Corrosion Behavior of Electrogalvanized Steel Plated Under Static & Rotational Conditions

By A.Y. Hosny, M.E. El-Rafey, S.H. Kandil and Y.A. El-Samadisy

The effect of plating conditions, such as current density and the rotation of specimens, on the corrosion resistance of pure zinc coatings was studied. The corrosion rates were determined by weight loss technique, through atomic absorption spectrophotometry and electrochemical measurements. The results indicate that a minimum corrosion rate of 18.9 *mpy* was obtained at a current density of 200 mA/cm^2 and rotational speed of 500 rpm. The deterioration in deposit morphology of Zn coatings was examined by scannning electron microscope. The results were in agreement with the corrosion rate measurements. A simplified energy study for the process was made, indicating that total energy consumption at 200 mA/cm^2 and 3.0 min is 2.0 and 4.2 kwh/kg for static and rotated specimens, respectively.

Coating is the most common means of combating corrosion of metals. It works on the principle of completely separating the metal from the cause of the corrosion, or slowing the reaction that may occur between the metal to be protected and the corrodent. Zinc is the most important coating metal for iron and steel. The success of zinc can largely be attributed to ease of application, sacrificial nature and low cost. The production rate of the zinc coating process is considered an important factor from the economic point of view; it needs to be maximized without sacrificing the quality of the coating. Accordingly, a primary thrust in the industry is directed to increasing the operating current density without sacrificing metal quality. The latter is most often gauged in terms of deposit smoothness, because rough, irregular growth occurs when the current density becomes excessive.[1-4]

Recent theoretical and applied studies, ranging from bench-scale to full-sized pilot cell, have shown the importance of enhanced mass transfer in improving the performance of many electrolytic systems, whether by means of optimized alternative cell design or improved forced convection in existing plants.

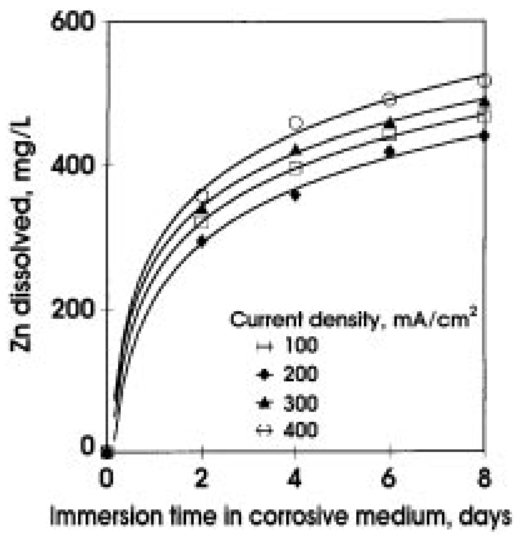

Fig. 1—Effect of current density on the corrosion resistance of Zn coatings in 3.5 wt percent NaCl at 0 rpm.

Table 1
Chemical Composition of Mild Steel

(Wt percent)

C	Si	Mn	P	S	Ni	Mo	As	Pb	Sb	Fe
0.09	0.09	0.57	0.03	0.01	0.02	0.01	0.01	0.01	0.01	Bal.

The present research investigated the effect of current density on the corrosion rate of Zn-coated steel at room temperature. The research also studied the effect of rotation on zinc coating quality. The corrosion rates were measured by weight loss and potentiodynamic techniques. The morphologies of Zn coatings were examined by scanning electron microscope (SEM).

Experimental Procedure

The plating process was employed on mild steel rods 4 mm in diameter. The chemical composition of the mild steel used is given in Table 1. A 250-mL glass container was used as an electroplating cell. The anode had a cylindrical shape and was made from pure zinc. The steel cathode was fixed in the center of the container by a holder. The composition of the zinc electrolyte and the corresponding plating conditions are shown in Table 2.

Before plating, the steel rods were degreased and polished electrochemically, then rinsed with tap and distilled water. The substrate was isolated with Teflon® tape, except 5 cm^2 left for zinc plating. Corrosion measurements were carried out by immersing the substrates in 3.5 wt percent NaCl solution, used as a corrosive medium. Atomic absorption spectroscopy (AAS) technique was used to measure the amount of zinc dissolved during the time of immersion. The values of zinc concentration obtained were converted to *mpy*.

Table 2
Zinc Electrolyte & Plating Conditions

Composition	
$ZnSO_4 \cdot 7H_2O$	442.4 g/L
Na_2SO_4	26.5 g/L
$CH_3COONa \cdot 3H_2O$	13.8 g/L
NaCl	1.0 g/L
Conditions	
Current density	100–600 mA/cm^2
Specimen rotational speed	0–700 rpm
Plating time	3.0 min
Temperature	25 °C
pH	4.0

The polarization measurements were made with a potentiostat. A scanning electron microscope was used to examine the morphology of zinc coatings on the steel substrates.

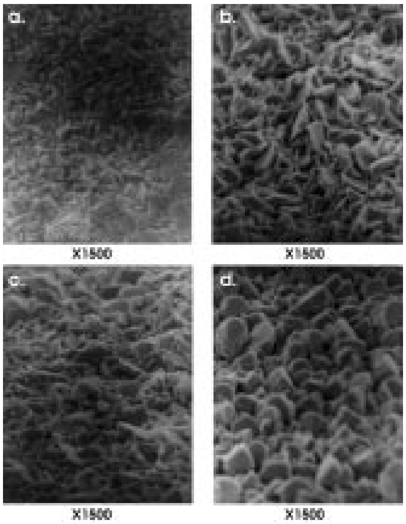

Fig. 2—SEM photographs for pure Zn coatings at: (a) 100 mA/cm^2; (b) 200 mA/cm^2; (c)400 mA/cm^2; (d) 600 mA/cm^2.

Results and Discussion

Figure 1 shows the effect of current density on the corrosion resistance of zinc coatings immersed in 3.5 wt percent NaCl solution. The results obtained show that increasing current density enhances zinc dissolution. For example, the concentrations of Zn resulting from corrosion after 192 hr (8 days) immersion time are 468, 443, 490 and 515 mg/L for current densities of 100, 200, 400 and 600 mA/cm^2, respectively. Current density of 200 mA/cm^2 is considered an optimum value to study the effect of rotation on the corrosion rate and morphology of coatings, because at higher current densities, Zn corrodes more rapidly. In addition, coatings obtained at lower current density, such as 100 mA/cm^2, also had greater corrosion rates. Visual examination of the surface of zinc coatings shows changes in texture, where they tend to be rough, porous and powdery as the current density increases. The micrographs shown in Fig. 2 indicate that lower current densities give finer, more compact coatings. The high loss of zinc resulting from the increase in plating current density could be attributed to the change in morphology of the deposit surface. It was recognized that deposit quality deteriorates quickly at current densities approaching the limiting values; consequently, corrosion rate is increased. Current density is considered an important factor in increasing the production rate of zinc coatings. A balance must be reached, therefore, between the production rate and the corrosion rate.[5]

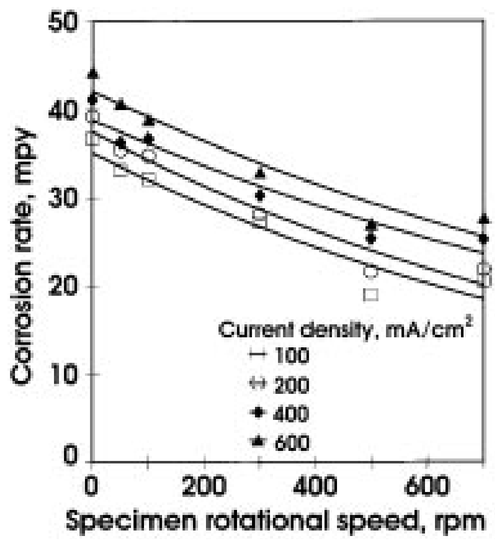

Fig. 4—Corrosion rate vs. specimen rotational speed at several current densities.

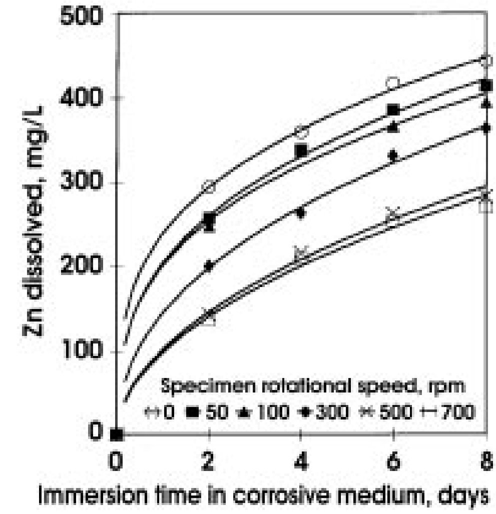

Fig. 3—Effect of specimen rotational speed on corrosion resistance of Zn coatings in 3.5 wt percent NaCl at 200 mA/cm^2.

Figure 3 shows the effect of specimen rotational speed on the corrosion resistance of zinc immersed in 3.5 wt percent NaCl solution. The results obtained indicate that increasing the rotational speed of a specimen decreases the dissolution of zinc in a corrosive medium. For example, plated Zn at a current density of 200 mA/cm^2, immersed for 192 hr in NaCl solution, gives zinc concentration of 443, 398 and 281 mg/L for 0, 100 and 500 rpm, respectively. Figure 4 shows the relationship between the corrosion rate in *mpy*, calculated from the total area under the curves of zinc dissolution with several plating conditions and rotational speeds. In all the current densities examined, the increase of specimen rotational speed decreases the corrosion rate. For example, the corrosion rate drops from 31.5 to 18.9 *mpy* as the rotational speed increases from 100 to 500 rpm at a current density of 200 mA/cm^2. The electrochemical technique supports the weight loss results measured by AAS. Figure 5 shows the polarization measurements carried out in 1-percent NaCl solution. The corrosion current density, I_{corr}, decreased from 9.3 x 10^3 to 3.9 x 10^3 nA/cm^2 as the specimen rotational speed increased from 0 to 500 rpm. It was also noticed that 14 mV difference between the equilibrium potentials, E_{corr}, was a result of rotation. This change is in the noble direction.

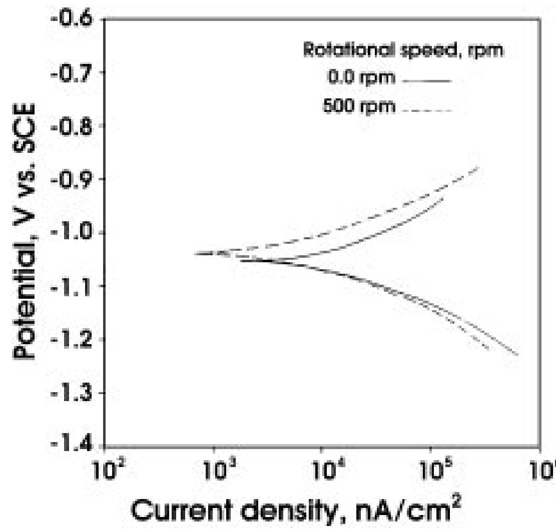

Fig. 5—Polarization curve for pure Zn coatings in 1-percent NaCl.

Table 3
Effect of Plating Conditions on the Corrosion Rate (*mpy*) & Power Consumption (kwh/kg)

Plating Conditions		Specimen Rotational Speed			
		0.0 rpm		500 rpm	
Current density mA/cm²	Plating time min.	Corrosion rate (mpy)	Power consumption (kwh/kg)	Corrosion rate (mpy)	Power consumption (kwh/kg)
100	6.0	39.5	1.7	22.4	4.0
200	3.0	36.5	2.0	18.9	4.2
400	1.5	45.1	2.9	26.9	6.0
600	1.0	49.8	4.2	29.9	7.2

obtained at 200 mA/cm² and 3 min in both the static and rotated conditions. It is important to realize that, in both conditions, the weight of zinc coatings is the same and equal to 120 g/m². The rate of production of zinc coatings, using plating conditions of 200 mA/cm² and 3.0 min, is twice the case of 100 mA/cm² and 6.0 min. From the point of production and corrosion resistance, therefore, it is preferable to carry out the coating process at 200 mA/cm² and 3.0 min. This can be applied on both the static and rotated conditions. The results in Table 3 indicate that power consumption doubles when specimens are rotated during plating. Although rotation was proven effective in improving the deposit quality and corrosion resistance, the production cost is expected to double. In addition, improving mass transfer by means of stirring is recommended and needs more study. Moreover, improving the corrosion resistance by changing bath composition, by alloying or addition of metallic additives, is also an attractive approach.[9,10]

The scanning electron micrographs for zinc coatings (plated at 200 mA/cm²) are shown in Figs. 6a and 6b for static and rotated specimens, respectively. The zinc facets in the case of rotation are smaller and more compact than in static condition. The morphology of these coatings was examined also after immersion in 3.5 wt percent NaCl solution for 48 hr. The resulting SEM photographs are shown as Figs. 7a and 7b. It was also observed that the dissolution of Zn for rotated specimens is less than that for the static condition. Therefore, the morphology studies agree also with the corrosion measurements.

The increase of specimen rotational speed enhances the connective mass transfer and decreases the diffusion layer thickness. As a result, the limiting current density for zinc electrodeposition would increase. This suggests carrying out the coating process at a current density not exceeding a certain fraction of the limiting value. Consequently, a smooth uniform deposit with regular growth is obtained.[6-8]

Power Consumption

Table 3 represents the results of simplified power consumption calculations for several plating conditions, for both static and rotated specimens. The study indicates that minimum power consumption per kg coat is obtained at a current density of 100 mA/cm² and plating time of 6 min. A wattmeter totaled the power consumed in mechanical rotation of specimens. Nevertheless, the minimum rate of corrosion is obtained at 200 mA/cm² and 3 min in both the static and rotated conditions.

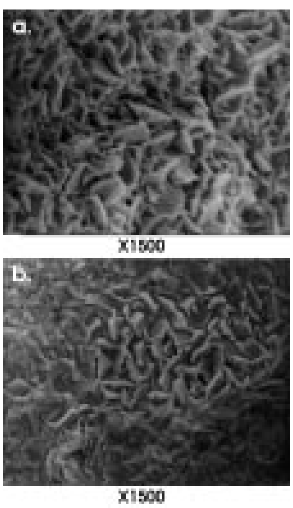

Fig. 6—SEM photographs of pure Zn coatings plated at: (a) 0 rpm; (b) 500 rpm.

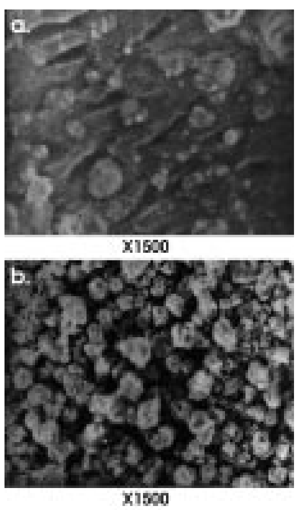

Fig. 7—SEM photographs of pure Zn coatings plated at: (a) 0 rpm; (b) 500 rpm; after immersion in 3.5 wt percent NaCl for 48 hr.

Findings

Plating current density of 200 mA/cm² offers the minimum corrosion rate for plating zinc on steel rods in both static and rotated conditions. Rotational speed of 500 rpm provides great enhancement in corrosion resistance and coating quality. The corrosion rate drops from 36.5 to 18.9 *mpy* when the rods are rotated at 500 rpm, indicating 50 percent improvement in corrosion resistance. The total power consumption at 200 mA/cm² and 3.0 min are 2.0 and 4.2 kwh/kg for both static and rotated conditions, respectively.

Editor's Note: *Manuscript received, September 1994; revisions received, April 1995.*

References

1. U.R. Evans, *An Introduction to Metallic Corrosion,* 3rd ed., Thomson Litho Ltd., East Kilbride, Scotland, 1981.
2. J.C. Seully, *The Fundamentals of Corrosion,* 2nd ed., Reber Mascwell, New York, NY, 1983.
3. K.R. Trethewey and J. Chamberlain, *Corrosion,* John Wiley & Sons Inc., New York, NY, 1988.
4. Moudlar Tutorial Course, "Unit Processes in Extractive Metallurgy," V.A. Ettel, National Science Foundation, Sec. IV, 1984.
5. F.A. Lowenheim, *Electroplating Fundamentals of Surface Finishing,* McGraw-Hill Book Co., New York, NY, 1978.
6. J.R. Cuzmar, PhD Thesis, University of Missouri, Rolla, 1985.
7. Y.A. El-Samadisy, MSc Thesis, University of Alexandria, Egypt, 1993.
8. T. Tsuda, K. Asano and A. Shibya, *Trans. ISU,* **26**, 53 (1986).
9. A.Y. Hosny, M.E. El-Rafey, S.H. Kandil and Y.A. El-Samadisy, *Metall,* **48**, 951 (1994).
10. A.Y. Hosny, M.E. El-Rafey, S.M. Morsy, T.A. Ramadan and B.A. El-Gafari, *Metal Finishing J.* (Accepted 1995).

About the Authors

Dr. Ashraf Y. Hosny is an associate professor in the Department of Materials Science, Institute of Graduate Studies, Alexandria University, Alexandria, Egypt. Currently, he is on sabbatical leave at the College of Technology, Riyadh, Saudi Arabia. He holds a PhD in chemical engineering from the University of Missouri-Rolla and is the author of several publications in zinc electrodeposition, in addition to studies on corrosion and electrochemical processes.

Dr. M.E. El-Rafey is an associate professor in the Department of Materials Science, Institute of Graduate Studies, Alexandria University, Alexandria, Egypt. He holds a PhD in mechanical engineering and is a researcher in mechanical and thermal properties of materials. He is also the author of several publications in the field of dental materials.

Dr. S.H. Kandil is a professor in the Department of Materials Science, Institute of Graduate Studies, Alexandria University, Alexandria, Egypt. Currently, he is on sabbatical leave at El-Ain University, United Arab Emirates. He holds a PhD in physical chemistry from Lancaster University, UK, and has more than 70 papers in materials science and polymer science.

Y.A. El-Samadisy is an analytical chemist at the Abu Kair Co. for the fertilizer and chemical industries. He holds a BSc in chemistry and an MSc in materials science from Alexandria University, Alexandria, Egypt. His research activities include electroplating and materials science.

Zinc-plated carbon steel (washer) and stainless steel (screw and part) were used together. The surface area of the more noble metal â€" the stainless steel â€" is larger, causing heavy corrosion of the washer. Corrosion handbook.Â Many methods for testing corrosion resistance are specific to particular materials and are based on conditions prevailing in certain environments. A large number of factors affect corrosion behavior. Hence there is not a unique and universal corro-sion test covering all aspects of materials in use. The most reliable indicator of corrosion behavior is service history, but this information is not always available exactly as needed. For that reason, other tests are required, i.e. ranging from accelerated laboratory tests to field tests. The behavior of corrosion in reinforced concrete, buried in a soil type silt of higher plastic (MH), the present study represents the conditions of exposure that can find the foundations of infrastructure such as bridges, buildings, pavements, when in contact with a soil that could contain aggressive agents like chlorides and sulfates. In such concrete specimens a carbon steel bar AISI 1018 and Galvanized Steel was embedded as reinforcement, the mixed In this way, the real corrosive conditions of the rolls were evaluated and an electrochemical cyclic treatment was designed [10] . This treatment was used to generate the same type of corrosion pattern that was observed in the DSS. ...Â Conductor rolls carry electrical current from steel strip during plating on a continuous electrogalvanizing line. Wear of type 316L (UNS 31603) stainless steel (SS) sleeves on the conductor rolls can lead to increased line downtime and higher operating costs.Â When under a wide potential range and a relatively negative upper potential, pits tend to grow into big size with a low density.Â Their corrosion behaviour was investigated in sulphuric acid and sodium chloride solutions using potentiodynamic polarization and chronoamperometric techniques. Corrosion of carbon steel and even alloy steels in micro-environments can be very complex. For example, the pH, moisture content, and chloride level are just three of the variables determining the corrosion rate of galvanized steel in soil. Corrosion charts are difficult to develop because of the many variables present in any given micro-environment. For example, corrosion in water must consider factors such as oxygen content, the extent of agitation, wave action, temperature, chloride levels and more. This makes developing a chart predictive of corrosion rates for any specific location extens This report reflects the state of the art of corrosion of metals, and espe-cially reinforcing steel, in concrete. Separate chapters are devoted to the mechanisms of the corrosion of metals in concrete, protective measures for new concrete construction, procedures for identifying corrosive environ-ments and active corrosion in concrete, and remedial measures. Keywords: admixture; aggregate; blended cement; bridge deck; calcium chloride; carbonation; cathodic protection; cement paste; coating; corrosion; corrosion inhibitor; cracking; deicer; deterioration; durability; parking struc-tures; polym