Original Article

Effect of the roughness produced by plasma nitrocarburizing on corrosion resistance of AISI 304 austenitic stainless steel

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ARTICLE INFO

Article history:
Received 2 April 2018
Accepted 8 January 2019
Available online 20 February 2019

Keywords:
Plasma nitrocarburizing
Surface roughness
Electrochemical impedance spectroscopy
3D confocal microscopy
Corrosion resistance

ABSTRACT

In this work, we studied the influence of surface roughness produced by sputtering during plasma nitrocarburizing treatments on corrosion resistance of AISI 304 austenitic stainless steel in an aqueous solution of sodium chloride. Plasma nitrocarburizing treatments were carried out in a gaseous atmosphere containing 80% N2 + 2% CH4 + 18% H2, at 400 Pa, for 2 h and at temperatures of 375 °C, 430 °C and 475 °C. Surface roughness after plasma nitrocarburizing was characterized using 3D confocal microscopy. Corrosion susceptibility of the plasma nitrocarburized surfaces was investigated by electrochemical impedance spectroscopy, potentiodynamic polarization, and scanning electron microscopy. The results showed that when increasing the temperature of the plasma nitrocarburizing treatment, both thickness and amount of precipitates increased, as expected. Analyses by 3D confocal microscopy also showed increased surface roughness with increasing plasma nitrocarburizing temperature. When comparing two plasma nitrocarburized specimens with similar precipitate-free structure, it was found that thinner thickness of the expanded austenite layer and lower surface roughness resulted in higher corrosion resistance.

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https://doi.org/10.1016/j.jmrt.2019.01.006
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1. Introduction

Austenitic stainless steels are used in components of nuclear reactors, chemical and oil industries, biomedical prostheses, marine engineering, among other applications. Plasma thermochemical treatments are widely used for improving the surface properties of metal components [1], increasing their lifespan. In the plasma nitrocarburizing of the stainless steels, a duplex layer formed of nitrogen ($\gamma_N$) and carbon ($\gamma_C$) in solid solution [2], known as S-phase [3] or expanded austenite [4], is produced. During the treatment, the plasma ions collide against the surface. After that, a fraction of the ions becomes neutral and diffuses through high energy regions [5], filling in interstitial sites of the crystalline structure [6]. The driving force behind duplex layer formation is due to a difference between the diffusion coefficients of carbon and nitrogen [7,8]. Different process parameters, such as temperature, time and pressure, allow the formation of layers with different characteristics and properties.

Evaluating plasma nitriding and nitrocarburizing of 2205 duplex stainless steel at different temperatures, Alphonse et al. [8] obtained enhanced corrosion resistance below 400 °C in sodium chloride solution. Lee [9] investigated the effect of molybdenum on the characteristics of expanded austenite layers produced by plasma nitrocarburizing of AISI 304L and 316L stainless steels. The authors identified that the solid solution molybdenum inhibits precipitation and promotes the diffusion of interstitial atoms increasing corrosion resistance of expanded austenite layer. A high corrosion resistance was also obtained at temperatures below 400 °C. In both investigations with different types of alloys, the improvement in corrosion resistance was associated with the precipitate-free expanded austenite produced at low treatment temperatures.

The process temperature has a significant effect not only on the development of the structure and thickness of the layer [10,11] but also on the surface roughness [12–14]. During the plasma treatment, the accelerated ions colliding against the surface may lead to a sputtering process that removes both the impurities and the alloying elements [15,16]. As a result, the sputtering produces erosion that leads to microcracks and reveals grain boundaries on the surface [12,17,18], thus increasing the surface roughness. However, both the surface cleaning and sputtering-induced microcracks are essential for activating and forming the duplex layer, as they enhance the diffusion of carbon and nitrogen [13]. The lower kinetic energy of the incident ions of DC-pulsed plasma discharges produces less surface roughness when compared to other methods using microwaves [19,20], ion implantation (PI) [21], or radio frequency (r.f.) [22,23].

The main goal of the present work was to investigate the influence of the roughness caused by sputtering produced during plasma nitrocarburizing on the corrosion resistance of AISI 304 austenitic stainless steel in an aqueous solution of sodium chloride. Plasma nitrocarburizing experiments were carried out at different temperatures, resulting in duplex layers with different structures, degrees of roughness and thickness. After each plasma treatment, the expanded austenite layer was characterized by optical microscopy and the surface roughness was evaluated by 3D confocal microscopy. The corrosion analyses were performed using electrochemical impedance spectroscopy, potentiodynamic polarization, and scanning electron microscopy to observe corrosion after the tests. In addition to corrosion susceptibility, the electrochemical impedance spectroscopy technique also allowed identifying and analyzing surfaces with different degrees of roughness.

2. Experimental

2.1. Material and sample preparation

Circular samples measuring 31.5 mm in diameter and 2.0 mm in height were cut from a cylindrical bar of AISI 304 austenitic stainless steel (chemical composition, in wt.%: 18 Cr, 8.34 Ni, 1.92 Mn, 0.55 Si, 0.10 C, 0.01 P). The surface of the samples was polished at #1200 and finished in a polishing step in 1.0 and 0.3 µm colloidal alumina, washed in distilled water using an ultrasound apparatus, and then hot-dried.

2.2. Plasma nitrocarburizing

Plasma nitrocarburizing experiments were performed using an SDS Plasma model Thor NP 500 plasma reactor with pulsed voltage source of 750 V maximum and frequency of 3.5 kHz (see diagram in Fig. 1). Prior to the nitrocarburizing experiments, the samples were cleaned in a gaseous atmosphere containing an H$_2$ flow rate of 200 sccm, at 150 °C, 133 Pa, for 30 min. The values of $T_{ON}$ were increased at 5 µs intervals until the temperature of 150 °C was reached at 65 µs. This process is performed to remove the thin oxide layer and for surface activation [15,16]. After sputter cleaning, a gaseous mixture containing 80% N$_2$ (320 sccm), 2% CH$_4$ (8 sccm) and 18% H$_2$ (72 sccm) at a pressure of 400 Pa was introduced in the vacuum chamber for 2 h, for plasma nitrocarburizing. A low methane concentration was chosen in order to avoid precipitates from forming in the structure of the growing layers [24]. Plasma nitrocarburizing was performed at $T_{ON}$ of 97 µs for 375 °C, 112 µs for 430 °C and 125 µs 475 °C. X-ray analyses were made to identify the phases on plasma nitrocarburized surfaces at different temperatures. The thickness of the expanded austenite layers was measured on an optical microscope from the cross section of the sample. For the morphological observations, the samples were chemically etched with modified aqua regia solution (50% HCl + 25% HNO$_3$ + 25% H$_2$O). A 3D confocal microscope was used for micrographs and for measuring the surface roughness, without chemical attack.

2.3. Electrochemical measurements

The electrochemical tests were performed by using a potentiostat/galvanostat model IVIUM™ using a conventional three-electrode electrochemical cell with aerated 3.5%NaCl solution. The plasma nitrocarburized samples were cut in 20 mm high and 5 mm wide pieces and used as working electrodes (WE). For measurements purposes, these sample pieces were insulated with epoxy resin, exposing only a work side of approximately 20 mm$^2$ (to maintain contact with the electrolyte) and another area for electrical connection. The
counter electrode (CE) used was of 99%-pure platinum, and the reference electrode (RE) was a saturated calomel electrode (SCE).

The electrochemical techniques used were electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization. The open circuit potential (OCP) was monitored during scan times of 3600 s. The electrochemical impedance spectroscopy was performed in potential amplitude of ±10 mV, measuring 11 points per decade and frequency varying from 10 kHz to 5 mHz and potentiodynamic polarization with scan of −0.20 V_{SCE} from the open circuit potential to +1.50 V_{SCE}. The values of corrosion potential (E_{corr}), corrosion current density (i_{corr}), pitting potential (E_{pit}) and current density (i_{pit}) were obtained from potentiodynamic polarization. In order to ensure statistical relevance, triplicates of each experiment were conducted. Images of the performed surfaces were obtained by scanning electron microscopy.

3. Results and discussion

3.1. Microstructure after plasma nitrocarburizing

Fig. 2 shows X-rays analyses of AISI 304 austenitic stainless steel (SS), untreated and plasma nitrocarburized at temperatures of 375 °C, 430 °C and 475 °C. For the untreated 304SS, the detected peaks of the austenite phase (Fe-γ) were (111), (200), (202), (311) and (222) matched to the angles 43.6°, 50.8°, 74.7°, 90.7° and 96.0°, respectively. On the plasma nitrocarburized 304SS, expanded austenite (YN + γC) and different types of nitride were identified for different treatment temperatures. The expanded austenite peaks were broad and displaced to the left due to the presence of interstitials elements, nitrogen (N) and carbon (C) [25]. On the 304SS plasma nitrocarburized at 375 °C and 430 °C, peaks corresponding only to expanded austenite (YN + γC) phases were found. However, at 475 °C some peaks corresponding to γN + γC phases disappeared and this behavior likely is due to a partial decomposition of expanded austenite into precipitates, identified as iron nitride (Fe3N-e) and chromium nitride (CrN). This formation of chromium nitrite occurs in grain boundary and leads to chromium depletion in the expanded austenite structure [26].

Micrographs of the cross-sectional areas of untreated AISI 304 austenitic stainless steel and plasma nitrocarburized specimens are shown in Fig. 3. In the untreated sample (Fig. 3A), the microstructure of the 304SS consists only of austenite (Fe-γ) and inclusions. For the plasma nitrocarburized specimen (Fig. 3B–D), the formation of a two-phase layer composed of nitrogen-rich expanded austenite (YN) and
carbon-rich expanded austenite ($\gamma_C$) can be observed at the top and at the bottom, respectively [3]. This layer is referred to a duplex layer ($\gamma_N + \gamma_C$) and it is formed due to different diffusion coefficients of carbon and nitrogen atoms in the crystalline structure [7,8].

The nitrocarburized surfaces treated at 375 °C and 430 °C are composed of homogenous expanded austenite layers (Fig. 3B–C), confirming X-rays analyses (Fig. 2). On the surface nitrocarburized at 475 °C, both expanded austenite and precipitates formation were observed (Fig. 3D). X-ray analyses showed that the precipitates are formed of chromium nitrite (CrN) and iron nitrite (Fe3N) (Fig. 2).

The increasing temperatures lead to increased layer thickness, which varied from 6.4 μm for the 375 °C to 22.9 μm for the 475 °C specimens. Increasing temperature increases concentration of species that collide and diffuse through the steel substrate, producing a thicker layer [27]. These thickness results can be explained by means of the role of plasma pulse width ($T_{ON}$) in controlling treatment temperatures: 97 μs for 375 °C, 112 μs for 430 °C, and 125 μs for 475 °C. The larger the plasma pulse width used, the longer are time intervals of bombardment of the plasma species on the cathode surface, meaning higher treatment temperatures. In pulse relaxation ($T_{OFF}$), the potential and the electric field stayed at residual levels, and the particles are no longer accelerated [5,28].

Therefore, for specimen nitrocarburized at higher temperature, the effective collision time of energetic plasma particles is longer than the collision time for specimens treated at lower temperatures. Thus, increasing treatment temperature leads to two simultaneous effects. Firstly, the higher adsorption of plasma particles yields thicker layers (Fig. 3) as previously reported in the literature [27]. Secondly, the effect of plasma sputtering is more pronounced, due to increased generation, as well as acceleration and bombardment of the ionic species toward the surface of the samples [29].

Fig. 4 shows 3D images of the surface of untreated and of plasma nitrocarburized at 375 °C, 430 °C and 475 °C 304SS specimens. The images show that increasing treatment temperatures led to an increase in surface roughness. The roughness values for the untreated specimen was approximately up to 0.46 μm (Fig. 4A), while the roughness of the plasma nitrocarburized specimens varied from 0.56 μm at 375 °C to 3.74 μm at 475 °C (scales of Fig. 4B–D).

The roughness of the 375 °C nitrocarburized surface was fairly close to that of the untreated surface, indicating that in this condition there was a very slight relief variation (Fig. 4A and B). On the surface of the specimens nitrocarburized at 430 °C and 475 °C more surface roughness and grain boundary cavities were observed (Fig. 4C and D). This occurs due to the priority bombardment of ions against high energy regions on
the metal surface [5]. The increase in surface roughness with temperature is due to phenomena of as thermal, chemical and physical nature. Of these, physical sputtering is well-understood and occurs when a flux of plasma particles is accelerated toward the specimen surface causing higher bombardment intensity, eventually leading to erosion on the target material [17,30]. The more energy particles collide against the surface, the higher the sputtering yield [12,18]; consequently, microcracks are generated and the grain boundaries become deeper, increasing surface roughness.

3.2. Electrochemical impedance spectroscopy

The measurements of electrochemical impedance spectroscopy (EIS) allow analyzing the different processes that occur within the bulk solution and at the electrode/solution interface. When applying low potential amplitudes (∓10 mV) it is possible to analyze phenomena close to steady-state. Adsorption and charge transfer at the electrode interface, as well as roughness and surface heterogeneities are all considered in the EIS [31–33]. The Nyquist diagram in Fig. 5A shows the real component (Z) and the imaginary component (−Z*) of the impedance of the AISI 304 austenitic stainless steel before and after plasma nitrocarburizing (PNC) at different temperatures. The Bode diagram is represented by the phase angle (θ) (Fig. 5B) and impedance module (IZI) (Fig. 5C), both as a function of the frequency. The specimen behavior in high-frequency (HF) volume phase, medium-frequency (MF) surface roughness and the low-frequency (LF) metal/solution interface was analyzed.

In Nyquist diagram (Fig. 5A) all 304SS samples show a capacitive behavior, as expected for austenitic stainless steel in aerated NaCl 3.5%w/v solution. The 304SS nitrocarburized at temperatures of 375 °C and 430 °C resulted in semicircles with larger diameters indicating higher values of polarization resistance, due to a faradaic process of high charge transfer resistance. The 304SS treated at the highest temperature (475 °C) showed the smallest diameter semicircle resulting in the lowest polarization resistance.

In Bode diagram (Fig. 5B) the phase angle (θ) of the untreated sample was lesser than in 375 °C-PNC specimen, which shows that dissolution caused by corrosion increased the surface roughness. The frequency range of constant phase element (Q) of the untreated sample was smaller than all treated sample and two time constants were identified: first at higher frequencies (between 10² and 10⁴ kHz) associated

Fig. 4 – 3D confocal micrographs of 304SS surfaces: untreated (A), plasma nitrocarburized at 375 °C (B), 430 °C (C) and 475 °C (D). Magnification 100x.
with double electric layer capacitance and one maximum at intermediate frequencies (between $10^0$ and $10^1$ Hz) associated with the surface condition.

In the 304SS specimen nitrocarburized at 375 °C (Fig. 5B), the constant phase element ($Q$) remained stable from high to low frequency, an overlapping characteristic [34]. In HF region, the stability in its constant phase element can be explained by the double layer capacitance while in the MF region by the low surface roughness and in LF region by the chromium oxide passive layer. The phase angle ($\phi$) was $-75^\circ$, which is closest to an ideal capacitor ($-90^\circ$) and it also can be associated with a less surface roughness, confirming the 3D images (Fig. 4B). In 375 °C-PNC, the constant phase element was shifted to low-frequency range (Fig. 5B) and reached the highest impedance module (IZI) (Fig. 5C), typical behaviors related to more corrosion resistant surfaces.

As for the 304SS plasma nitrocarburized at 430 °C (Fig. 5B), the phase angle ($\phi$) decreased indicating an increase in surface roughness when compared to the sample treated at a lower temperature (375 °C), as shown in the 3D images in Fig. 4B and C. The constant phase element ($Q$) was unstable from HF to LF. However, it is possible to differentiate three discrete time constants (at $10^3$ Hz, $10^1$ and $10^{-1}$ Hz), probably associated with the double layer capacitance (HF region), the increase in surface roughness (MF region) and a less protective chromium oxide film (LF region). In Nyquist diagram in low-frequency region (5 mHz) (Fig. 5A), the semicircle also presented a resistance reduction probably due to the formation of
a non-protective layer. The impedance module (|Z|) (Fig. 5C) of 430 °C-PNC sample was lower than the impedance module of sample treated at 375 °C, showing a reduction in polarization resistance in this treatment condition.

In the 475 °C treatment (Fig. 5B), the Bode diagram clearly shows the formation of two time constants, with the first peak (HF region) being associated with the double layer capacitance and the second peak (LF region) with a strong nitride (CrN and Fe3N) precipitation (Figs. 2 and 3D) and non-protective oxide layer, also identified in Nyquist diagram at 5 MHz (Fig. 5A). In this case, the depression in MF region can be associated with a higher surface roughness, as shown in the 3D images of Fig. 4D. These conditions led to the lowest impedance module (|Z|) (Fig. 5C).

The Nyquist and Bode diagrams (Fig. 5A–C) show that the polarization resistance, phase angle, constant phase element and the impedance module decrease due to a yield precipitates and surface roughness in plasma nitrocarburizing of 304SS. When comparing similar structure at 375 °C-PNC and 430 °C-PNC, the EIS results confirmed the relationship between surface roughness and corrosion susceptibility.

3.3. Potentiodynamic polarization

Fig. 6 shows the potentiodynamic polarization curves obtained from the induction of corrosion up to an anodic potential of +1.50 V(0.5%NaCl) in untreated AISI 304 austenite stainless steel and plasma nitrocarburized (PNC) specimens in NaCl solution. The corrosion potential (Ecorr), corrosion current density (icorr), pitting potential (Epit) and current density at potential of +1.50 V (i(1.5 V)) are summarized in Table 1. Fig. 6 and Table 1 show that all plasma nitrocarburized specimens showed a higher corrosion resistance than the untreated one, and the corrosion resistance gradually increased with decreasing treatment temperatures.

For 304SS plasma nitrocarburized at the lowest temperature (375 °C), the Ecorr was −0.176 V, close to that of the untreated sample (−0.168 V), without a substantial cathodic shift and corrosion current density (icorr), of about 10−10 mA cm−2, while for the untreated steel it was 10−8 mA cm−2. Variations in current density can be observed, first for a potential of −0.029 V and then for a potential of +0.991 V, during the formation of chromium oxide film. The maximum current density was 10−6 mA cm−2 which indicates formation of a passive film on the surface. Therefore, the 375 °C-nitrocarburized specimen showed the highest corrosion resistance and surface passivation.

When exposing the plasma-nitrocarburized 304SS to anodic polarization, the corrosion resistance at 430 °C was expected to be higher than at 375 °C, because the layer was twice (12.9 μm) as thick as at 375 °C (6.4 μm), and both layers had a precipitate-free structure (Fig. 3B and C). However, the corrosion current density for the 430 °C-nitrocarburized specimen was 10−7 mA cm−2, and the corrosion potential was cathodically shifted to −0.278 V. At potential of +0.294 V pitting corrosion occurred and i(1.5 V) increased four decades (about 10−3 mA cm−2).

As for the 304SS plasma nitrocarburized at 475 °C, there was a significant loss of corrosion resistance with the treatment due to high corrosion current density (10−2 mA cm−2), the lowest corrosion potential (−0.380 V), and a low pitting potential (+0.035 V), respectively.

3.4. Surface characterization of the plasma nitrocarburized 304SS, after electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization measurement

Surface micrographs of the untreated 304SS and plasma nitrocarburized specimens after electrochemical impedance spectroscopy and potentiodynamic polarization are shown in Fig. 7. The values of the expanded austenite layer thickness, surface roughness and depth of corrosion points are summarized in Table 2. Fig. 7 and Table 2, show that the corrosion on the untreated 304SS was the most aggressive and deeper than that on the plasma nitrocarburized. In the untreated sample (Fig. 7A), the morphology of the surface of the corroded areas reveals severe attack by pitting corrosion. Among plasma nitrocarburized specimens (Fig. 7B–D), the corrosion decreased on surfaces treated at lower temperatures. The corrosion did not break any of the layers of expanded austenite (Table 2), including that in which nitrides precipitation was observed.

On the surface of the specimen nitrocarburized at 375 °C (Fig. 7B and Table 2), no corrosion process was observed. There were only inclusions and little relief variation, which changed from 0.56 μm to 0.67 μm after corrosion tests. As for 430 °C-nitrocarburized surface (Fig. 7C and Table 2) pitting corrosion was identified in some regions, and the relief variation measured changed from 1.42 μm to 2.28 μm after corrosion tests. Despite the layer thickness at 375 °C being half (6.4 μm) of that at 430 °C (12.9 μm) and both having similar free precipitate structures (Figs. 2 and 3B–C), the surface micrographs showed that the surface treated at the lowest temperature was free of corrosion, confirming the surface passivation identified in the electrochemical results (Figs. 5 and 6). All results clearly lead to a direct relationship between the corrosion resistance and surface roughness produced during plasma nitrocarburizing, as
Table 1 – Corrosion potential ($E_{\text{corr}}$), corrosion current density ($i_{\text{corr}}$), pitting potential ($E_{\text{pit}}$), and current density at potential of +1.50 V ($i_{E=1.50\,\text{V}_{\text{SCE}}}$) for the 304SS untreated and plasma nitrocarburized (PNC) at different temperatures.

<table>
<thead>
<tr>
<th>304SS</th>
<th>$E_{\text{corr}}$ (V$_{\text{SCE}}$)</th>
<th>$i_{\text{corr}}$ (mA cm$^{-2}$)</th>
<th>$E_{\text{pit}}$ (V$_{\text{SCE}}$)</th>
<th>$i_{E=1.50,\text{V}_{\text{SCE}}}$ (mA cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>−0.168</td>
<td>$1.90 \times 10^{-8}$</td>
<td>−0.003</td>
<td>$4.66 \times 10^{-1}$</td>
</tr>
<tr>
<td>PNC 375 °C</td>
<td>−0.176</td>
<td>$5.64 \times 10^{-10}$</td>
<td>−</td>
<td>$1.13 \times 10^{-6}$</td>
</tr>
<tr>
<td>PNC 430 °C</td>
<td>−0.278</td>
<td>$3.79 \times 10^{-7}$</td>
<td>+0.294</td>
<td>$5.60 \times 10^{-3}$</td>
</tr>
<tr>
<td>PNC 475 °C</td>
<td>−0.380</td>
<td>$2.52 \times 10^{-6}$</td>
<td>+0.035</td>
<td>$5.57 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Fig. 7 – SEM micrographs of the 304SS surfaces: untreated (A), plasma nitrocarburized at 375 °C (B), 430 °C (C), and 475 °C (D), after corrosion tests.

identified in confocal 3D analyses (Fig. 4B–D). Rougher surfaces contain more regions of the high energy as microcracks and grain boundaries. These regions with high energy act as active sites for the nucleation of corrosion. Burstein and Pistorius [35] reported that the surface roughness has a pronounced effect on the pitting corrosion of SS in chloride solution. A smoother surface finish reduces substantially the incidence of metastable pitting by reducing the number of sites capable

Table 2 – Thickness of expanded austenite layer ($\gamma_N + \gamma_C$) and variation in surface roughness of “304SS untreated” and plasma nitrocarburized (PNC) at different temperatures, before and after corrosion tests.

<table>
<thead>
<tr>
<th>304SS</th>
<th>Thickness $\gamma_N + \gamma_C$ layer (µm)</th>
<th>Relief variation PNC surfaces (µm)</th>
<th>Relief variation PNC surfaces (µm)</th>
<th>Relief variation After corrosion tests (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>−</td>
<td>0.46</td>
<td>75.94</td>
<td></td>
</tr>
<tr>
<td>PNC 375 °C</td>
<td>6.4</td>
<td>0.56</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>PNC 430 °C</td>
<td>12.9</td>
<td>1.42</td>
<td>2.28</td>
<td></td>
</tr>
<tr>
<td>PNC 475 °C</td>
<td>22.9</td>
<td>3.74</td>
<td>4.74</td>
<td></td>
</tr>
</tbody>
</table>
of being activated into metastable pit growth. This explains the higher corrosion resistance of the 304SS plasma nitrocarburized at 375 °C than at 430 °C. For the 475 °C-plasma-nitrocarburized surface (Fig. 7D and Table 2), higher roughness was clearly visible, and pitting corrosion was more pronounced than with other treatment temperatures. The relief variation changed from 3.74 μm to 4.74 μm after corrosion tests. This occurred due to increasing surface roughness and high precipitation of chromium nitride (CrN), which brings about chromium depletion in grain boundaries, leaving these regions more susceptible to corrosion attacks [26,36].

The result suggests that the enhancing in corrosion resistance of the expanded austenite (γN + γC) produced by plasma technique at low temperature is related not only to homogeneous and precipitate-free layers [8,9], but also to low surface roughness. Therefore, preserving the surface during the plasma nitrocarburizing treatments is decisive for corrosion resistance. Among the deposition techniques, the DC pulsed plasma methods produce less surface roughness compared to other methods such as microwaves [19,20], ion implantation (FI²) [21], or radio frequency (r.f.) [22,23].

4. Conclusions

Plasma nitrocarburizing treatment at 375 °C, 430 °C and 475 °C improves corrosion resistance of AISI 304 austenitic stainless steel when immersed in 3.5% w/v NaCl solution.

The corrosion resistance gradually increases with decreasing plasma nitrocarburizing temperatures and the roughness produced in surface.

Erosion control of the surface during plasma nitrocarburizing is a determining factor for enhancing corrosion resistance. A low treatment temperature promotes less roughness and reduces surface area, consequently decreasing the active sites for corrosion nucleation.

At the lowest temperature (375 °C), plasma nitrocarburizing forms a thinner duplex layer of precipitate-free expanded austenite (γN + γC), passivating the steel surface with a current density of approximately 10⁻⁶ mA cm⁻².

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

The authors wish to acknowledge the IFES - Federal Institute of Espírito Santo and the Brazilian research funding agencies FINEP, CAPES, FAPES and CNPq for their financial support.

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