Galvanic Action of Zinc-Coated Steel
Fundamentals and Practical Applications

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INTRODUCTION

Corrosion protection of steel by zinc coatings, whether pure zinc or zinc alloy, is attributed principally to two effects: barrier protection due to its high corrosion resistance and cathodic protection due to its galvanic action with steel. Many factors, including type of coating, coating weight and pre-treatment, can affect the corrosion performance of zinc-coated steel, essentially through affecting the balance between barrier resistance and galvanic protection capacity[1-3].

The corrosive environments experienced by zinc-coated steel may have different forms e.g. condensed water, rain, melting snow and splashed road water. These moisture forms are basically thin layer electrolytes with significant variations in thickness and chemical composition. Quantitative knowledge of galvanic action (i.e. the consumption rate of zinc coatings and the extent of galvanic protection) under these various forms of moisture is useful in understanding corrosion mechanisms and in developing zinc coating/paint systems with a good balance of barrier protection and galvanic protection. This paper presents the results of theoretical modeling of the galvanic action on a partially zinc-coated steel under a thin layer electrolyte.

Theoretical model

A partially zinc-coated surface that is covered by a relatively thin layer of electrolyte can be represented by co-planarly coupled metals as illustrated in Figure 1.
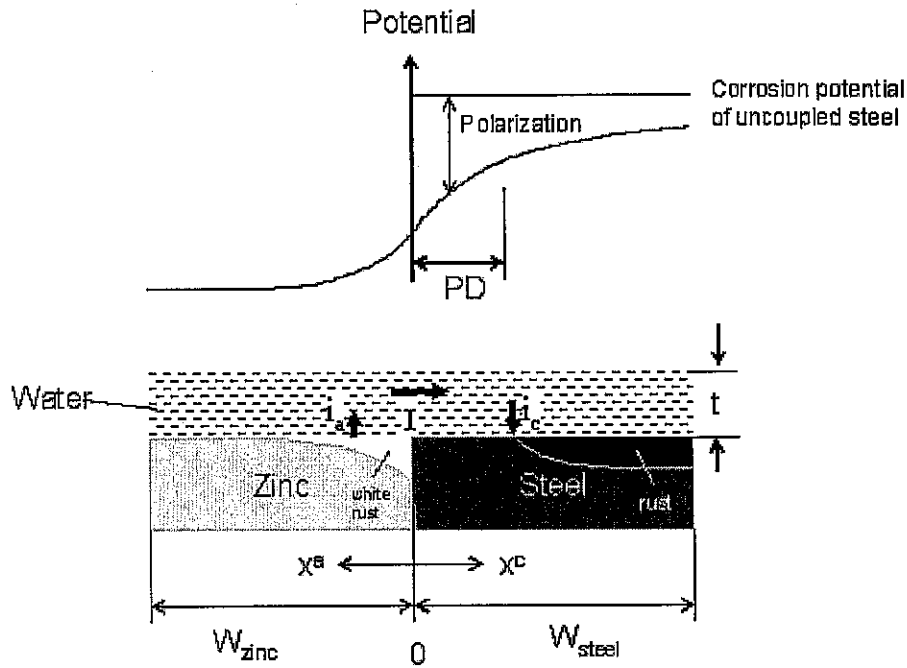
Figure 1 Schematic illustration of a planar zinc/steel bimetallic galvanic couple under a thin layer electrolyte.

The basic current and potential relationships for the geometric arrangement shown in Figure 1 can be expressed as follows:

$$I = I_a = I_c \tag{1}$$

and
$$E_{c,\,corr} - E_{a,\,corr} = ?_a(x^a) - ?_c(x^c) + ?\,V_R(x^a, x^c), \qquad \begin{array}{l} x^a \leq 0 \\ x^c \geq 0 \end{array} \tag{2}$$

where I_a is the total anodic current; I_c is the total cathodic current; $E_{a,\,corr}$ and $E_{c,\,corr}$ are the uncoupled corrosion potentials of the anode and cathode, respectively; $?_a$ and $?_c$ are the overpotentials of the anode and cathode, respectively, in the couple; and $?V_R$ is the ohmic potential drop across the electrolyte between x^a on the anodic surface and x^c on the cathodic surface.

I_a and I_c can be described by the following equations:

$$I_a = \int_0^{X_{ae}} i_a(x^a) l\, dx^a \tag{3}$$

$$I_c = \int_0^{X_{ce}} i_c(x^c) l\, dx^c \tag{4}$$

where l is the width of the electrodes; and $i_a(x^a)$ and $i_c(x^c)$ are the anodic and cathodic current densities, respectively.

The total ohmic potential drop in the electrolyte between any two points on the surface of the anode and the cathode for the situation in Figure 2 consists of two parts:

$$\Delta V_R(x^a, x^c) = \Delta V_a(x^a) + \Delta V_c(x^c) \qquad (5)$$

where ΔV_a and ΔV_c represent the ohmic potential drop in the electrolyte in the x direction across the anode and across the cathode, respectively. These potential drops can be further expressed by:

$$\Delta V_a(x^a) = \int_0^{x^a} \int_{x^a}^{x_{ae}} i_a(x^a) l\, dx^a\, dR(x^a) \qquad (6)$$

$$\Delta V_c(x^c) = \int_0^{x^c} \int_{x^c}^{x_{ce}} i_c(x^c) l\, dx^c\, dR(x^c) \qquad (7)$$

where ρ is the resistivity of the electrolyte; t is the electrolyte thickness; and d is the distance between the anode and cathode. The detailed consideration and procedure to form the above equations can be found in reference [2].

RESULTS AND DISCUSSION

When both the anodic and cathodic reactions are activation-controlled, $i(x^a)$ and $i(x^c)$ as a function of the anodic and cathodic overpotentials as expressed in Equation (2) can be expressed by the Butler-Volmer equation. Assuming the corrosion potential of steel is $E_{c,\,corr} = -0.55\ V_{sce}$ and that of zinc is $E_{a,\,corr} = -1.05\ V_{sce}$, which are commonly observed in aqueous solutions, the set of Equations (1) to (7) can then be solved numerically. Descriptions of the current-potential relationships, definitions of boundary conditions, and meanings of constants, as well as description of the numerical method, are detailed in reference [6].

A number of parameters are included in the theoretical model to account for the effect of many factors such as size of exposed steel, resistance of electrolyte (resistivity and electrolyte thickness), and surface activity of steel and zinc (kinetic constants in the Butler-Volmer equation, e.g. exchange current density). Through variations of these parameters, the galvanic action of partially zinc-coated steel, in terms of potential and current distributions on zinc and steel surfaces, can be studied for a specific set of material, environmental and geometric conditions. The results on potential and current distributions can then be used to obtain information regarding galvanic protection distance, distribution of galvanic corrosion on zinc surfaces, and rate of coating consumption.

In particular, protection distance (PD) is a quantifiable and measurable parameter that can be used to evaluate the effectiveness of galvanic protection in practical situations. PD, as shown in Figure 1, is defined as the width of the steel between the steel edge next to the zinc and the line of critical potential value, below which the steel can be considered to be fully cathodically protected. The critical potential value for cathodic protection of steel has been defined in a NACE Standard[4].

For zinc-coated steel, PD is essentially determined by the potential drop in the lateral direction in the electrolyte arising from the current flow from zinc to steel. The ohmic potential drop within PD depends on many factors, but can be simply described[5].

$$?V_e \, (PD) = \int_0^{PD} J(x^c)dR(x^c) = \int_0^{PD} J(x^c)[?/(tl)]dx^c \qquad (8)$$

where J is the total current flow in the electrolyte at x; $dR(x^c)$ is the resistance change over distance dx^c; ? is the resistivity; and tl is the cross-sectional area of the electrolyte, with t being the electrolyte thickness and l the length of the sample. Apparently, PD is a function of electrolyte resistivity, current and electrolyte thickness.

In the following, some results generated from the modelling are presented with consideration of their implications to practical interests. The results are also compared with experimental data to verify the relevance and accuracy of the theoretical modelling.

Effect of width of steel

Figure 2 shows the galvanic current and protection distance as a function of the width of the steel obtained from the numerical solution of Equations (1) to (8). The parameters were set to simulate the environmental condition that is under a thin layer electrolyte of moderate conductivity and surface activity. It shows that protection distance increases with the width of the exposed steel up to a critical width marked by W_{crit}, when the entire exposed steel surface area is cathodically protected. At widths larger than the critical steel value, PD becomes less than the width of the exposed steel. This means that, for an exposed steel width larger than the critical width, only a part of the surface is galvanically protected. Also, PD changes little with further increases in the actual width of the steel. The results from the modelling are in agreement with experimental data as shown in Figure 3 [5].
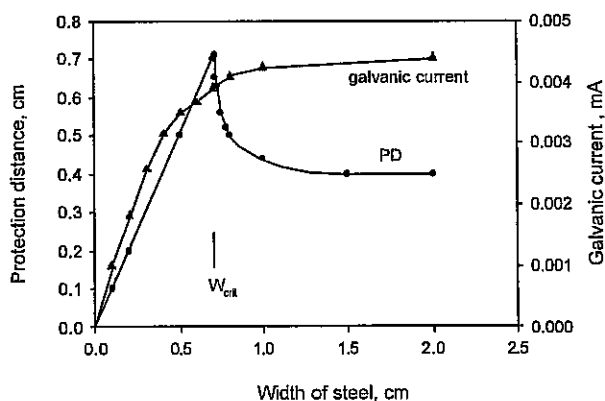

Figure 2 Results from theoretic modelling on protection distance, PD, and galvanic current as a function of the width of the steel.
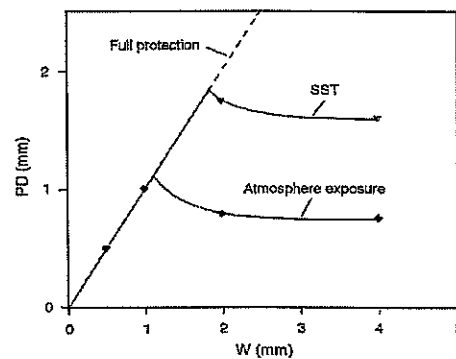
Figure 3 PD as a function of the width of exposed steel of planar zinc/steel couples experimentally determined in atmospheric and Salt Spray Test environments.

Figure 2 also shows that the galvanic current which resulted from the action between zinc and exposed steel increased with the width of the steel, that is, the larger the steel surface, the larger the current and the larger the corrosion rate of the zinc coating. The current becomes relatively constant when the steel width is greater than the critical width. One can conclude that galvanic action of partially zinc-coated steel under a thin layer

electrolyte, in terms of galvanic corrosion rate and galvanic protection distance, is active only within limited distance from the contact line.

Effect of surface activity

Figure 4 shows the effect of zinc surface activity on galvanic action. When the activity of a zinc surface is very low such as a passive surface, PD is practically zero, that is, the entire exposed steel surface is not protected. Meaningful PD values result as zinc surface activity increases to a certain value and it increases with increasing surface activity. The change in PD levels off at high surface activity. On the other hand, galvanic current increases with the increasing surface activity of zinc. Unlike PD, it does not level off at a high zinc surface activity.

The result has significant implications for practical applications. For a given environmental condition, there is a given range of zinc surface activity within which the exposed steel surface is protected effectively (with a relatively large PD and moderate I). The result explains the fact that there is no galvanic protection for an exposed steel surface when the zinc surface is in a passive condition as may occur in some hot waters.
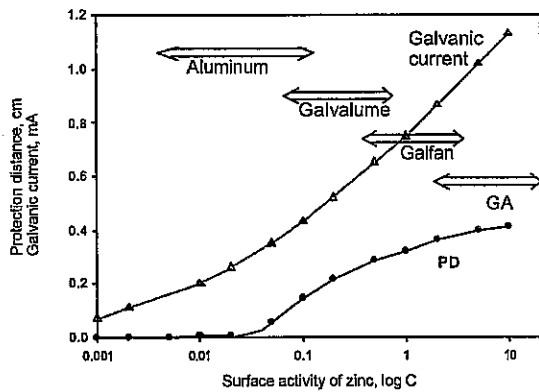

Figure 4   Results from theoretic modelling on protection distance, PD, and galvanic current as a function of surface activity of zinc; the length of the arrows in the figure illustrates the typical variation of surface activity of these different materials that may be involved in normal situations of application.
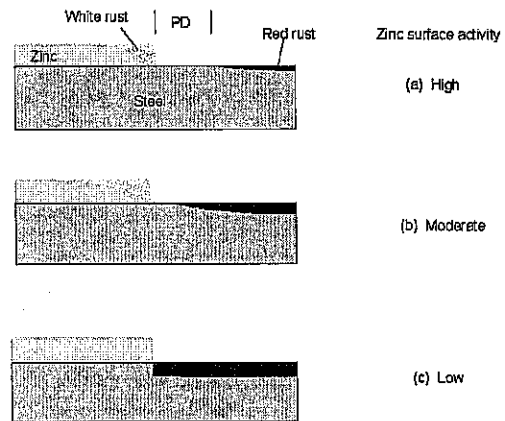
Figure 5   Schematic illustration for the distributions of galvanic corrosion, protection distance and red rust of steel for different surface activities of zinc.

The data in Figure 4 can also be used to explain the differences in galvanic properties between varied commercial Zn-Al alloy coated sheet products. Under normal environmental conditions, the surface activity decreases from galvanized to Galfan to Galvalume to aluminium-coated steel as qualitatively marked by the arrows in Figure 4. There are significant differences in PD and galvanic current for these materials. On one end, the pure zinc coating (i.e. galvanized steel) has the largest PD and galvanic corrosion rate of the coating. On the other end, aluminium-coated steel has the lowest PD and corrosion rate. This is why zinc-coated steel, due to its large PD, is widely used in atmospheric environments and aluminium-coated steel is not because it, having

insignificant PD, offers very little galvanic protection. Galfan and Galvalume have surface activity and thus galvanic properties between that of zinc and aluminium and are used in situations where high corrosion resistance and moderate galvanic protection are preferred.

Distributions of the galvanic current, i.e. galvanic corrosion, on zinc surfaces for different surface activities are illustrated in Figure 5, in which the boundary profiles of zinc/white rust and steel/rust were also determined from the modelling. In general, for zinc surface of high surface activity the galvanic corrosion is mostly localized near the boundary between zinc and steel. The corrosion can essentially be seen as propagating laterally as is commonly observed for a partially coated steel such as at cut edges and scratches in atmospheric environments, i.e. the zinc coating recedes over time from the boundary to exposed steel. On the other hand, for a zinc surface of low activity, there is very little galvanic corrosion of the zinc coating, but there is no protection of the steel and red rust forms on the entire exposed surface.

Effect of environmental condition

A dominant factor of environmental conditions on galvanic action on a bimetallic couple is conductivity of the electrolyte. Figure 6 gives the results on the galvanic current and PD as a function of electrolyte resistance. At a very low resistance, for a steel surface with a width of 1 cm, the entire surface is protected, i.e. PD = 1cm. PD starts to decrease with further increasing resistance at a critical value and reaches almost zero at very high resistance.

Thus, galvanic action has a strong electrical character. There is little galvanic action if the media allows very little current to flow between the two couple metals. This means that a large exposed steel area can be protected in a media of low electrical resistance while there is practically no protection when the resistance is high. As can be expected, the galvanic corrosion rate reduces with increasing resistance due to reduced galvanic action.
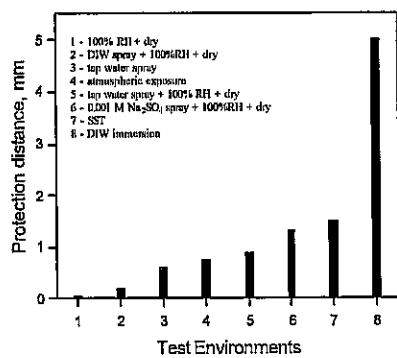

Figure 6 Results from theoretic modelling on protection distance, PD, and galvanic current as a function of electrolyte resistance.
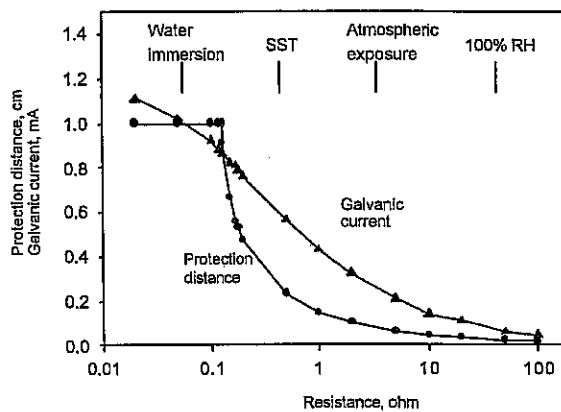
Figure 7 PD experimentally determined in different environments using planar zinc/steel galvanic couples.

The drastic effect of electrolyte resistance has been experimentally observed. Figure 7 shows the PD determined for a zinc/steel galvanic couple tested under various environmental conditions. In Environment 1, PD is close to

zero due to the extremely high resistance of the very thin moisture layer formed on the surface under the humid condition. On the other hand, a large PD, about 5 mm, was observed under a full immersion in de-ionized water (Environment 8). The large galvanic action under an immersion condition is due to low resistance of the large volume of electrolyte although the resistivity of DI water is very high. Several typical environments are placed in Figure 6 to illustrate the relative correlations between galvanic action and resistance of the electrolyte that are characteristic of these environments.

SUMMARY

The galvanic action between a partially zinc-coated steel under a thin layer electrolyte has been theoretically modelled. Numerical solution of the equations describing the model revealed valuable quantitative information regarding the relationship between galvanic action and the major materials, environmental and geometric elements in the planar bimetallic couple. In particular, the numerical results on the effect of the width of the steel, surface activity of the zinc surface and resistance of the electrolyte on galvanic current and protection distance were provided and discussed as examples. The results were found to be in good agreement with those obtained from experiments. They can also be used to successfully explain the phenomena observed in practical situations such as the difference in the galvanic action of various zinc-aluminum alloy coated steels.

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