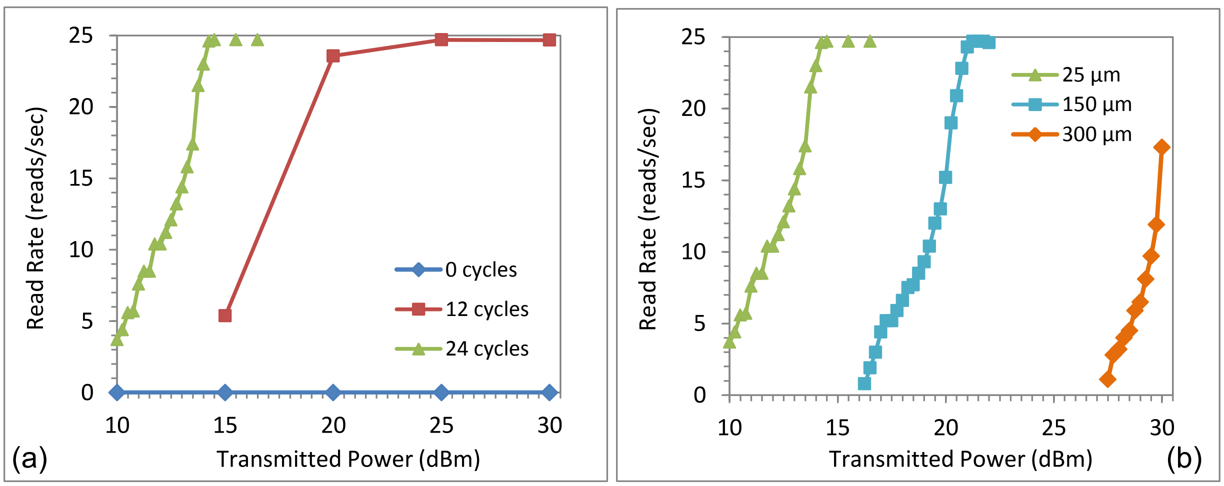

Figure 3: Read rate vs. transmitted power for RFID tags coated with steel shim stock and subjected to accelerated corrosion cycles (a) 25 µm shim stock following 0, 12 and 24 corrosion cycles (b) 25, 150 and 300 µm shim stock following 24 corrosion cycles

Figure 4 shows the read rate of the tag coated with 620 and 1100 µm thick composite coatings following 0, 12, 24, 48 and 60 corrosion cycles. Unlike the tags coated with the shim stock, the shielding effectiveness of the composite coating changed slowly, and in fact increased over the first 24 corrosion cycles, as indicated by the higher power required for the minimum number of reads. In Figure 4b, this is evident in the order of the curves; the curves for 12 and 24 cycles are to the right of that for 0 cycles indicating an initial increase in shielding effectiveness, while the curves for 48 and 60 cycles are to the left indicating a decrease in shielding effectiveness. This phenomenon was also observed with thinner composite coatings, although it was not as pronounced. The initial increase in shielding effectiveness yields a non-linear relationship between the total amount of corrosion and the signal strength, making the correlation between corrosion of a metallic object and the sensor readings somewhat more complicated. This increase in shielding effectiveness was not observed in the tags covered with the shim stock, likely due to the signal not being readable prior to the corrosion tests, as well as the long intervals between reads.

It is postulated that the initial increase in shielding effectiveness was due to the formation of ferrous oxides such as Fe_3O_4 which have considerably higher magnetic permeability than steel, thus providing magnetic dipoles for the shielding layer.[12,19] From Equation (1), an increase in permeability would cause an increase in absorption losses, and decrease in reflection losses. Scanning Electron Microscope (SEM) examination and Energy Dispersive X-Ray Spectroscopy (EDS) analysis of the composite coating following 24 corrosion cycles (Figure 5) indicated that most of the steel particles were converted to oxides and chlorides, which resulted in the expansion of the steel particles. This expansion led to an increased connectivity of the particles, which is likely another cause for the higher shielding effectiveness. As the corrosion continues, a decrease in electrical conductivity appears to dominate over the hypothesized increase in magnetic permeability, resulting in the overall decrease in the composite coating's shielding capability.

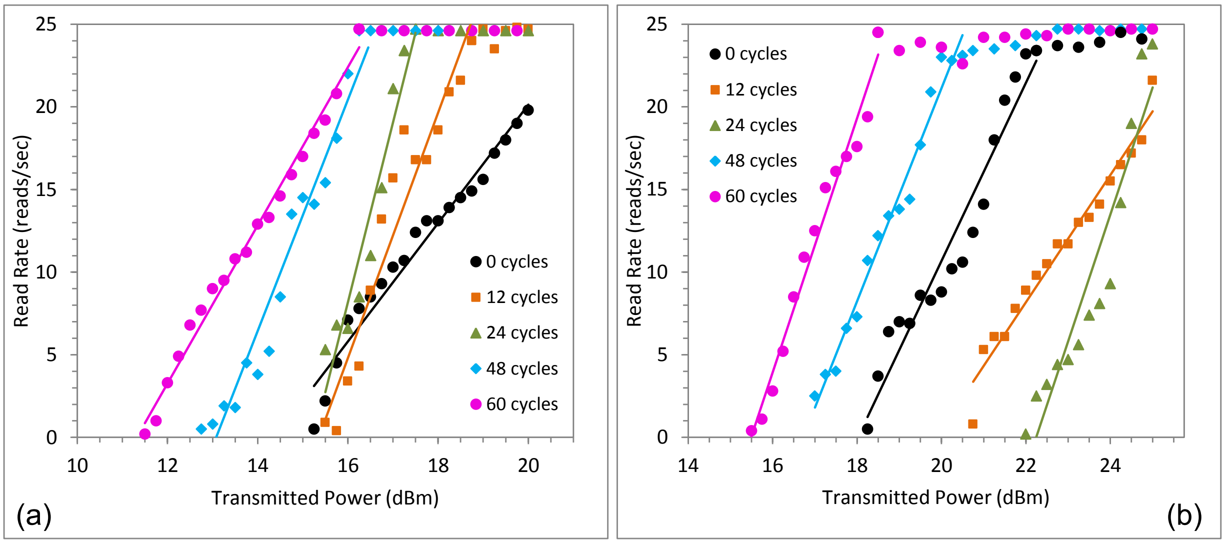

Figure 4: Read rate vs. transmitted power for RFID tags with (a) 620 μm and (b) 1100 μm thick composite coatings following 0, 12, 24, 48, and 60 corrosion cycles. Linear trend lines added for emphasis.

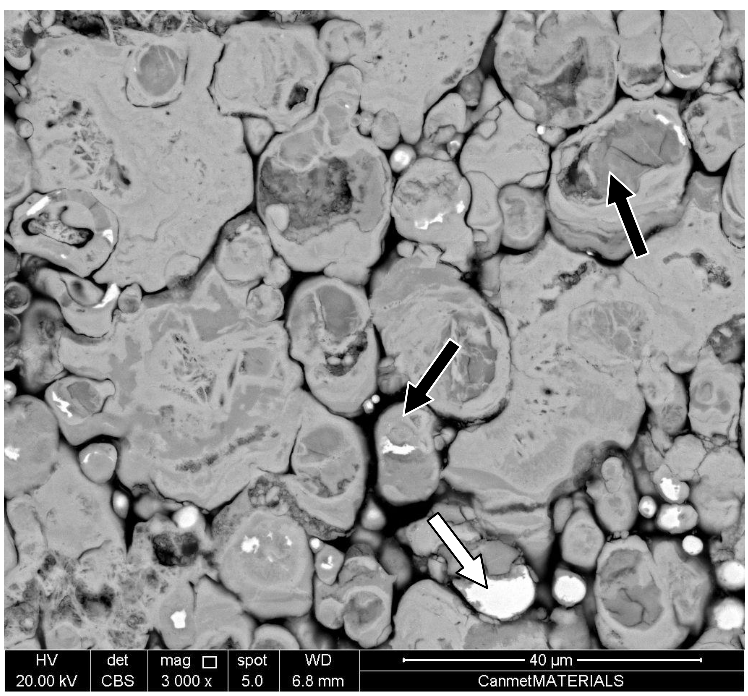

Figure 5: SEM image of cross section of composite coating after 24 corrosion cycles. The un-corroded steel particles appear as white regions (white arrow) while the oxides appear as darker grey regions (black arrows).

The coating type and thickness can be used to customize a sensor for a particular application, i.e., early detection, or long-term monitoring. Fully blocking the signal between the tag and reader means that the early onset of corrosion cannot be easily detected. Since the performance of the tags was not measured for fewer than 12 corrosion cycles, it is unknown what the minimum exposure period would be for the signal to be partially restored at any of the steel shim stock thicknesses. The incomplete shielding offered by the composite coatings allowed for the establishment of a baseline reading on the newly coated tags. Any subsequent changes in the coating chemistry and physical connectivity of the steel particles due to corrosion damage would be reflected in changes in reading performance relative to this baseline. As demonstrated in Figure 4, a thicker composite coating is desirable for longer term corrosion monitoring: while a higher power is required to activate the tag, there is a larger power range over which the damage is detectable, thereby allowing for longer detection of incremental damage. Another advantage of the thicker coatings is the clear delineation between corrosion cycles in the read rates at various power levels. The thinner coating (620 µm, Figure 4a) shows crossing of the curves between 0, 12, and 24 corrosion cycles at a power range of 15 to 16 dBm, while for the most part, the thicker coating (1100 µm, Figure 4b) shows clearly delineated curves. Thus, it is considerably easier to determine where in the corrosion process this tag would be, and to assess the potential amount of damage on the structure that it is monitoring.

SUMMARY AND CONCLUSIONS

Applying an EMI shielding to commercial RFID tags to manufacture low-cost, wireless corrosion monitoring sensors is a simple and straightforward concept. The principle involves coating the RFID tag with a material to provide a moderate amount of RF shielding which would degrade the tag/reader performance. When exposed to a corrosive environment, the coating material corrodes resulting in changes in the RF shielding properties of the coating that could be detected as changes in tag/reader performance.

Theoretical analysis and experiments showed that a solid metallic coating of only a few micrometers in thickness would completely block the RF signal. In contrast, moderate shielding could be achieved with a much thicker layer of a non-conductive polymer or resin matrix filled with a conductive material.

A composite steel powder/acrylic resin conductive paint was developed and applied to the surface of the tags. Performance of the coated tags depends on both the thickness and metal content of the paint. The performance of coated RFID tags changes when corrosion causes the degradation of the steel filled conductive coating layer. However, this change is not a linear relationship with respect to the number of cycles of accelerated corrosion. At the beginning of corrosion, the reading performance decreased due to the formation of higher permeability oxides. Reading performance then increased as corrosion continued, and finally was restored to close to the original uncoated values.

The results presented in this paper show that RFID based corrosion sensing has the potential to provide a low-cost and easy-to-implement wireless alternative to expensive and connected commercial sensors. Preliminary experimentation showed that the sensible life time of the composite coated sensors increases with the thickness of the coating and for long time corrosion sensing, a thick coating is needed. Additional work is required to optimize the coating thickness for a particular application, and to determine a suitable algorithm to combine the various read metrics into a parameter which can assess corrosion of the infrastructure to be monitored.

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