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Cr₃C₂-NiCr Coating for the Protection of API Steel Corrosion in Concentrated Sodium Chloride Solution

El-Sayed M. Sherif ^{1,2,*} , Magdy M. El Rayes ³ and Hany S. Abdo ^{1,4}

¹ Center of Excellence for Research in Engineering Materials (CEREM), King Saud University, P.O. Box 800, Al-Riyadh 11421, Saudi Arabia; habdo@ksu.edu.sa

² Electrochemistry and Corrosion Laboratory, Department of Physical Chemistry, National Research Centre, El-Behoth St. 33, Dokki, Cairo 12622, Egypt

³ Department of Mechanical Engineering, College of Engineering, King Saud University, P.O. Box 800, Al-Riyadh 11421, Saudi Arabia; melrayes@ksu.edu.sa

⁴ Mechanical Design and Materials Department, Faculty of Energy Engineering, Aswan University, Aswan 81521, Egypt

* Correspondence: esherif@ksu.edu.sa

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Abstract: In the present work, a layer of 75%Cr₃C₂–25%NiCr with thickness of 260 ± 15 µm was coated onto the API-2H pipeline steel surface using high-velocity oxy-fuel deposition. The effect of 75%Cr₃C₂–25%NiCr coating on the corrosion of the API steel after 1 h, 24 h, and 48 h exposure in 4.0% sodium chloride solutions is reported. The corrosion tests were performed using potentiodynamic cyclic polarization, electrochemical impedance spectroscopy, and chronoamperometric current–time techniques along with scanning electron microscopy and energy-dispersive X-ray analyses. The curves of polarization indicated that the presence of the coating increases the corrosion resistance of the steel through decreasing its corrosion current and corrosion rate. Impedance data showed that all resistances recorded higher values for the coated API steel. Chronoamperometric current–time measurements confirmed that the coated API steel has lower absolute current values and thus lower corrosion rate. All results proved that the presence of 75%Cr₃C₂–25%NiCr coating enhances the corrosion resistance of the API steel via the formation of a protective layer of Cr and Ni oxides, which could lead to decreasing the corrosion rate.

Keywords: API pipeline steel; inorganic coatings; corrosion; electrochemical measurements; spectroscopic analysis

1. Introduction

It is well known that API pipeline steels have good toughness, high strength and weldability, low ductile to brittle transition temperature, and a low crack sensitivity coefficient [1–5]. Therefore, API pipeline steels have been widely used in construction, transportation pipelines, oil/gas storage tanks, off-shore rigs, agitators, pumps, and chemical processing [4–9]. Due to the exposure of these steels to corrosive media in most of their applications, corrosion takes place. The electrochemical corrosion behavior of different grades of API steels in many harsh environments have been reported by several researchers [1–6]. Alizadeh and Bordbar [2] investigated the effect of microstructure on the product layer formed on this steel in chloride media. They [2] have found that the corrosion of the API steel is decreased upon heat treatment due to the formation of a protective corrosion product layer. Bellaouchou et al. [10] have also reported the influence of changing the microstructure on the corrosion behavior of the welded joint in the pipeline steel. The alteration of microstructure on the corrosion of API pipelines was also reported by Hemmingsten et al. [11]. In this regard, changing the microstructure

is usually accompanied by a change in the composition of the materials of the API steel and also, the phases. This leads to corrosion via the galvanic form due to the increased dissimilarity and thus the great potential difference between the base metal and the weld metal [11,12].

We have reported the corrosion of two API steel grades, namely API-2H and API-4F steels after being exposed to varied exposure periods of time in sodium chloride solutions using different electrochemical and spectroscopic measurements [13]. It was found that these API steels suffer both uniform and localized corrosion; the severity of the pitting attack was found to decrease by increasing the time of exposure in the test solution. It was also found that the corrosion resistance of API-2H recorded a higher value as compared to API-4F steel [13]. However, the failure of steel pipelines was reported to take place as a result of a combination between uniform corrosion and localized attack [14–17]. The presence of welds within the steel pipelines has been shown to lead to the occurrence of localized corrosion, either via pitting attack or galvanic corrosion in the area of the welds [14–18].

The protection of pipeline steel by the use of inorganic coatings has been reported by many researchers [19–22]. Fan et al. [19,20] investigated the protection of pipeline steels enamel coatings, while Chatha et al. [21] studied the effect of the Cr_3C_2 -NiCr coating layer on the corrosion protection of T91 boiler steel under different types of environments. The authors [21] claimed that this coating offers a high melting point and maintains high hardness, strength and wear resistance up to a maximum operating temperature of 900 °C. Tillmann et al. [22] also claimed that the Cr_3C_2 -NiCr coating features a very low porosity, low oxidization and low carbide decomposition or carbide-matrix dissolution, which leads to increasing hardness and abrasion resistance. Thi et al. [23] reported the advantage of using a Cr_3C_2 -NiCr cermet coating, which was applied onto the surface of 410 stainless steel substrate to protect the corrosion of this steel 3.5 wt. % NaCl solution. These authors [23] found that the sprayed layer of Cr_3C_2 -NiCr provides high resistance to corrosion in the sodium chloride solution. This cermet coating was also applied onto the surface of carbon steel (SC45) pipes using high-velocity oxy-fuel (HVOF) and plasma and was found to greatly increase the corrosion resistance in 3.5% NaCl solution [24]. The objective of this study was to manufacture an inorganic Cr_3C_2 -NiCr coating layer to be applied on the surface of a hot-rolled API-2H grade 50 pipeline steel using HVOF deposition. Furthermore, the effect of 75% Cr_3C_2 –25%NiCr coating, whose thickness after its application was $260 \pm 15 \mu\text{m}$, on the severity of corrosion of this steel after 1 h, 24 h, and 48 h exposure in 4.0% sodium chloride solutions was reported. The work was carried out using potentiodynamic cyclic polarization (PCP), electrochemical impedance spectroscopy (EIS), and chronoamperometric current–time measurements. Scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) surface examinations were employed for surface morphology and analysis. It is expected that this inorganic coating will greatly increase the corrosion resistance of the API pipeline steel as compared to the uncoated steel.

2. Experimental Procedures

2.1. Materials and Solutions

API-2H grade 50 (hot-rolled) steel with the chemical composition (weight percentage, wt%) of 0.14% C, 1.5% Mn, 0.2% Si, 0.04% Nb, 0.03% P, 0.02% Ti, 0.015% S, and the remaining balance of Fe was used in this study. The mechanical parameters of the API-2H steel was 345 MPa yield, 520 MPa ultimate, and 18% elongation. A layer of 75% Cr_3C_2 –25%NiCr coating with thickness of $260 \pm 15 \mu\text{m}$ was applied on the surface of the API-2H steel using high-velocity oxy-fuel (HVOF) deposition. Sodium chloride (NaCl) of 99% purity was purchased from Merck (As Sulimaniyah, Riyadh, Saudi Arabia) and was used as received to prepare the 4.0% NaCl solution.

2.2. Electrochemical Techniques

An electrochemical cell with a three-electrode configuration that accommodated 250 mL of the electrolytic solution was used. A silver/silver chloride (Ag/AgCl, in 3M KCl solution) and a Pt

wire were used as the reference and the counter electrodes, respectively. The uncoated and coated API-2H steels were the working electrodes. The working electrodes were prepared by connecting a copper wire to the surface of each electrode. These welded steels with the copper wire as a connector were cold mounted using an epoxy resin and left to dry in air. The uncoated steel electrode surface was polished with different emery papers up to 1000 grit. This electrode was then degreased with acetone and washed by distilled water just before being immersed in the test medium. The corrosion measurements were acquired by the use of an Autolab Potentiostat-Galvanostat (purchased from Metrohm, Utrecht, Netherlands). PCP curves were collected via scanning the potential from -1.200 V in the anodic direction up to -0.200 V and the scan rate of 0.00166 V/s. The potential was then scanned at the same scan rate in the backward direction until the reversed currents intersected with the forward ones. The EIS measurements were performed at the open-circuit potential of the electrode over a change of frequency from 100 kHz to 1 mHz and at an AC wave of ± 5 mV peak-to-peak overlaid. The EIS data were collected using PowerSINE software that is already installed within the Autolab. The chronoamperometric current–time curves were obtained after applying a value of -0.7 V (Ag/AgCl) on the working electrodes after their immersions in the chloride test solution for the different exposure times. For ensuring the reproducibility of our measurements, each electrochemical experiment was performed in triplicate and was carried out on a new portion of the chloride solution at room temperature (25 ± 2 °C) and a new polished electrode surface.

2.3. Surface Characterization

The morphology of the surface after being immersed in the chloride solution for 48 h followed by stepping the potential to -0.7 V for 40 min was obtained using a scanning electron microscopy (SEM, JEOL FE-SEM Model 7600 (Tokyo, Japan)), which was operated at 15 kV. An energy-dispersive X-ray analyzer (EDX) was employed to obtain the elemental analysis of corroded surfaces via an EDX (JEOL, Tokyo, Japan) unit attached to the SEM instrument.

3. Results and Discussion

3.1. Potentiodynamic Cyclic Polarization (PCP) Measurements

Evaluating the polarization is a well-known technique in understanding the corrosion and corrosion mitigation of metallic materials in corrosive solutions [25–29]. The PCP curves of (1) API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after 1 h exposure in 4% NaCl solutions are depicted in Figure 1. The same measurements were also carried out for the same materials after 24 h and 48 h immersion in the test solution and the curves are shown in Figures 2 and 3, respectively. The parameters obtained from Figure 1, Figure 2, and Figure 3 are listed in Table 1. Here, β_c is the cathodic Tafel slope, E_{Corr} is the corrosion potential, β_a is the anodic Tafel slope, j_{Corr} is the corrosion current density, E_{Prot} is the protection potential before which the pitting corrosion does not occur, and R_{Corr} is the corrosion rate. The β_c , E_{Corr} , β_a , and j_{Corr} values were calculated as previously reported [28–30]. The values of R_{Corr} , which are mostly expressing the uniform corrosion, were calculated using the following equation [31]:

$$R_{Corr} = \frac{j_{Corr} k E_W}{d A} \quad (1)$$

where, R_{Corr} is in millimeters per year, k is a constant with a value of 3272 mm/(amp·cm·year), E_W is the equivalent weight in grams, d is the density of the metal or alloy in g/cm³, j_{Corr} is in $\mu\text{A}/\text{cm}^2$, and A is the tested surface area in cm².

The polarization curves indicated that the current of both coated and uncoated API-2H decreased in the cathodic branch upon sweeping the potential from the most negative values until it reached the

corrosion current. Here, the reaction at the cathode for most metals and/or alloys in sodium chloride solutions is the oxygen reduction [28];

Figure 1. Cyclic potentiodynamic polarization (PCP) curves of (1) API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after exposure in 4% NaCl solution for 1 h.

Figure 2. PCP curves of (1) API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after exposure in 4% NaCl solution for 24 h.

Figure 3. PCP curves of (1) API-2H steel and (2) 75%Cr₃C₂ –25%NiCr coated API-2H steel after exposure in 4% NaCl solution for 48 h.

Table 1. Cyclic potentiodynamic polarization (PCP) data obtained for the API-2H steel and coated API-2H steel samples after the different immersion periods in NaCl solutions.

Sample/ Time	β_c / mVdec^{-1}	E_{Corr} / mV	β_a / mVdec^{-1}	j_{Corr} / μAcm^{-2}	E_{Prot} / mV	PE/ %	R_{Corr} / mmpy
API-2H steel (1 h)	120	−928	220	47 ± 0.35	−616	–	0.5452
Coated API-2H steel (1 h)	110	−756	225	28 ± 0.28	−405	40.43	0.3248
API-2H steel (24 h)	125	−958	225	42 ± 0.32	−623	–	0.4872
Coated API-2H steel (24 h)	115	−765	230	23 ± 0.27	−340	45.24	0.2900
API-2H steel (48 h)	125	−965	230	38 ± 0.30	−627	–	0.4408
Coated API-2H steel (48 h)	110	−770	235	18 ± 0.25	−315	52.63	0.2088

The current then increased again with increasing potential in the positive side as a result of the iron dissolution from the surface as follows [29];

The Fe^{2+} cations get further oxidized via potential increases and chloride solutions attack, which leads to the formation of ferric cations, Fe^{3+} , as follows:

For the uncoated API-2H steel, the current has an active–passive behavior. The active region appears as a result of the dissolution of Fe to Fe^{2+} and Fe^{3+} , while the passivation occurs due to the formation of a corrosion product layer on the steel surface as per the following reaction:

The current continues to increase even in the backward direction to create a hysteresis loop (curve 1), which results from the pitting corrosion. The bigger the area of the hysteresis loop, the more severe the pitting corrosion is.

Coating the steel with 75%Cr₃C₂–25%NiCr decreases the overall currents in the cathodic and anodic sides and also reduces the possibility of pitting corrosion that could take place as indicated from the presence of a tiny size of the hysteresis loop (curve 2). The values tabulated in Table 1 indicated that the coated API-2H steel has less negative values of E_{Corr} and E_{Prot} lower values of j_{Corr} and R_{Corr} . This means that the layer of 75%Cr₃C₂–25%NiCr protects the steel against uniform corrosion as well as pitting attack.

Prolonging the immersion time from 1 h to 24 h and further, to 48 h greatly decreases its corrosion via increasing the corrosion resistance and decreasing both corrosion currents and corrosion rates, while it slightly shifts the values of E_{Prot} toward more negative values. This effect is further increased with prolonging the time of immersion in the presence of 75%Cr₃C₂–25%NiCr coated surface. Moreover, the values of E_{Prot} shift largely to less negative ones. This is because increasing the time of immersion allows both the API-2H steel and the coated steel one to form an oxide film; this film becomes thick with time and leads to increasing the resistance against corrosion. It is worth mentioning that the percentage of the protection efficiency (PE%) as listed in Table 1 was calculated for the coated API steel samples, as reported in our previous work [32], using this equation;

$$PE\% = \frac{j_{Corr}^1 - j_{Corr}^2}{j_{Corr}^1} \times 100 \quad (6)$$

Where, j_{Corr}^1 and j_{Corr}^2 are the corrosion current density obtained for the uncoated and the coated API steels after the different exposure periods of time, respectively. It is seen from Table 1 that the value of PE% recorded only 40.43% after only 1 h immersion in the chloride solution. This value was found to increase to 45.24% and 52.63% when the exposure time was increased to 24 h and 48 h, respectively. This also confirms that the prolonging of the exposure time increases the protection of the surface against corrosion in the present test solution.

3.2. EIS Measurements

EIS experiments have been carried out to understand the impedance parameters for studying the influence of 75%Cr₃C–25%NiCr coating and also, the effect of increasing the exposure time on the corrosion of API-2H steel in 4.0% NaCl solutions. Figure 4 shows the Nyquist plots of (1) API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after 1 h immersion in 4% NaCl solutions. The measurements were also obtained for API-2H steel and coated API-2H steel after 24 h and 48 h and the Nyquist plots are depicted in Figures 5 and 6, respectively. All impedance data were analyzed and fitted to the equivalent circuit model shown in Figure 7. The values of the parameters obtained from fitting these data are listed in Table 2. The elements of the equivalent circuit are defined as following; R_s the solution resistance, Q the constant phase elements (CPEs), R_p the polarization resistance and can be classified as the charge transfer resistance between the surface of the uncoated/coated API-2H steel and the chloride solution interface, and W is the Warburg [33].

Figure 4. Nyquist plots of (1) uncoated API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after 1 h immersion in 4% NaCl solutions.

Figure 5. Nyquist plots of (1) uncoated API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after 24 h immersion in the chloride solutions.

Figure 6. Nyquist plots of (1) uncoated API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after 48 h immersion in 4% NaCl solutions.

Figure 7. The equivalent circuit model used for best fitting the EIS experiments.

Table 2. Impedance (EIS) parameters of the uncoated and coated API steels in NaCl solutions.

Sample/Time	$R_s / (\Omega \text{ cm}^2)$	Q		$R_p / (\Omega \text{ cm}^2)$	$W / (\Omega \text{ cm}^2 \text{ s}^{-\frac{1}{2}})$
		$Y_Q / S^* s^n$	n		
API-2H steel (1 h)	4.55	0.000214	0.90	2267	0.1867
Coated API-2H steel (24 h)	4.73	0.000205	0.91	2619	0.1293
API-2H steel (24 h)	4.62	0.000194	0.91	2516	0.1086
Coated API-2H steel (24 h)	4.78	0.000184	0.91	2834	0.1038
API-2H steel (48 h)	4.74	0.000175	0.91	2746	0.1061
Coated API-2H steel (48 h)	4.96	0.000171	0.91	3309	0.1018

The Nyquist plots of all samples after all immersion times showed only one semicircle in the chloride solution. The spectra depicted in Figure 4 prove that the spectrum plotted for the uncoated API-2H steel after 1 h immersion (spectrum 1) has the smallest-diameter semicircle. Coating the surface of the steel with 75%Cr₃C₂–25%NiCr increased the diameter of the semicircle and confirms that the corrosion resistance increased in the presence of the coating layer. This was further indicated by the parameters listed in Table 2 as the values of R_s and R_p are higher for the coated API-2H steel compared to their values for the bare API-2H steel.

It is well knowing that the CPE, constant phase elements, (Q) can represent various components thanks to the n -values, where it is a Warburg impedance when $n = 0.5$, or a double-layer capacitor with some pores when $n \rightarrow 1.0$, and a resistor when $n = 0$ [34]. According to this principle, the Q 's in the current work represent double-layer capacitors with some pores. Accordingly, the value of Y_Q obtained

for the coated API-2H steel was lower than that obtained for uncoated API-2H steel, which indicates that the corrosion of coated API-2H steel is lower. The presence of the Warburg (W) impedance in the circuit indicates that the mass transport limits the access of the chloride ions through the formed layer of the corrosion products and/or oxide layers on the surface. The reason for the greater protection obtained for the coated API-2H steel is that the top layer of the coating decreases the dissolution of the steel surface via increasing its resistance against the aggressiveness action of the chloride ions. This is because the presence of the 75%Cr₃C₂–25%NiCr layer on the surface of API-2H steel electrode allows the formation of chromium oxide that provides more corrosion resistance compared to the formed iron oxide on the surface of the uncoated API-2H steel.

Extending the time of immersion to 24 h is shown to reduce the diameter of the plotted semicircles for both bare and coated API-2H steel electrodes, as can be seen from Figure 5. Further decreasing of the diameter of the semicircle was obtained upon increasing the immersion time to 48 h, as depicted in Figure 6. This means that the increase of immersion time at the same condition decreases the corrosion resistance of the tested electrodes. This was further confirmed by the data shown in Table 2, where the increase in exposure time decreases the values of the surface and polarization resistances, R_s and R_p . The value of Y_Q was also found to slightly increase with the increase of immersion time and thus the dissolution of both uncoated and coated API-2H steel increase. In all cases, the corrosion resistance for the coated API-2H steel has a greater value as compared to the uncoated API-2H steel at all exposure times.

In order to further confirm the Nyquist data, the Bode impedance of the interface ($|Z|$) and the degree of the phase angle (Φ) are also given. Figure 8 shows (a) the Bode impedance of the interface and (b) the degree of phase angle obtained for the steels after 1 h exposure to the NaCl solutions. It is clear from Figure 8a that the obtained values of the impedance of the interface are higher for coated API-2H steel compared to its values for uncoated API-2H steel. Also, the maximum values obtained for coated API-2H steel are higher than those obtained for the uncoated API-2H steel. This proves that coating the carbon steel with 75%Cr₃C₂–25%NiCr protects its surface from being corroded easily via increasing the resistance to corrosion in 4% NaCl solutions.

Figure 8. Change of (a) $|Z|$ and (b) Φ with frequency plots obtained for (1) API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after their immersion in 4% NaCl solution for 1 h.

Figures 9 and 10 depict (a) the Bode impedance of the interface and (b) the degree of phase angle after 24 h and 48 h immersions in the chloride solutions. It is obvious that prolonging the time of immersion to 12 h and 24 h does not change the behavior of the Bode plots. However, coating API-2H steel with 75%Cr₃C₂–25%NiCr allows the steel to provide higher corrosion resistance even after the longer immersion periods of time. It was previously reported [35] that obtaining higher values of $|Z|$ and also, a higher maximum value of Φ , indicate a higher resistance against corrosion in corrosive media.

Figure 9. Change of (a) $|Z|$ and (b) Φ with frequency plots obtained for (1) API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after their immersion in 4% NaCl solution for 24 h.

Figure 10. Change of (a) $|Z|$ and (b) Φ with frequency plots obtained for (1) API-2H steel and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel after their immersion in 4% NaCl solution for 48 h.

3.3. Chronoamperometric Current-Time Experiments

The change of potentiostatic current with time after applying a constant value of potential at -0.70 V (Ag/AgCl) was carried out in order to investigate the effect of coating on the general and localized corrosion of the carbon steel. The effect of increasing the exposure periods of time to 24 h and further to 48 h on the corrosion of the uncoated and coated steels was also investigated. Figure 11 depicts the change of current with time curves of (1) uncoated and (2) 75%Cr₃C₂–25%NiCr coated API-2H steel at -700 mV (Ag/AgCl) after 1 h immersion in 4% NaCl solutions. The initial current values for both uncoated and coated API-2H steel are seen to rapidly decrease with time, which is due to the thickening of an oxide film formed on the surface of the steel. Finally, the current slightly decreased until the end of the experiment, indicating that the film thickening continued to occur. This behavior also indicates that there is no pitting corrosion for coated or uncoated steel. The lower absolute current values for coated API-2H steel confirm that the surface of coated steel has more resistance to corrosion as compared to the uncoated API-2H steel.

Figure 11. The obtained current vs. time curves at -700 mV for (1) API-2H steel and (2) $75\%\text{Cr}_3\text{C}_2-25\%\text{NiCr}$ coated API-2H steel after immersion in 4% NaCl solution for 1 h.

The obtained chronoamperometric current–time curves at -700 mV (Ag/AgCl) after prolonging the exposure time to 24 h for (1) API-2H steel and (2) $75\%\text{Cr}_3\text{C}_2-25\%\text{NiCr}$ coated API-2H steel are shown in Figure 12. The current values decreased from the first moment of the measurement with a slight decrease with time. Here, the values of current obtained for uncoated API-2H steel slightly increased, accompanied with little fluctuations after 10 min of stepping the potential and until the end of the experiment, which reveals that the occurrence of pitting attack on the surface of API-2H steel. On the other side, the recorded currents for the coated API-2H steel slightly decreased confirming that there was no pitting corrosion occurred at this potential.

Figure 12. The obtained current vs. time curves at -700 mV for (1) API-2H steel and (2) $75\%\text{Cr}_3\text{C}_2-25\%\text{NiCr}$ coated API-2H steel after immersion in 4% NaCl solution for 24 h.

Prolonging the period of time to 48 h prior to measurements as can be seen from Figure 13 has shown almost similar current–time behavior to those obtained after 24 h immersion (Figure 12) but with lower values of the absolute currents for both coated and uncoated steel electrodes. It is also noticed that the absolute currents obtained after immersion 24 h were lower in compared to those collected at a shorter immersion time—1 h. This is because the long immersion periods of time allow the API-2H steel electrodes to form a thick layer of an oxide film onto its surfaces. This confirms that the increase of time before measurements increases the possibility of pitting attack for the uncoated

API-2H steel and also, decreases the overall currents obtained for both coated and uncoated API-2H steel at the same value of potential, -0.700 mV.

Figure 13. The obtained current vs. time curves at -700 mV for (1) API-2H steel and (2) $75\%\text{Cr}_3\text{C}_2-25\%\text{NiCr}$ coated API-2H steel after immersion in 4% NaCl solution for 48 h.

3.4. Surface Analysis

The surface morphology investigations for the uncoated and coated API-2H steel have been carried out using SEM and the EDX techniques to report whether the uniform attack and pitting corrosion in 4% NaCl solutions. Figure 14 depicts (a), (b) the SEM images and (c), (d) the corresponding EDX profile analyses for API-2H steel and $75\%\text{Cr}_3\text{C}_2-25\%\text{NiCr}$ coated API-2H steel, respectively, after their immersions for 48 h in 4% NaCl solutions then stepping a value of -0.7 V for 40 min. Although, the values of the recorded currents for both API-2H steel electrodes, the surface of the uncoated API-2H steel (Figure 14a) looks deteriorated due to the attack of chloride ions; the deterioration becomes aggressive at the anodic value of the applied potential of -0.7 V. The surface morphology here indicates that the uniform corrosion is severe as well as the pitting attack that occurred. This confirms the change of current with time behavior we have seen in Figure 13 (curve 1). The weight % (wt%) of the elements found on the surface of the uncoated API-2H steel represented by the EDX spectra of Figure 14c recorded the following: 54.86% Fe, 29.51% O, 12.78% C, and 1.33% Cl. The wt.% of Fe and O are high and confirm that the surface of the uncoated API-2H steel develops a layer that is mainly iron oxide [36].

The image shown in Figure 14c depicts that the uncoated API-2H steel is covered with a thick layer of corrosion products. The wt.% for elements in the case of the $75\%\text{Cr}_3\text{C}_2-25\%\text{NiCr}$ coated API-2H steel, which is depicted in Figure 14d, upon EDX profile analysis, are listed as the following; 32.33% C, 26.48 Cr, 20.26% O, 15.44% Ni, 3.48% Fe, 1.04% Na, and 0.97% Cl. It is evident that the highest wt.% were for C, Cr, and Ni; these elements are the main contents of the coating layer on the steel surface. The presence of high wt.% of O indicates that the compounds formed on the surface are Cr and Ni oxides. Furthermore, the presence of low wt.% of Fe confirms that the steel surface is well coated with Cr_3C and NiCr coating. Moreover, both Na and Cl at low wt.% reveals an NaCl salt deposited on the surface. The SEM and EDX investigations are in good agreement with PCP, EIS, and chronoamperometric data.

Figure 14. (a,b) the SEM images and (c,d), the corresponding EDX spectra for API-2H steel and 75%Cr₃C₂–25%NiCr coated API-2H steel, respectively, after their immersions for 48 h in NaCl solutions before stepping a value of -0.7 V for 40 min.

4. Conclusions

The effect of 75%Cr₃C₂–25%NiCr coating on the corrosion protection of API-2H pipeline steel after different exposure periods of time in 4 wt. % NaCl solution using varied electrochemical and spectroscopic measurements has been reported. Polarization experiments indicated that coating the steel with 75%Cr₃C₂–25%NiCr decreased the corrosion current and corrosion rate and increased corrosion resistance. Impedance data showed that the top layer of the inorganic coating increased the solution and polarization resistance for the steel. Chronoamperometric current–time measurements revealed that the presence of coating decreased the absolute currents with increasing time, which reflects on the decreasing of the uniform corrosion and the prevention of the pitting attack. Surface investigations taken by SEM and EDX confirmed that the coating layer protected the steel against uniform and pitting corrosion. Application of 75%Cr₃C₂–25%NiCr coating onto the steel surface thus highly protects the steel corrosion in 4% NaCl chloride solution. The long immersion of the steel remarkably magnified the corrosion resistance via formation of corrosion products that have the ability to weaken the corrosivity of the chloride test solution. Building on the outcome of this study, 75%Cr₃C₂–25%NiCr can be used as an inorganic cermet coating to minimize the corrosion of API-2H pipeline steel grade in the chloride, 4% NaCl, solution.

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