Original Article

Effect of ionic plasma nitriding process on the corrosion and micro-abrasive wear behavior of AISI 316L austenitic and AISI 470 super-ferritic stainless steels

Elieser de Araújo Junior a, Rafael Marinho Bandeira b, Marcos Dorigão Manfrinato a, Jéferson Aparecido Moreto c, Roger Borges d, Sandra dos Santos Vales e, Paulo Atsushi Suzuki f, Luciana Sgarbi Rossino a,g,*

a Sorocaba Technological College – FATEC, Sorocaba, SP, Brazil
b Department of Physical Chemistry, São Carlos Institute of Chemistry, University of São Paulo (USP), São Carlos, SP, Brazil
c Institute of Exact Sciences, Naturals and Education, Federal University of Triângulo Mineiro (UFTM), Minas Gerais, MG, Brazil
d Department of Chemistry, Federal University of Paraná (UFPR), Curitiba, PR, Brazil
e Department of Materials Engineering, Federal University of São Carlos (UFSCar), São Carlos, SP, Brazil
f University of São Paulo (USP), Engineering School of Lorena, Polo Urbo-industrial, Gleba Lorena, SP, Brazil
g Federal University of São Carlos (UFSCar), Sorocaba Campi, Sorocaba, SP, Brazil

ARTICLE INFO

Article history:
Received 1 September 2018
Accepted 19 February 2019
Available online 19 April 2019

Keywords:
Corrosion
Wear tests
Expanded ferrite
Expanded austenite

ABSTRACT

The aim of this work was to study the influence of thermochemical treatment of ionic plasma nitriding on the resistance to micro-abrasive wear and to the corrosion process of AISI 316L and AISI 470 stainless steels. The thermochemical treatment was performed at different times and temperatures with a gas mixture of 25% H2 and 75% N2. The treated materials were characterized by using optical microscopy (OM), scanning electron microscopy (SEM), X-ray diffraction (XRD), microhardness tests, micro-abrasive wear tests (MAWTs) and corrosion tests. The results show an increase in the thickness of the layer formed by increasing treatment time and in the wear resistance of the materials studied. Temperatures exceeding 450 °C favor the formation chromium nitrides, which, for being very hard broke making the formed layer brittle decreasing the wear resistance of the material. In addition, the formation of these phases substantially decrease the corrosion resistance of stainless steels.

© 2019 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

* Corresponding author.
E-mail: lu.sgarbi@gmail.com (L.S. Rossino).
https://doi.org/10.1016/j.jmrt.2019.02.006
2238-7854/© 2019 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
1. Introduction

Stainless steels are widely used by the chemical, oil, gas and orthopedic industries because of their high resistance to the corrosion process, which is mainly due to the high content of chromium (Cr) present in solid solution [1,2]. According to Metals Handbook (2005) [1] and ASM Specialty Handbook (1994) [2] the stainless steels can be classified as austenitic, ferritic, martensitic, duplex and precipitation hardenable, presenting different mechanical and corrosive behaviors due to the predominant microstructures and the presence of hardening precipitates.

Austenitic stainless steels, which includes the AISI 316L stainless steel, have a wide industrial application due to their excellent corrosion resistance and their application as biomaterial [2,3]. The 316L is a variant of the 316 stainless steel, having a lower carbon content, lower yield limit and tensile strength [1]. However, in some situations, its low hardness and tribological characteristics compromise its application [3]. Thus, the thermochemical treatment is a suitable alternative to raise the surface hardness and, consequently, its resistance to the wear process when this is required in service [4].

The ionic nitriding process has been used in order to improve the surface characteristics of stainless steels [5]. Studies developed by Borgioli (2005) [3] and Pereira Neto (2016) [6], show that the thermochemical treatment of ionic plasma nitriding in austenitic stainless steels at temperatures above 400 °C produces an increase in surface hardness and an improvement in the wear resistance due to the precipitation of chromium nitride. However, a substantial decrease in the corrosion resistance of the material has been verified.

The high-Cr (24%) 470 super-ferritic stainless steel appears as a potential candidate when compared to 316L stainless steel for various applications such as industrial plants, buildings, marine environment, oil and petroleum refinery equipment [7,8]. The AISI 470 features alloying elements that increase resistance to intergranular corrosion and prevent the sensitization process. In addition, titanium (Ti) and niobium (Nb) elements act as stabilizers, providing good plasticity, weldability and corrosion resistance equal and/or superior to AISI 316 stainless steel [7]. Nevertheless, 470 super-ferritic stainless steel presents low hardness and wear resistance. In this context, thermal and thermochemical treatments have been widely used in order to improve these properties [7,9,10].

Here, we present a detailed study of the influence of ionic plasma nitriding treatment on 316L austenitic and 470 super-ferritic stainless steels in the wear and corrosion resistance. The treated materials were characterized by using optical microscopy (OM), scanning electron microscopy (SEM), X-ray diffraction (XRD), micro abrasive wear tests (MAWTs) and potentiodynamic polarization curves (PPc) in chloride ions medium (0.6 mol L⁻¹ NaCl).

2. Experimental

The wt% compositions of the major elements in the AISI 316L austenitic stainless steel and AISI 470 super-ferritic stainless steel were determined using an Ametek SpectroMaxx optical emission spectrometer model LMF05 and are presented in Table 1.

To perform the thermochemical treatment, samples of AISI 316L and AISI 470 in the dimensions of 30 × 20 × 10 mm were used. All samples were polished and cleaned with acetone in ultrasonic method for a period of 10 min. The ionic plasma nitriding treatment was performed at MetalPlasma company (São José dos Campos, São Paulo, Brazil), and the parameters are shown in Table 2. Before the treatment, sputtering with argon was performed in all samples during 3 h.

To microstructural analyzes of studied materials with and without treatment, all samples were transversal cut, bakelite inset, mechanically abraded (220–1500#,), and polished using 3 μm diamond paste and 0.05 μm colloidal silica. The samples of AISI 316L austenitic stainless steel were attacked with the aqua regia reagent (15 mL of nitric acid, 20 mL of hydrochloric acid and 30 mL of distilled water) and the samples of the AISI 470 super-ferritic stainless steel were attacked using the Vilella reagent (5 mL HCl, 2 g picric acid and 100 mL ethyl alcohol). The base materials images were obtained using an Olympus optical microscope from the Metallography Laboratory of the Federal University of São Carlos (UFSCar – Campus

### Table 1 – Composition of the steels (wt%).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Ti</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 470 (nominal)</td>
<td>0.01</td>
<td>0.35</td>
<td>0.19</td>
<td>24.30</td>
<td>0.04</td>
<td>0.24</td>
<td>0.13</td>
<td>0.20–0.30</td>
</tr>
<tr>
<td>AISI 470 (obtained)</td>
<td>0.01</td>
<td>0.20</td>
<td>0.18</td>
<td>21.97</td>
<td>0.03</td>
<td>0.28</td>
<td>0.17</td>
<td>0.29</td>
</tr>
<tr>
<td>AISI 316L (nominal)</td>
<td>0.03 max</td>
<td>1.00 max</td>
<td>2.00 max</td>
<td>16.00–18.00</td>
<td>2.00–3.00</td>
<td>10.00–14.00</td>
<td>–</td>
<td>0.20 max</td>
</tr>
<tr>
<td>AISI 316L (obtained)</td>
<td>0.02</td>
<td>0.53</td>
<td>0.30</td>
<td>16.83</td>
<td>1.91</td>
<td>9.97</td>
<td>–</td>
<td>0.10</td>
</tr>
</tbody>
</table>

### Table 2 – Parameters used in ionic plasma nitriding treatment.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Atmosphere</th>
<th>Work pressure</th>
<th>Voltage</th>
<th>Atmosphere</th>
<th>Work pressure</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>520 °C</td>
<td>25% H₂ and 75% N₂</td>
<td>300 Pa</td>
<td>350–450 V</td>
<td>25% H₂ and 75% N₂</td>
<td>300 Pa</td>
<td>350–450 V</td>
</tr>
<tr>
<td>400 °C</td>
<td>2, 4 and 6 h</td>
<td>4 h</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sorocaba). A Hitachi TM-3000 bench-scanning microscope was used in the Biomass and Bioenergy Laboratory at Federal University of São Carlos (UFSCar - Sorocaba) in order to assess the nitrided layer of the studied materials. The nitrogen diffusion in the surface layers was verified by using the X-ray dispersive energy spectroscopy technique (EDX). The measurement was performed in the central region of the formed layer (named as Point 1) and in the material matrix (named as Point 2).

The Vickers (HV) microhardness tests were performed on the treated and base materials using a Mitutoyo model HM 220 from the Fatec-Sorocaba Metallography Laboratory. For this purpose, a load of 0.2 kgf was used for base materials and materials treated at 520 °C and a load of 0.025 kgf for materials treated at 400 °C.

The X-Ray Diffraction (XRD) analysis were performed at Lorena Campi at University of São Paulo using a LabXShimadzu, model XRD-6000 instrument. The measurements were performed using MoKα radiation with Zr filter and the source voltage and amperage of 40 kV and 30 mA, respectively. The measurements conditions were: 10° < 2θ < 70° angular interval, 0.05 step and 3 s couting time.

The MAWTs tests were performed using a fixed ball microwear device. Further information about the device may be found in [11]. The S2100 steel ball with 25.4 mm of diameter was used. The fixed frequency used in this test was 744 rpm, normal load of 8.3 N and test time of 10 min. The MAWTs tests were realized in all samples (with and without treatment) and any type of abrasive or lubricant liquid was used. After tests, all the samples were analyzed by OM using an OLYMPUS stereoscope, model SZ61, with a 6 Megapixel camera and Software analysis 2.0 to measure the diameters and the crater radio generated in a coated system by rotation of the ball. The wear volume (V) was defined by Eq. (1), as described by Rutherford and Hutchings [12].

\[
V = \frac{\pi b^4}{64r} \quad b \ll r
\]

where “b” denotes the diameter of the wear crater and “r” the radius of the standard ball that was used in the test.

Potentiodynamic polarization (PP) curves were obtained in aerated 0.6 mol L⁻¹ sodium chloride (NaCl) solution by using an AUTOLAB potentiostat/galvanostat that was coupled to a personal computer for data control and processing. A single-compartment electrochemical cell with three electrodes named as work electrode (WE) of AISI 316L stainless steel and 470 super-ferritic stainless steels with 1 cm² exposed area, a counter electrode of platinum (CE) and a reference electrode (RE) of silver-silver chloride (Ag/AgClsat) were used on the electrochemical tests. The PP measurements were carried out in triplicate using a scan rate of 0.5 mV s⁻¹.

3. Results & discussion

3.1. Optical microscopy

Fig. 1(a) and 1(b) shows the metallographs of the base materials AISI 316L and AISI 470 without treatment, respectively. It is observed that the microstructure of the substrate 316L austenitic stainless steel is formed by austenite, with evidence of maclé, characteristic of ductile materials formed by CFC crystalline structure. In the case of 470 super-ferritic stainless steel, the substrate is ferritic, without the presence of maclé.

Figs. 2 and 3 illustrate the micrographs of the layers formed for AISI 316L and AISI 470 at 520 °C, respectively, at treatment times of 2, 4 and 6 h. The results show the compound layer and absence of the diffusion layer on all the treated materials. With regarding to AISI 316L treated, it is possible to observe the formation of a white layer between the substrate and the dark nitride layer due to the high temperature of the thermo-chemical treatment (see Fig. 2(a)–(c)), promoting the formation in a larger proportion of chromium nitrides. With respect to AISI 470 treated (Fig. 3(a)–(c)), it is observed that for the time of 2 h, the nitrided layer formed had a lighter color. This result shows that the AISI 470 presented a higher resistance to the chemical attack when compared to the AISI 316L.

Fig. 4 shows the micrographs of the layers obtained on AISI 316L and AISI 470 treated at 400 °C for 4 h. As a consequence of the treatment carried out at lower temperature, a white layer was formed on both materials. It can be noted that the two materials treated at this temperature exhibited a resistance to chemical attack, demonstrated by the lighter color layer compared to the layers formed at 520 °C.

Table 3 shows the thickness of the layers obtained for each treatment parameter in both materials. An increase in the thickness of the nitriding layer is observed with increasing treatment time at 520 °C. This result corroborates those presented by Manfrintao et al. [5,13,14]. It can also be observed that the thickness of the layer formed on the 470
super-ferritic stainless steel is equivalent to the thickness of the layer formed on the 316L austenitic stainless steel at this treatment temperature.

As for the treatments performed at the temperature of 400 °C, it is possible to notice that the thickness of the layer formed on the 470 super-ferritic stainless steel is slightly larger than the thickness of the layer formed on the AISI 316L austenitic stainless steel. In addition, the thickness of the layer produced at 400 °C is evidently smaller than the layers produced at 520 °C, independent of the studied material. As discussed by Oliveira et al. [15], the ferrite (α-BCC) exhibit a maximum solubility limit of 0.4 wt% of nitrogen in iron. The austenite (γ-CFC) exhibit a maximum solubility limit of 10.3 wt% of nitrogen. Therefore, the austenitic material presents a higher nitrogen solubility into its structure, but a lower diffusion rate, because this structure is more compact when compared to the ferritic structure [15,16]. Thus, 470 super-ferritic stainless steel presented a thicker layer when treated at 400 °C because its diffusibility is relatively higher than 316L austenitic stainless steel, but a smaller percentage of nitrogen in the formed layer, as indicated in the Table 4.

The magnitude of the diffusion coefficient is indicative of the atomic motion rate and depends both on the diffusing host components and on the temperature. According to
Fig. 4 – Micrographs of the layers formed on the materials (a) AISI 316L and (b) AISI 470, treated at 400 °C with treatment time of 4 h.

Table 3 – Comparison of the thickness of the layers obtained in the treatment of ionic plasma nitriding for the studied materials.

<table>
<thead>
<tr>
<th>Treatment time (h)</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>520 °C 316L</td>
<td>2  26.20 ± 1.15</td>
</tr>
<tr>
<td>416L</td>
<td>4  41.60 ± 1.56</td>
</tr>
<tr>
<td>616L</td>
<td>54.70 ± 2.02</td>
</tr>
<tr>
<td>470</td>
<td>2  27.20 ± 1.44</td>
</tr>
<tr>
<td>4170</td>
<td>40.05 ± 1.58</td>
</tr>
<tr>
<td>6170</td>
<td>54.40 ± 1.78</td>
</tr>
<tr>
<td>400 °C 316L</td>
<td>4  4.07 ± 0.18</td>
</tr>
<tr>
<td>316L</td>
<td>6.72 ± 0.37</td>
</tr>
</tbody>
</table>

Askeland [16], the diffusion coefficient of nitrogen in the iron (CFC structure) is approximately 0.0034 cm² s⁻¹, while for iron (BCC structure) is 0.0047 cm² s⁻¹. The results obtained in the present study corroborate the previous explanation, in which the nitrogen diffusion on the 470 super-ferritic stainless steel is greater when compared to the nitrogen diffusion in the AISI 316L austenitic stainless steel, responsible for the greater thickness of the layer formed on the AISI 470 super-ferritic stainless steel at the temperature of 400 °C.

Table 4 – Percentage of nitrogen (%N) on the layers of the AISI 316L and AISI 470 nitrided to plasma. The measurement was performed in the central region of the formed layer (named as Point 1) and in the material matrix (named as Point 2).

<table>
<thead>
<tr>
<th>Treatment (h)</th>
<th>Point 1 (%N)</th>
<th>Point 2 (%N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>520 °C</td>
<td>316L</td>
<td>2  42.05 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>4  37.08 ± 0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6  25.34 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>470</td>
<td>2  31.85 ± 0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4  28.46 ± 0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6  26.26 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>400 °C</td>
<td>316L</td>
<td>4  6.20 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>4  6.57 ± 0.04</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5 – Microhardness as a function of the treatment time of nitrided samples at temperatures of 520 and 400 °C.

3.2. Microhardness test

Fig. 5 presents the measure of surface microhardness for each studied material, with and without treatment. As can be seen, for both materials, the hardness of the formed layer is much higher than the base material, evidencing the effectiveness of ionic plasma nitriding. The original surface hardness of AISI 316 and AISI 470 stainless steels without nitriding are found to be 183 and 166 HV, respectively, and after the nitriding process at 400 °C the hardness is raised to 572 HV for the AISI 316L austenitic stainless steel and 534 HV for AISI 470 super-ferritic stainless steel, demonstrating the high hardening potential in this condition (approximately three times the initial value). As reported by Mingolo [4] these hardness values are similar when compared to the formation of martensite in conventional steels with the supersaturation caused by carbon. It is also observed that the higher treatment temperature (520 °C) produced a harder layer compared to the lower treatment temperature (400 °C), corroborating with the work developed by Yang et al. [17] and Pereira Neto et al. [6].

It is possible to observe at 520 °C the increasing of hardness with subsequent stabilization by increasing treatment time. The surface microhardness of the untreated AISI 316L (matrix) is equivalent to AISI 470, and the nitriding treatment increases the surface hardness of 470 and 316L stainless steels, presenting an equivalent hardness for the two materials for all treatment conditions. For the treatment performed at 400 °C, the hardness of both materials was also equivalent. Lower
treatment times generate a high concentration of nitrogen in the surface, which increases its hardness. As the treatment time is increased, the concentration of nitrogen on the surface decreased, diffusing to the substrate, which causes the increase of diffusion depth and surface hardness stabilization [18].

The hardness obtained in the nitride layer is due to the kind of the structure formed, beyond the hardness of the base material. With the formation of the compounds layer, especially expanded austenite ($\gamma'$), compressive residual stresses are generated in the outermost layers of the material, decreasing the magnitude of the effective stresses generated on the workpiece, increasing the wear resistance and hardness of the material. According to Muller’s theory of the blockade of slippage of dislocations, the nitrogen dissolved in the lattice and in the grain boundaries increases the roughness of the sliding surfaces. Thus, to start the sliding process causing an increase in the elastic limit, higher stresses are required which results in a higher hardness and an increase in fatigue strength [19,20].

3.3. XRD analysis

The diffractograms of the phases formed on the surface of AISI 316L and AISI 470 stainless steels treated at temperatures of 400 °C, respectively, are shown in Fig. 6(a) and (b). The XRD

Fig. 6 – Phases formed on the surface of 316L austenitic stainless steel (a) and 470 super-ferritic stainless steel (b) treated at 400 °C.
patterns show the presence of expanded austenite ($\gamma'$) for AISI 316L austenitic stainless steel, expanded ferrite ($\alpha'$) for AISI 470 super-ferritic stainless steel and iron nitrides (Fe$_3$N, Fe$_4$N and Fe$_7$N) in both materials. It is important to mention that there was no formation of chromium nitrides in the treated materials at 400˚C. According to Bortoli [21] and Christiansen [22], the $\gamma'$ phase leads to mechanical resistance and high wear resistance with high hardness, explained by the formation of a supersaturated solution of interstitial nitrogen in the iron, which causes distortion in the lattice and hinders the movement of dislocations. The presence of the interstitial element in a quantity much higher than the limit of solubility of the structures results in an elastically distorted and thermodynamically metastable phase, which promotes a condition of compressive residual stress resulting in the strong hardening effect caused by the formation of this phase during the nitriding process. However, the Modulus of Elasticity of these phases remains unchanged [22].

As pointed out by Leyland and Matthews [23] and discussed by Tschiptschin and Pinedo [24], the stresses in the interface between substrate and coating are minimized when the value of the Modulus of Elasticity of the coating can be adjusted to a value close to that of the substrate, thereby obtaining improved system performance. Thus, the formation of $\gamma'$ and $\alpha'$ contribute to an improvement in the tribological properties of the steel due to its hardening effect and also to maintain the Modulus of Elasticity at levels close to the substrate [24]. The $\alpha'$ phase presents the same characteristic of $\gamma'$ phase, but because of its smaller network parameter, the $\alpha'$ phase presents less capacity to solubilize nitrogen in its interstices.

Fig. 7 presents the XRD spectra for AISI 316L and AISI 470 at different treatment times at 520˚C. The Fe$_3$N, Fe$_4$N, FeN and Cr$_2$N hardened nitrides were observed for both studied materials. And about 470 super-ferritic stainless steel it should be noted the formation of $\alpha'$ phase. As mentioned by Pinedo [25], chromium nitride exhibits high hardness but affects the corrosive properties of the material.

3.4. Micro abrasive wear test

Fig. 8 shows the wear resistance in relation to the different treatment times and temperatures for the 316L austenitic stainless steel and 470 super-ferritic stainless steels treated and untreated. For the treated samples were observed a relevant decrease of the wear volume compared to the base material, highlighting the effectiveness of treatment. It can be observed that the wear resistance of the AISI 470 nitrided is higher than that for the AISI 316L, evidenced by the lower wear volume presented by this material, regardless of the treatment time at 520˚C. Souza et al. [10] related the ionic plasma nitriding provided higher hardness and wear resistance to ferritic stainless steel when compared to austenitic stainless steel.

Since the hardness of the two materials was similar, regardless of temperature and treatment time, the higher wear resistance of the 470 material treated at 520˚C is due to the brittleness of the layer produced on the 316L material, which reduces the wear resistance of this material. In the treatment performed at 400˚C, the wear resistance of both materials studied was similar. This is probably due to the type of layer
produced. According to Bortoli [21], the $\alpha'$ and $\gamma'$ phases exhibit good resistance to wear and corrosion.

Fig. 9 presents the results of wear volume as a function of temperature for 4 h of treatment. The results show that there is no great influence of the treatment temperature on the wear volume for 470 super-ferritic stainless steel. However, for AISI 316L, the opposite effect was observed as the treatment temperature was increased. It should be emphasized that the thickness and hardness of the layer formed at the treatment temperature of 400 °C was much lower than the thickness of the layer formed in the treatment performed at 520 °C. The wear resistance of the AISI 316L stainless steel treated at 400 °C was much higher compared to the material treated at 520 °C.

The chromium nitrides formed in ionic plasma nitriding treatment have high hardness, but low wear and corrosion resistance [6]. According to Pereira Neto [6] the thermochemical treatment of ionic plasma nitriding in super duplex stainless steel above 500 °C promotes an increase in surface hardness and a decrease in the wear resistance of the material. As stated by Dalibon [26] this behavior occurs because very hard layers (around 1300 HV) are very fragile and brittle when subjected to the wear test. Besides the decrease in wear resistance, this very hard layer, characterized by the chromium nitrides formation, causes a decrease in the corrosion resistance of stainless steels. The results obtained by the cited authors corroborate those presented in this work, since it was observed that the thermochemical treatment carried out at 520 °C produced a hard and brittle layer, which negatively influenced the wear behavior of AISI 316L austenitic stainless steel when compared to the treatment performed at 400 °C for both studied materials. The debris formed during the wear process acts as an abrasive, and the greater the hardness of the generated debris, the more intense the wear process. Fig. 10 presents the OM images of the caps after the MAWTs on the AISI 316L and AISI 470 with and without thermochemical treatment. As can be seen in all figures, the wear mechanism was characterized by a mixture of scratching and rolling [27].

3.5. Corrosion tests

The results of the OCP evolution with the immersion time for the 316 L austenitic stainless steel and 470 super-ferritic stainless steel are presented in Table 5. A slightly difference in the corrosion potential ($E_{\text{cor}}$) values for both base materials was observed. As reported by ASM Specialty Handbook [2], ferritic stainless steels present high amounts of Cr, responsible for ferrite stabilizing. This fact ensures these materials a good resistance to corrosion process. However, the Ni element is responsible for the austenite stability and consequently for better corrosion resistance to austenitic stainless steel.
Table 5 – Corrosion potential for 316L austenitic stainless steel and 470 super ferritic stainless steel.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>Time (h)</th>
<th>$E_{ocp}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>316L</td>
<td>520</td>
<td>4</td>
<td>−0.575</td>
</tr>
<tr>
<td>316L</td>
<td>400</td>
<td>4</td>
<td>−0.553</td>
</tr>
<tr>
<td>316L</td>
<td>BM</td>
<td>–</td>
<td>−0.152</td>
</tr>
<tr>
<td>470</td>
<td>520</td>
<td>4</td>
<td>−1.638</td>
</tr>
<tr>
<td>470</td>
<td>400</td>
<td>4</td>
<td>−0.224</td>
</tr>
<tr>
<td>470</td>
<td>BM</td>
<td>–</td>
<td>−0.140</td>
</tr>
</tbody>
</table>

Fig. 10 – Crater of (a) AISI 316L base material, (b) AISI 470 base material, (c) AISI 316L treated at 520 °C for 4 h, (d) AISI 470 super-ferritic steel treated at 520 °C for 4 h, (e) AISI 316L treated at 400 °C for 4 h and (f) AISI 470 super-ferritic treated at 400 °C treated for 4 h.

Considering the effect of thermochemical treatment, the most active potential was obtained for the 470 super-ferritic stainless steel at 520 °C treated for 4 h. Fig. 11(a) and (b) presents the characteristic potentiodynamic polarization curves for AISI 316L and AISI 470 in 0.6 mol L$^{-1}$ NaCl aqueous solution. The cathodic zones are very close to the AISI 316L stainless steel treated at 400 °C and the base material, indicating that the number of cathode sites are very similar. It is also possible to observe the influence of treatment...
temperature on the corrosion process of the material. For the treatment performed at 520 °C the corrosion current density ($I_{corr}$) are greater and the increase in corrosion current density may be related to the formation of chromium nitrides as observed by DRX analysis (Fig. 7). Another interesting fact in these curves is the formation of a passive region. The passivation property results from the formation of a highly adherent and thin oxide film on the surface of the metal, which acts as a protective barrier against the corrosion process.

Stainless steels are highly resistant to corrosion in a wide range of atmospheres because of passivation.

4. Conclusion

The aim of this work was to compare the wear and corrosion resistance of AISI 316L austenitic stainless steel and AISI 470 super-ferritic stainless steels with and without
 thermochemical treatment of ionic plasma nitriding. The development of the present work allowed the authors to obtain the following conclusions:

- The treatment of ionic plasma nitriding caused a significant increase in the hardness of the studied materials, evidencing the effectiveness of the treatment performed. The hardness of the materials increased with the treatment time to the temperature of 520°C, with stabilization in 4 h of treatment, being 1196 HV for AISI 316L and 1306 HV for AISI 470;

- Thermochemical treatment of ionic plasma nitriding significantly increased the wear resistance of the studied materials. The 470 super-ferritic stainless steel showed a higher wear resistance in the treatment performed at 520°C compared to AISI 316L austenitic stainless steel, but the strength of the materials were similar when treated at 400°C;

- The materials under study showed a similar behavior in corrosion. AISI 316L austenitic stainless steel treated at 400°C for 4 h presented the best corrosion behavior of all materials studied. The 470 super-ferritic stainless steel treated at 400°C for 4 h showed a slight worsening in corrosion behavior compared to the base material. The treatment performed at 520°C, regardless of the treatment, presented non-beneficial results to the corrosion resistance of the studied materials;

- Similar behaviors of hardness, wear resistance and corrosion were observed for the two untreated materials. This shows that 470 super-ferritic stainless steel may be an economical alternative for the replacement of 316L austenitic stainless steel in some practical applications;

- The two materials treated at 400°C exhibit similar behavior in hardness and wear, however, AISI 316L stainless steel presented better resistance to corrosion compared to AISI 470 stainless steel. It is believed that the improvement of the thermo-chemical treatment parameters allows a better performance of the AISI 470;

- The treatment of ionic plasma nitriding at temperatures above 450°C favors the formation of chromium nitrides which, because they are very hard, weaken the formed layer favoring the wear of the material. In addition, the formation of these phases substantially diminishes the corrosion resistance of stainless steels.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

The authors gratefully acknowledge the São Paulo Research Foundation FAPESP (2014/19535-4) for the financial support.

References


[21] Bortoli EB, Vito AA, Franco JRR. Influência da temperatura de nitretação a plasma na espessura e resistência ao


