Electrolytic plasma processing for cleaning and metal-coating of steel surfaces

E.I. Meletis, X. Nie*, F.L. Wang, J.C. Jiang

Materials Science and Engineering Program, Mechanical Engineering Department, Louisiana State University, Baton Rouge, LA 70803, USA

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Abstract

Electrolytic plasma processing (EPP) involves electrolysis and electrical discharge phenomena and it is an emerging, environmentally friendly surface engineering technology. Electrolytic-plasma/material surface interactions during processing can be used for cleaning of metal surfaces, formation of diffusion layers and/or deposition of metal, ceramic and composite coatings. The present work was concerned with cleaning and deposition of metal coatings on steel surfaces for corrosion protection. The effects of processing parameters on (i) cleaning steel surfaces (oxides and contamination); and (ii) Zn and Zn–Al coating deposition were investigated. Surface roughness and oxygen content prior to and after cleaning were evaluated by profilometry and energy dispersive X-ray analysis (EDAX), respectively. The structure of the EPP cleaned outer surface layer as it evolves after the electrolytic–plasma interaction was studied by high resolution TEM. Morphology, microstructure, composition, adhesion and density of EPP-deposited Zn and Zn–Al coatings on cleaned surfaces were studied as a function of processing parameters. Corrosion properties of the cleaned and coated steels were evaluated by corrosion potential and potentiodynamic polarization measurements. The results show that EPP can effectively produce clean surfaces and also metal and alloy coatings at high deposition rates, and it has a great potential as a new plasma surface engineering technique. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Corrosion; Cleaning; Coating; Zn; Zn–Al; Plasma electrolysis

1. Introduction

Metallic coatings (such as zinc and zinc–aluminum) can provide corrosion protection to the base metal from a corrosive environment by acting as sacrificial anodes (cathodic protection). Such protection requires a more active corrosion potential for the coating compared to the substrate material. Under these conditions, the coating corrodes preferentially and provides protection to base metal even when exposed due to coating discontinuities or mechanical damage. Corrosion tests and data of a zinc protective coating for steel have been developed and widely used to describe its performance [1,2].

In the majority of applications for structural steel (ship and marine structures, pipelines, bridge supports, industrial structures, etc.), cleaning is required prior to coating of the surface. Cleaning is needed firstly because steel is covered by a layer of mill-scale (produced by the hot-rolling mill), other ‘soil’ and oil and grease contamination. Secondly, adhesion to base metal is of utmost importance to coating performance and is directly related to the cleanliness of the surface and the ability to develop an ‘anchor’ surface profile (surface with microscale roughness) providing a key or mechanical interlocking for the coating.

Traditional methods of cleaning steel include: acid pickling and sand/shot grit blasting. These conventional methods have major disadvantages (high energy cost, environmentally-unfriendly, disposal problems, unfavorable surface profile, etc.). Electrolytic cleaning methods are known, but they have not been successfully commercialized since in their present state they are unable to remove mill-scale and other heavy contaminants. Likewise, current metal coating methods have several limitations. For example, electro- and electroless plating are relatively slow and may use environmentally hazardous chemicals. Dipping and metal spraying methods are faster but the resulting coatings may have adhesion problems during bending and formation in some cases.
Thus, there is a need at present for new, cost-effective cleaning and coating methods that can produce quality, long-lasting surfaces.

Plasma electrolysis is a relatively new surface engineering technique, which includes an anodic process (such as plasma electrolytic anodic oxidation) [3,4] and a cathodic process (such as plasma electrolytic saturation) [5]. Plasma electrolysis has a similar configuration to a conventional anodic oxidation or electroplating process. However, the applied electrode potential in all the electrolytic plasma processes is much higher than that of the conventional processes. The bi-phase electrode/electrolyte system normally encountered in conventional electrolysis is transformed into a four-phase electrode/dielectric/gas(plasma)/electrolyte couple for the anodic oxidation processing or a three-phase electrode/gas(plasma)/electrolyte couple for the cathodic processing [6]. In the plasma discharge channel/area, plasma chemical interaction occurs, and oxides [3,4] or nitrides [5] can form on substrate surfaces to be treated.

Plasma electrolysis can be quite versatile. For example, it can be utilized in conjunction with PVD/CVD processes for improvement of tribological and corrosion properties [4], or with electrophoresis to form biomimetic ceramic coatings [7]. In this work, plasma electrolysis was extended to cleaning mill-scales on steel surfaces, and to depositing Zn and Al–Zn coatings on steel substrates as well, for the purpose of corrosion protection.

Electrolytic plasma process (EPP) may have the potential to overcome limitations of conventional methods, both for the cleaning and metal-coating of steel [8,9]. In the present work, EPP was studied in relation to cleaning steel surfaces and developing zinc (Zn) and zinc–aluminum (Zn–Al) coatings.

2. Process description

Electrolytic plasma processing involves two characteristic phenomena (i) electrolysis of a liquid environment by application of different electrical potentials between the workpiece material and a counter-electrode; and (ii) the production of an electrical discharge at, or in the vicinity of, the workpiece surface. Although the discharge phenomena associated with electrolysis were discovered more than a century ago by Sluginov [10], their importance as an emerging surface engineering process were realized only very recently [11]. A typical electrode current–voltage characteristic curve of the electrolytic cathodic process is shown in Fig. 1. The normal glow discharge zone $U_2$–$U_3$–$U_3$ is usually selected as the work region, where the electrode current decreases but plasma intensity increases when the electrode voltage increases from $U_2$ to $U_2$. The samples (as a cathode) can be either immersed in the electrolyte (Fig. 1a), or dripped with electrolyte (Fig. 1b). However, the corresponding slope of the electrode current–voltage curve in the $U_2$–$U_2$ segment is different in these two cases. For the configuration shown in Fig. 1a (i.e. the workpiece is immersed in the electrolyte), the current sharply drops from the highest point to the lowest point when the electrode voltage increases from $U_2$ to $U_2$. For the configuration in Fig. 1b (i.e. in this case, the electrolyte drips down to the workpiece through small diameter holes on the cathodic electrode plate), the slope of the $U_2$–$U_2$ line (i.e. current reduction rate) is much smaller than that of Fig. 1a. It is found that the plasma intensity increases when electrode voltage increases, and when $U_2$ is reached, a continuous envelope is formed on the sample surface, which results in rapid increase of the surface temperature with increasing electrode voltage. The normal operation voltage in this work is within $U_2$–$U_2$. Although there is heating of the substrate due to plasma action, the bulk substrate temperature remains relatively low (less than 200–300°C) due to the simultaneous cooling action by the electrolyte solution. The local surface temperature adjacent to plasma bubbles, however, is very high, which is critical to cleaning mill-scale and enhancing the metallurgical connection of the coating microstructure.

There appears to be several distinct physical processes involved in cleaning and subsequent coating using EPP [8,9,12]. While the electrolyte flows through the perforated anode onto the workpiece (cathode) (Fig. 2), a potential is applied across the electrode gap and sets up a strong electric field. The hydrogen evolution reaction begins to occur at the surface of the workpiece, creating fine hydrogen bubbles. A strong electrical potential is established on the bubble adjacent to the workpiece surface, and hydrogen plasma is thus generated in a thin layer, just above the steel surface. Metal cations present in the electrolyte film begin to migrate toward the steel surface, but the large majority of these ions are attached to the hydrogen bubbles. These ions are either original additions to the electrolyte or are generated from the anode metal by electrolytic decomposition.

In particular, in the case of cleaning, the cations may be sodium (i.e. sodium carbonate solution) which will participate in the process but ultimately remain in solution. The ions due to adsorption gradually concentrate on the hydrogen bubble surface and the bubble is thus converted into a small capacitor. The electrical field between the positive ions at the bubble surface and the negatively charged steel surface ionizes the hydrogen gas in the bubble, resulting in a high temperature plasma. This occurs quickly once hydrogen starts forming. The lifespan of the average hydrogen bubble is less than 1 ms and the plasma exists for 1–10 μs [8,11]. The plasma is continuously forming at this high rate over the entire steel surface. The nature of the plasma bulb generation and extinction results in local surface melting
and also creates forceful pressure disruptions at the surface associated with bubble collapsing and shock wave production. The net effect of these processes is the removal and/or reduction of the milling-scale at the steel surface and the formation of circular wavelets and spheroids. Also, the freezing that follows local melting causes a quenching effect that may result in ultra fine grained (or even amorphous) structures, as shown later in this work.

In the coating process, some metal ions may find their way to the steel surface by diffusion through the electrolyte but the predominant modes of transport are ion acceleration through the plasma and ion bubble adsorption transport where ions are carried to the steel surface by riding the surface of the hydrogen bubble as it collapses. Both of the latter processes eliminate the boundary layer diffusion and result in high deposition rates.

3. Experimental

The present work involved characterization and study of corrosion behavior of surfaces and coatings cleaned and deposited, respectively, by EPP. Low carbon steel (AISI 1010) was selected as the substrate material. A laboratory unit was utilized to produce the aforementioned cleaned surfaces and coatings according to the processing conditions shown in Table 1. These conditions were selected based on previous experience with EPP and the desire to systematically study the effect of processing parameters on the characteristics of the cleaned surfaces and produced coatings. Zn coatings were produced under two different process arrangements. In the first, a stainless steel anode was used and Zn deposition occurred entirely from the electrolyte (Zn coating I) and in the second, a Zn anode was utilized thus Zn was deposited from the electrolyte and the anode (Zn coating II).

After processing, specimen surfaces were examined by scanning electron microscopy (SEM) to characterize the surface morphology. The microstructure of the outer surface layer evolved by the electrolytic–plasma interaction was studied by focused ion beam (FIB) methods [13] and high resolution transmission electron microscopy (TEM) (JEOL 2010) on cross-sections of EPP cleaned surfaces. Metallographic cross-sections were also prepared to determine coating thickness, density and uniformity. Density was assessed by taking microhardness measurements (Knoop at 10 g) on coating cross-sections. Energy dispersive X-ray analysis (EDAX) was conducted in conjunction with SEM (Hitachi S 4500) to analyze the composition prior to and after EPP cleaning. Wavelength dispersive spectroscopy (Jeol JXA 733 super electron probe microscope) was conducted (at 15 keV accelerated voltage and 10 nA beam current) to analyze Zn and Al content in the Zn–
Fig. 2. Schematic illustration of the electrolytic plasma process.

Al coatings. Profilometry was performed after processing to characterize surface topography. Coating adhesion was determined by pull tests. Tapered Al pins (2.7-mm head diameter) were bonded to the coating with an epoxy (cured at 150°C for 30 min). The adhesion strength was estimated from the force required to pull the pin from the specimen.

Corrosion potential measurements and anodic polarization tests were performed to characterize the general corrosion behavior of the clean steel surfaces as produced by EPP. Tests were also conducted on the background low carbon steel (cleaned by grinding with 600 grit paper) for comparison purposes. Anodic polarization tests were also carried out on the Zn and Zn–Al coatings produced by EPP. Such tests were also performed on hot-dip galvanized steel (denoted as: galvanized) specimens that were supplied by the International Lead Zinc Organization (ILZRO).

The first type of experiments involved corrosion potential measurements for clean steel and background steel as a function of time in tap water for a total duration of $8 \times 10^3$ s. The second type of experiments involved anodic polarization scans that were conducted for all surfaces and coatings in two different environments: tap water and 3.5% NaCl solution using an EG&G Corrosion Measurement System (Model 273). In these tests, the potential was first allowed to stabilize and then scanned from a value of approximately 200–300 mV below the open circuit potential (OCP) to a value of approximately 800 mV above OCP at the scan rate of 0.2 mV s$^{-1}$, while current was continuously recorded. The corrosion rate was calculated from these tests using the Tafel extrapolation method. All corrosion potentials were measured with respect to a saturated calomel electrode (SCE).

4. Results and discussion

4.1. Effect of processing parameters

The processing parameters used for the EPP cleaning and coating treatments are listed in Table 1. The EPP cleaned surfaces were characterized in terms of surface morphology, roughness and oxygen content. The characteristics of the cleaned surface with the lowest oxygen content are presented in Table 2. Similarly, coatings were assessed in terms of adhesion, density (microhardness), roughness, composition, thickness, uniformity and continuity. Table 2 presents the range of these characteristics and those of the best coatings (based on a statistical analysis of performance data).

Fig. 3a and b shows the surface morphology in plan view and cross-section, respectively, of an EPP-cleaned steel specimen. The observed topography is a direct result of the interaction between physical processes taking place during EPP. As noted earlier, a high temperature plasma is created within the small size hydrogen bubbles in the thin electrolyte layer on the

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Cleaning</th>
<th>Zn coating I</th>
<th>Zn coating II</th>
<th>Zn–Al coating</th>
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<tbody>
<tr>
<td>Voltage (V)</td>
<td>170–200</td>
<td>180, 200, 220</td>
<td>180, 200</td>
<td>180, 200, 220</td>
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<td>Current density (A/cm²)</td>
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<td>0.11–0.78</td>
<td>0.3–0.5</td>
<td>0.8–1.2</td>
</tr>
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<td>Anode material</td>
<td>Stainless steel</td>
<td>Stainless steel</td>
<td>Zn plate</td>
<td>Stainless steel</td>
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<tr>
<td>Electrode gap (mm)</td>
<td>8, 12, 16</td>
<td>8, 12, 16</td>
<td>8, 12, 16</td>
<td>8, 10, 12</td>
</tr>
<tr>
<td>Electrolyte (wt.%)</td>
<td>NaHCO₃</td>
<td>ZnSO₄</td>
<td>ZnSO₄ 24%</td>
<td>[20% ZnSO₄ + 80% Al₂(SO₄)₃]</td>
</tr>
<tr>
<td>Flow rate (l/min)</td>
<td>3–3.8</td>
<td>1.9–3.8</td>
<td>1.9–3.8</td>
<td>1.9–3.8</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>75</td>
<td>73</td>
<td>73</td>
<td>70</td>
</tr>
<tr>
<td>Treatment time (s)</td>
<td>13</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
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</table>
surface of the workpiece during EPP. This causes localized melting but also shock waves from the collapsing of the bubbles and thus, strong surface forces on small molten patches of steel. The action of hydrogen is able to reduce oxides present at the surface and results in a clean surface. As the present experimental results show, O content was reduced dramatically in all EPP-cleaned specimens (Table 2). Typical EDAX spectra prior to and after cleaning are shown in Fig. 4. Once the plasma has dissipated, the temperature drops rapidly causing freezing of the produced features on the surface. The above processes leave an essentially ‘renewed’ surface, which is virtually clean. The surface consists of force impact craters and spheroidal projections at the rim of the impact craters producing a highly desirable profile for a subsequent coating treatment. In the present study, the lowest O content was observed in the specimen cleaned under the following EPP conditions: 12-mm electrode gap, 170-V electrode voltage and 3.5 l/min electrolyte flow rate.

Fig. 3c and d shows the morphology of the Zn coating (Zn coating I) that exhibited the best characteristics. This coating was developed by using an 8-mm electrode gap, 200-V electrode voltage, 24% ZnSO₄ solution and 3.6 l/min electrolyte flow rate. The coating exhibited excellent adhesion (>70 MPa) and SEM observations showed a dense and continuous structure with a thickness of 12 μm with no discontinuities at the coating/substrate interface (Fig. 3d). It is interesting to note the similarities in the surface morphology between the cleaned steel surface (Fig. 3a), and the Zn coating (Fig. 3c). It is apparent that the plasma/surface interactions create similar effects during coating (i.e. localized melting) producing a very similar surface morphology. Microhardness measurements at cross-sections of this coating revealed high values (0.97 GPa) consistent with SEM observations. Hardness of bulk Zn is approximately 0.8 GPa but in view of freezing expected after localized melting during EPP, the coating grain size is expected to be in the nanoscale (or even amorphous) thus possessing a higher microhardness as observed experimentally. Finally, the results show that surface roughness can be controlled to a certain extent by the processing parameters and that of the aforementioned best coating was found to be approximately 3.6 μm.

The second type of Zn coating (Zn coating II) was deposited by the same processing conditions as the aforementioned Zn coating I but using a Zn anode instead of a stainless steel anode. Compared to Zn coating I, the best coating in this case exhibited a higher deposition rate (0.47 μm/s), a somewhat higher density (microhardness, 1.06 GPa) and lower roughness (2.5 μm). Also, a relatively large but uniform grain/cluster structure was present on the surface (Fig. 3e). Observations at cross-sections also showed a dense and uniform coating (Fig. 3f). It should be noted that when a Zn anode is utilized during EPP, erosion of the anode takes place under the electric field thus activating an additional deposition mechanism. This is expected to result in higher deposition rates, higher density and smoother surfaces and is consistent with the experimental measurements of thickness, microhardness and roughness. It is important to note that in both of these coating treatments the deposition rates achieved are significantly higher than those obtained by conventional electroplating processes.

Regarding the Zn–Al coatings, the WDS analysis showed that under the EPP conditions used only small amounts of Al could be incorporated into the coating. The maximum Al content reached 3.0 at.%. This may be considered significant in view of the fact that Al deposition by conventional electroplating is not possible. Surface and cross-section morphology of the best Zn–Al coating obtained in the present study is presented in Fig. 3g,h, respectively. This coating was developed under a 12-mm electrode gap, 220-V electrode voltage, 10% electrolyte concentration and 2.9 l/min flow rate. A uniform, large grain/cluster was evident on the

### Table 2

<table>
<thead>
<tr>
<th>Characteristic data of the cleaned surfaces and coatings</th>
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<tbody>
<tr>
<td>Cleaned surface</td>
</tr>
<tr>
<td>Thickness (μm)</td>
</tr>
<tr>
<td>Deposition rate (μm/s)</td>
</tr>
<tr>
<td>Roughness (Rₛ)</td>
</tr>
<tr>
<td>(1.8–3.4 μm)</td>
</tr>
<tr>
<td>Element content (wt.%): 1.38 wt.% O₂</td>
</tr>
<tr>
<td>(1.38–7.3 wt.% O₂)</td>
</tr>
<tr>
<td>Adhesion strength (MPa)</td>
</tr>
<tr>
<td>(20 to &gt;70)</td>
</tr>
<tr>
<td>Hardness (GPa)</td>
</tr>
</tbody>
</table>

Note: Values in parentheses show the range of characteristic data determined for all samples treated under the parameters described in Table 1. Adhesion values >70 MPa show that failure occurred in the epoxy.
surface. A high deposition rate was also achieved in this case (0.56 \( \mu \text{m/s} \)). The coating exhibited good continuity, with some voids due to the large cluster structure as observed in the coating cross-section. Microhardness measurements on coating cross-sections showed high values indicative of high coating density. The microhardness values obtained were significantly higher than those observed in pure Zn. This more than likely is due to solid solution strengthening effects.

For all of the Zn and Zn–Al coatings, the anchor profile can be observed at the interface between the coatings and steel substrates. SEM analysis also showed that both Zn coatings were dense with good uniformity and no voids present at the substrate/coating interface. Closer observations showed that the Zn–Al coating exhibited more irregularities on its top surface and some voids in the coating structure. The reasons for such differences in topography are not very clear at present. However, the high electrode current density during the Zn–Al coating treatment (Table 1) indicates that the process is at the initial stage of \( U_2 - U_3 \) (Fig. 1), which can lead to an unstable and weak plasma. The sintering effects due to melting/condensing in plasma discharge channel on the Zn–Al coating are not as strong as those...
during the Zn coating treatment. Thus, the Zn–Al coating is expected to exhibit a larger cluster size. These effects are under further investigation at present.

4.2. Characterization of EPP-cleaned outer surface layer

In an effort to obtain more information on possible metallurgical changes at the outermost surface region, FIB and TEM studies were conducted on the cleaned steel surfaces. A FIB cross-section into the surface of EPP-cleaned specimens was made and high-resolution imaging was obtained in secondary electron mode. Fig. 5a shows an overall view of the specimen surface and cross-sectional area. It is evident that the bulk steel structure has a relatively large grain size >10 μm whereas the outer surface layer exhibits a very fine grain structure. Fig. 5b is a high magnification image of the nodule cross-section that is shown in the center portion of Fig. 5a. Two very interesting observations can be made. The bulk of the nodule exhibits a fine grain structure with a size of approximately 0.5 μm. At the surface of the nodule there is a thin layer with an ultra-fine structure. This evidence strongly suggests that quenching effects during freezing of locally melted surface material produce a fine microstructure at the surface layer. The grain structure at the latter outer surface layer could not be resolved with secondary electron imaging and thus it was further investigated by high resolution TEM.

Thin foils were prepared from the cross-sectional area of EPP-cleaned surfaces. The results showed the presence of a distinct outer surface layer that developed after cleaning on the entire specimen surface (Fig. 6a).
The thickness of the surface layer was found to vary between 150 and 250 nm. Electron diffraction analysis from the surface layer showed that it consists of an ultra fine-grained structure (Fig. 6b), where the basic steel contains the original large grain structure (Fig. 6c). High resolution TEM showed that the grain size in that outer layer is between 10 and 20 nm (Fig. 7). Plasma discharge developing in the hydrogen bubbles at the material surface during cleaning seems to have two basic effects. Firstly it reduces and/or removes oxides and mill scale from the surface and second, locally melts the surface layer. Due to fast cooling rate of the thin molten surface layer a fine grain size develops. Thus, the end result is a clean, nanostructured surface.

4.3. Corrosion behavior

Fig. 8 presents the variation of the corrosion potential of EPP-cleaned steel and background steel (cleaned by mechanical grinding) as a function of time. Background steel initially shows a small tendency for passivation (increase in potential) but its potential is gradually moving in the active direction and stabilizes at approx-
The potential of the EPP-cleaned steel is significantly higher than that of the background steel during the entire testing period. Upon exposure, the potential of the EPP-cleaned steel moves in the noble (passive) direction at a relatively high rate and stabilizes at approximately 50 mV (approx. 250 mV higher than its initial potential). Also, a comparison between the stabilized potentials (after $80 \times 10^3$ s) shows that the EPP-cleaned steel has a potential that is approximately 640 mV higher than that of the background steel. These results indicate that the surface cleaned with the EPP method exhibits passivation that remains stable during the test duration while the plain steel tends to be significantly more active. Visual examinations after testing were consistent with the above results since the background steel surface was completely rusted where the surface of the EPP-cleaned steel seemed intact. During EPP treatment, hydrogen plasma develops at high temperatures, and besides oxides is expected to also remove C from the steel structure. Thus, the present potential measurements are consistent with the formation of a clean, pure iron surface layer (with no presence of Fe/C microgalvanic cells).

Fig. 9 presents the anodic polarization behavior of steel in tap water and 3.5% NaCl solution and Table 3 summarizes the corrosion properties calculated from these tests. Consistent with the previous results in tap water, the EPP-cleaned steel exhibited a more noble corrosion potential and passivated for the entire potential range tested. On the contrary, the background steel exhibited breakdown at a potential of approximately 170 mV. It should be noted that at even lower potentials, the background steel exhibits a more active behavior (higher corrosion current density) compared to EPP-cleaned steel. Also, the results show that the corrosion rate exhibited by the EPP cleaned steel in tap water is significantly lower (approx. 25 times lower) than that exhibited by the background steel. These results are consistent with the presence of a pure iron layer at the surface of EPP-cleaned steel.

The NaCl solution is an aggressive environment and the behavior in terms of corrosion rate, is similar for both types of steel surfaces. However, the results show that the corrosion potential difference remains at the same levels as in tap water indicating that even in the

<table>
<thead>
<tr>
<th>Material/condition</th>
<th>Corrosion potential (mV (SCE))</th>
<th>Corrosion rate (µA/cm²)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Tap water</td>
<td>NaCl sol.</td>
</tr>
<tr>
<td>Background steel</td>
<td>−325</td>
<td>−535</td>
</tr>
<tr>
<td>EPP-cleaned steel</td>
<td>−196</td>
<td>−385</td>
</tr>
</tbody>
</table>
NaCl solution, the EPP-cleaned steel surface is thermodynamically more stable than the background steel.

Fig. 10 presents the anodic polarization behavior of the EPP Zn and Zn–Al coatings and the hot dip galvanized coating in tap water and 3.5% NaCl solution. In tap water, all three coatings exhibit activation polarization and comparable corrosion rates with the EPP coatings possessing a little higher corrosion potential. The behavior in NaCl solution is along the same lines with the EPP coatings possessing a little higher corrosion potential. Again all three coatings show activation polarization at potentials close to the OCP. The hot dip galvanized coating exhibited a little lower corrosion rate that can probably be attributed to the particular surface topography of the EPP coatings. The presence of craters or discontinuities at the surface produced a larger surface area than the nominal area used to estimate the current density and therefore the actual corrosion current density may be smaller. Thus, the present results demonstrate that the EPP method is capable of producing sacrificial coatings for corrosion protection while at the same time produces a ‘passive’ steel outer surface that can serve as an additional corrosion resistance layer.

5. Conclusions

The results showed that EPP can effectively clean steel surfaces that possess highly desirable anchor profiles. The produced surfaces are nanocrystalline and exhibit a passive behavior. The latter is a direct outcome of the physics involved in the cleaning process and results in a significantly improved corrosion resistance compared to base steel. This feature of enhanced longevity of the cleaned surface is important when considering the quality of subsequent coating operations and the allowable time lag prior to coating. The EPP method is also capable of producing adherent, dense and uniform Zn and Zn–Al coatings that can function as sacrificial anodes protecting the underlying steel while the passive steel outer surface layer can provide an additional corrosion resistance mechanism. The present results show that EPP is an emerging, high potential cleaning and coating technology.

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