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COMMUNICATIONS

POLARIZATION RESISTANCE OF STAINLESS STEEL-COATED REBARS

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ABSTRACT

Stainless steel (316L) coated coupons and rebars were prepared using the twin-wire electric arc (TWEA) and high pressure/high velocity oxygen-fuel (HP/HVOF) processes. Metallographic examination was performed to characterize the coating density and the oxide content. The corrosion performance of the coatings was evaluated using linear polarization, AC impedance, and salt spray techniques. It appears that the coating prepared using the HP/HVOF process is far superior in terms of polarization resistance performance than that prepared using the TWEA process. The former process produces a dense, low-oxide-content coating while the latter produces relatively porous coatings. *© 1998 Elsevier Science Ltd*

Introduction

Treadaway et al. (1) conducted an intensive study on black steel, weathering steel (Corten), galvanized steel, types 405 and 430 ferrite steel, and types 302, 315, and 316 austenitic stainless steels. They reported that none of the austenitic stainless steel concrete specimens exhibited corrosion-induced cracks after 10 years of exposure. Cracks were observed in concrete reinforced with all other materials. Use of stainless steel rebar was also encouraged by the British Standards Institution (BSI) specifications for austenitic stainless steel bars used in the reinforcement of concrete in 1986 (2).

The solid stainless steel appears to be a potential alternative to black steel rebar due to its high polarization resistance. However, its high price has stimulated research to find cost-effective alternative materials, such as stainless steel-coated black rebar. In this work, the 316L stainless steel is used as a coating material because it has excellent polarization resistance, high temperature strength, and oxidation resistance. Ease of fabrication and weldability, good ductility, and good impact and chemical resistance are other attractive characteristics. This paper describes the evaluation of the polarization resistance of various stainless steel coatings produced by the spray process technology, i.e., twin-wire electric arc

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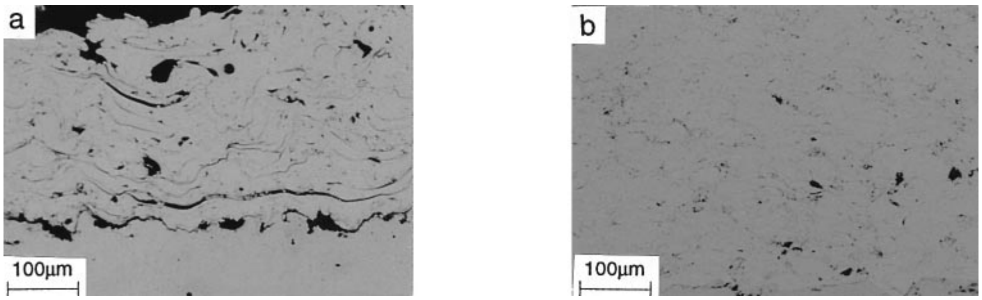

FIG. 1.
A) The microstructure of the coating prepared using the TWEA process; *B*) the microstructure of the coating prepared using the HP/HVOF process.

(TWEA) and high pressure/high velocity oxygen-fuel (HP/HVOF) processes. The linear polarization and AC impedance techniques, salt spray studies, and metallographic examinations were utilized to monitor the performance of the stainless steel-coated rebar.

Experimental

Thermal Spray Processes

Two thermal spray processes, twin-wire electric arc (TWEA) and high pressure/high velocity oxygen-fuel (HP/HVOF), were applied to produce high-polarization-resistance stainless steel coatings. The TWEA process was selected due to its high deposition efficiency, low cost, and the ease of spray application in the field. The HP/HVOF process was selected to produce a thick and dense coating with no open porosity. The thickness of the TWEA and HP/HVOF coatings produced for this investigation were 0.457 and 0.635 mm, respectively. The detailed TWEA and HP/HVOF deposition parameters are given elsewhere (3).

Porosity and Oxide Measurements

Porosity and oxide content were determined using computer-aided image analysis of the as-sprayed, impregnated, and polished sections. Micrographs were taken with a scanning electron microscope JEOL-6100 in the Backscatter Electron Imaging mode, using the optimum contrast to enhance the iron oxides and pores. There were significant differences in the microstructure between the TWEA and the HP/HVOF-sprayed samples. Figures 1A and B show the microstructure of the coatings prepared using the TWEA and HP/HVOF processes, respectively. The former coating has a porous microstructure with about 5.8% porosity and 5.6% oxide content, while the latter has less than 1% porosity and 2% oxide content.

Linear Polarization Measurements

The polarization resistance and corrosion current of the seven samples were measured in a 3.4% NaCl + saturated $Ca(OH)_2$ solution. The electrochemical measurements were made using an EG&G potentiostat model 273, which was computer-controlled using the SOFT-CORR software. The electrochemical measurements were taken on the coupons in an EG&G flat cell in which the center of one side (1 cm^2) was exposed to the test solution. A $Hg/HgCl_2$ reference electrode was used. Before the measurements, the stainless steel-coated coupons (7.62 $\times$ 7.62 cm) were degreased ultrasonically by immersion in acetone for 2 min. The samples were pre-soaked in the test solution for various times, from 10 min. to 24 h before the linear polarization measurements were taken. A slow potential scan (0.166 mV/s) close to the corrosion potential was employed. Duplicate measurements were then taken on the individual coupon in the flat cell at different times.

AC Impedance Measurements

An EG&G potentiostat (model 273) and EG&G lock-in analyzer (model 5301) were used for the AC impedance measurements. A sinusoidal voltage signal of 10 mV was applied over the range of frequencies of 10 kHz to 0.01 Hz. The current induced by this voltage perturbation was measured, as well as the phase shift of the current and voltage characteristics. The same electrochemical cell used for linear polarization was used.

Salt Spray Tests

Stainless steel-coated bars were placed in a Q-Fog Prohesion/Salt Spray Testing Machine and exposed to continuous cycles of 1 h salt spray/1 h drying for a period of 4 weeks. The salt spray cycle consists of spraying a 5% $\pm$ 1% (by mass) salt solution using compressed air under 48 psi into the chamber. Both spray temperature and chamber temperature are maintained at 22 $\pm$ 4°C during the salt spray cycle. The chamber was heated to 35 $\pm$ 4°C during the drying cycle. Visual inspection of the severity of corrosion was conducted at the end of the fourth week.

Results and Discussion

Potential-Current Density–Time Curves

Potential-current density curves recorded at various times for samples produced using the TWEA and HP/HVOF processes are shown in Figures 2A and B, respectively. Distinct differences were observed. For the coating prepared with the HP/HVOF process, the potential-current density (E-I) curve moved towards less negative potential (more noble) as the soaking time increased from 10 min. to 2 h, then remained relatively stable.

In contrast, the E-I curve for the coating prepared with the TWEA process moved towards more negative potential (less noble) as the soaking time increased to 24 h. The direction of the E-I curve shift is an instant descriptor of the quality of the stainless coatings. Corrosion potential, E_{corr}, is another clear indicator of the quality. In steel corrosion, a less negative corrosion potential is normally related to a lower corrosion rate. The coating prepared by the HP/HVOF process as depicted in Figure 3 exhibits a corrosion potential shift towards a less negative value indicating an ability to passivate. In contrast, the coating prepared by the TWEA shifts to more negative values, due to the high open porosity that allows chloride ion-containing solution to penetrate onto the surface of the substrate.

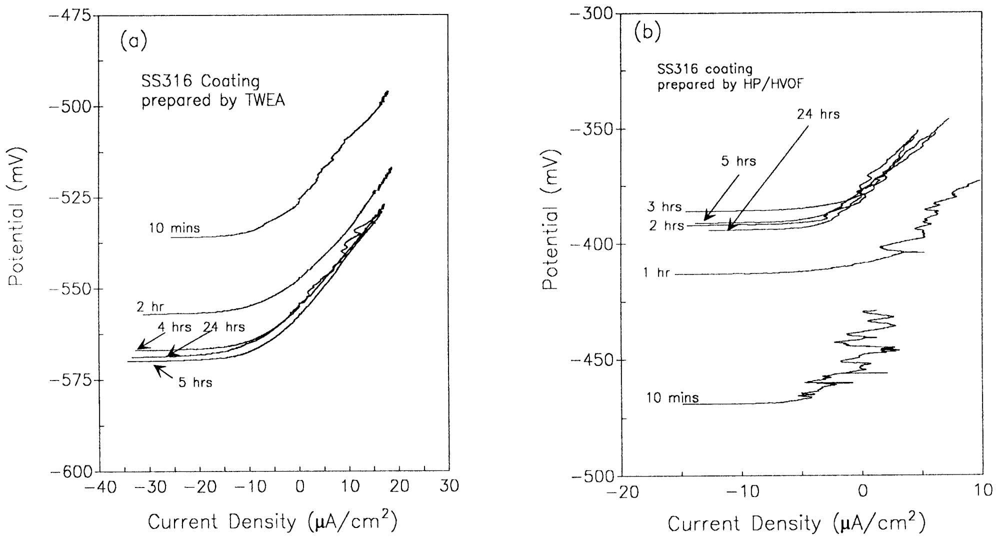

FIG. 2.

A Plot of Potential-Current Density curves recorded at various soaking times for the coatings: *A*) prepared using the TWEA process and *B*) prepared using the HP/HVOF.

Polarization Resistance and Corrosion Rate Measurements

The polarization resistance, R_p, is commonly used as a measure of the resistance of a metal to the corrosion damage. A high value of R_p is associated with a high corrosion prevention capability; a low value of R_p indicates potential high corrosion activity. The values of

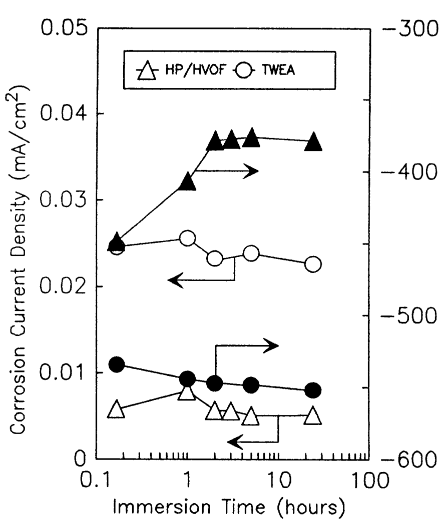

FIG. 3.

A plot of Corrosion Potential and Current Density vs. Soaking Time for the stainless steel coatings prepared by both the TWEA and HP/HVOF processes.

TABLE 1
Polarization resistance values, R_p, (Ω/cm^2).

Coating Process	0.167 h	2 h	5 h	24 h
HP/HVOF	4446	4559	5107	5031
TWEA	1057	1119	1090	1149

polarization resistance, R_p, of all the coatings subjected to a 3.4% NaCl + saturated $Ca(OH)_2$ solution were determined and listed in Table 1. The corresponding corrosion current density values (plotted in Fig. 3) were calculated using the Stern-Geary equation (4) $I_{corr} = B/R_p$, where the R_p was determined by the entire potential-current curve fitting procedure to overcome the curvature of the curve (5), and a value of $B = 26$ mV for active steel corrosion (6). A comparison of the coatings prepared by the TWEA and HP/HVOF processes indicates the latter has a higher polarization resistance and a lower corrosion rate. It is obvious that the coating produced by the HP/HVOF process has a much lower corrosion rate (about 4–5 times as indicated in Fig. 3) than that produced using the arc spray process. The low porosity (0.8%) and oxide content (2%) of the HP/HVOF coating certainly contribute to its superior performance. In the coatings produced by TWEA, the increase of surface area due to the open porosity and surface roughness may be one of the reasons for a large corrosion rate. When the surface of these samples is in contact with the 3.4% NaCl + $Ca(OH)_2$ solution, the coating prepared by the HP/HVOF process protects the substrate very well from the chloride-induced corrosion. However, the coating produced by the TWEA fails to protect the substrate. Chloride ions appear to penetrate into the substrate through the open porosity of the coating, resulting in the corrosion potential shift towards more negative values.

AC Impedance Characterization

A low frequency AC impedance study of the two coatings prepared by the TWEA and HP/HVOF processes was conducted. The impedance data recorded at the 24 h soaking time are presented in a complex-plane diagram (Fig. 4). Only a part of the semi-circle is observed for the coating prepared by the HP/HVOF process. Two arcs for the coating prepared by the TWEA process correspond to a different surface corrosion process. The diameter of these arcs is a function of polarization resistance. Qualitatively, the coating prepared by the HVOF process shows a much larger arc diameter than that prepared by the TWEA process. This is in agreement with the results obtained in the LPR study. This superior polarization resistance is attributed to the low porosity and oxide content of the coating produced by the HP/HVOF process.

Salt Spray Performance

A relatively long-term salt spray test was also conducted to evaluate the polarization resistance performance of the stainless steel coated rebars. This is a very aggressive test, because a 5% NaCl solution was used in the spraying. The coated rebars experienced wetting-drying cycles associated with temperatures of 22°C and 35°C respectively.

The rebar surface corrosion after 4 weeks is shown in Figure 5. The coating prepared by

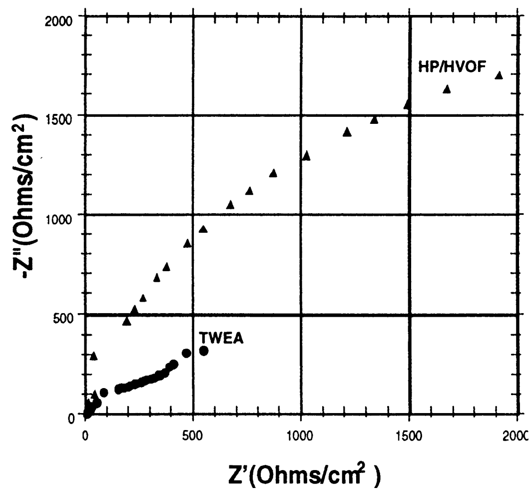

FIG. 4.
Impedance data (Nyquist plot) of the coatings recorded at 24 h soaking time.

the HP/HVOF process had no visible rust. This is in excellent agreement with the results obtained by electrochemical measurement. Galvanic coupling corrosion is evident for the coating prepared by the TWEA process. It is always a problem when a more noble coating is applied as a corrosion protection measure. Therefore, elimination of open porosity, cracks, and other defects, and minimizing oxide content in the stainless steel coating is the key to good protection. Otherwise, accelerated pitting corrosion will be the consequence. The combination of galvanic coatings such as Zn, Mg, or Al and epoxy will be examined in future studies in order to produce high polarization resistance.

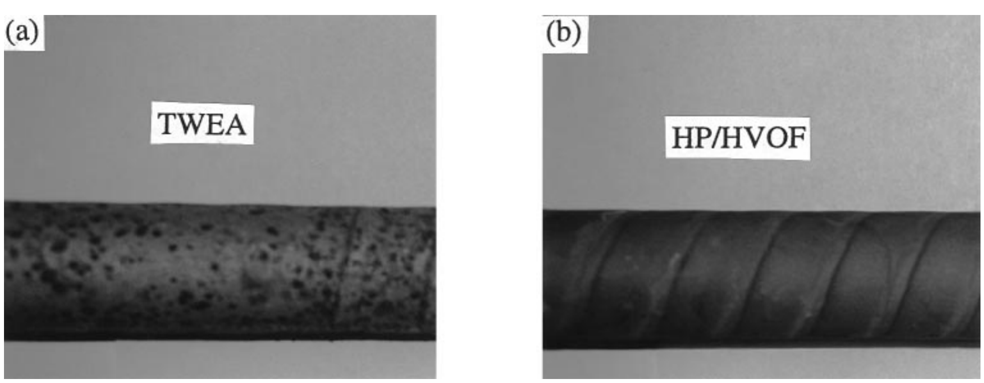

FIG. 5.
The rebar surface corrosion after 4 weeks exposure in the salt spray test: *A*) coating prepared by the TWEA process and *B*) by the HP/HVOF process.

Conclusions

The stainless steel coating prepared using the HP/HVOF process has superior polarization resistance compared to that prepared using the TWEA process. The former process produces a dense, low-oxide-content coating while the latter produces relatively more porous coatings. Galvanic coupling corrosion is a problem in this stainless steel coating. Elimination of open porosity, cracks, and other defects, and minimizing oxide content in the stainless steel coating is therefore an important protective measure. It is suggested that combinations of galvanic coatings using Zn, Mg, or Al and epoxy be considered in future research.

Acknowledgment

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