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Effect of Preliminary Nitric Chemical Treatment on Corrosion Behavior of 316 Stainless Steel in Chloride Solution Contain Glucose

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Abstract: The aim of this study is to analyze the impact of a preliminary nitric acid chemical treatment on the corrosion of 316 stainless steel particularly used in implant applications, in a 0.9% chloride solution containing glucose. The steel 316 study has a variety of distinct phases and inclusions. Chemical nitric acid treatment for three days at 22°C changes the open circuit potential in the chloride solution, containing one, two or four grams per liter of glucose, after one hour and eight days of immersion at 37°C. The results show that the open circuit potential is higher when the solution contains two or four grams of glucose per liter after one hour and eight days of immersion at 37°C. In contrast, the corrosion potential of chemically treated samples increases when immersed in a chloride solution containing two, or four grams of glucose per liter, while their resistance to polarization decreases after one hour of immersion. However, after eight days of immersion in sodium chloride solution, chemically treated samples have lower corrosion potentials for different glucose concentrations compared to untreated samples, and the polarization resistance decreases only for those immersed in chloride solutions containing two or four grams of glucose per liter. In addition, untreated samples show an increase in their polarization resistance and corrosion potential with the increase in glucose concentration after one week of immersion. A significant morphological difference in corrosion is observed between chemically treated and untreated samples when immersed in a chloride solution. In addition, the rate of pitting formation decreases for untreated samples after one week of corrosion; this may be explained by the passivation of untreated 316 steel after one week of free corrosion in the sodium chloride solution.

Keywords: Corrosion resistance, Corrosion morphology, Implants, Glucose, Nitric chemical treatment.

Introduction

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

Austenite stainless steels are distinguished by their exceptional properties. This has greatly expanded their applications. Notably, 316 SS and 316L SSL found extensive use as body implants (Bouaziz & Zanoun, 2011; Kannan et al., 2005; Varmaziar et al., 2022), due to their ability to develop a thin protective oxide layer spontaneously during air exposure, commonly referred to as the "passive layer". Although these materials are initially protected, following implantation they are instantly exposed to hostile bodily fluids. This can cause degradation over time, primarily from localized corrosion in physiological conditions, and may even result in in vitro failures. Consequently, even though passive film has benefits, it is clear that it cannot ensure long-term protection during implantation. Several studies have concentrated on ways to increase the corrosion resistance and operating life of stainless steels in order to address this difficulty(Ahmad et al., 2009; Bouaziz & Zanoun, 2011; Kannan et al., 2005; Noh et al., 2000a; Shalash & Nasher, 2010; Varmaziar et al., 2022).

Numerous researchers have delved into the impact of surface treatments—be they mechanical, chemical, or electrochemical—on enhancing the corrosion resistance of stainless steels. (Kannan et al., 2005; Noh et al., 2000b). An electrochemical study conducted by G. Hulquist and C. Leygraf (Hultquist & Leygraf, 1980) revealed that nitric acid passivation treatment fosters the development of chromium oxide Cr-O and chromium hydroxide Cr-OH bonds within the protective passive film. These bonds serve to prevent the rupture of the passive layer. Moreover, nitric acid passivation enhances the chromium content within the passive film. Consequently, this treatment enhances resistance against both crevice and pitting corrosion (Hultquist & Leygraf, 1980; Noh et al., 2000b). Many researchers consider nitric acid passivation treatment to be the most effective approach to strengthening corrosion resistance in aggressive environments (Hultquist & Leygraf, 1980; Kannan et al., 2005; Noh et al., 2000b).

Other research highlights not only the impact of surface treatments on corrosion resistance but also the effect of glucose addition at varying concentrations in the physiological solution. In a study by Alam-Eldein et al. (Alam-Eldein et al., 2018), the objective was to evaluate the impact of glycemic control on the stability of implant-attached mandibular prostheses. After three years of follow-up, it appeared that glucose control had an impact on the survival of implants supporting mandibular prostheses in type II diabetic patients. Zeng et al. (Zeng et al., 2015) found that the corrosion rate of pure Mg in the saline solution increased in proportion to the glucose concentration. However, in Hank’s solution, they found a noticeable improvement in the corrosion resistance of pure magnesium with an increase in glucose content. These observations highlight the impact of glucose on the corrosion behavior of implants in physiological solutions.

The normal concentration of glucose in the blood of a non-diabetic person on an empty stomach is generally between 70 and 120 mg/dl (Wimmer et al., 2019). In contrast, a person is diagnosed with diabetes when his fasting blood sugar exceeds 120 mg/dl (Maheshwari et al., 2012). In this study, three glucose concentrations were used: 100 mg/dl (representing a non-diabetic person), 200 mg/dl (corresponding to a diabetic person), and 400 mg/dl (simulating hyperglycemia) in order to assess the impact of glucose on 316 steels used as implants in non-diabetic people and those with the disease.

Experimental Methods

Materials and Procedures

The material selected for this study is austenitic stainless steel AISI 316, which is in the form of 2 mm thick sheets and has been subjected to heat treatment in the factory. This material consists mainly of 16.65% chromium (Cr) and 10.43% nickel (Ni), with a molybdenum content (Mo) greater than 2.19%. The latter is recognized for its ability to significantly improve the pitting corrosion resistance and stress corrosion of stainless steels (Bond et al., 1973; Brunet et al., 1967; Colombié et al., 1973; Steinemann, 1968; Sumita et al., 2004). The detailed chemical composition of this steel is presented in Table 1. The chemical analysis was performed using optical emission spectrometry (OES). For scanning electron and optical microscopic analyses, 1 cm² samples were cut with a guillotine and prepared according to the standard metallographic procedure. First, they were polished with sandpaper ranging from 400 to 4000 grains. Then the samples were cleaned with distilled water and finally air-dried. To characterize the structure and phases constituting our steel, we performed an analysis by X-ray diffraction (XRD). The identification of the phases present in our material was carried out using the software "HighScore plus".

We opted for the use of the Aqua Regia solution, consisting of 20 ml of nitric acid (HNO_3) and 60 ml of hydrochloric acid (HCl), to achieve a chemical attack on 316 stainless steel containing 2.19% molybdenum. This approach allowed us to analyze and observe its microstructure with precision. For surface treatment, the samples were immersed for 3 days in nitric acid [HNO_3], followed by a thorough rinsing with distilled water. All surface treatments were performed at room temperature.

Table 1. Chemical composition of AISI 316 stainless steel.

Elements (wt %)	AISI 316	Elements (wt %)	AISI 316	Elements (wt %)	AISI 316
C	0.049	Cu	0.12	Bi	0.009
Si	0.63	Nb	0.016	Ca	0.0006
Mn	0.95	Ti	0.006	Ce	0.012
P	0.007	V	0.066	Sb	<0.002
S	0.004	W	<0.007	Se	<0.001
Cr	16.65	Pb	<0.002	Te	0.005
Mo	2.19	Sn	0.017	Ta	0.057
Ni	10.43	Mg	0.012	B	0.0004
Al	0.003	As	0.013	Zn	0.002
Co	0.31	Zr	0.004	La	0.001
				Fe	68.4

Electrochemical studies were conducted using physiological solutions composed of 0.9% NaCl, to which different glucose concentrations were added (one, two, and four grams per liter). These experiments were conducted at a temperature of 37°C. The specific characteristics of the samples used are listed in Table 2.

Table 2. Sample types used for different electrochemical tests.

Sample characteristics	Without treatment	With treatment	Immersion time in the physiological solution	With 1g/l of glucose	With 2g/l of glucose	With 4g/l of glucose
1	x		1 hour	x		
2	x		1 hour		x	
3	x		1 hour			x
4		x	1 hour	x		
5		x	1 hour		x	
6		x	1 hour			x
7	x		8 days	x		
8	x		8 days		x	
9	x		8 days			x
10		x	8 days	x		
11		x	8 days		x	
12		x	8 days			x

Corrosion Behavior

Corrosion measurements were performed in a 0.9% NaCl solution with the addition of various glucose concentrations (one, two, and four grams/liter), maintained at a temperature of 37°C in an aerated environment. The electrochemical studies were conducted in a four-electrode cell, and the test environment remained stable throughout the duration of the evaluations. This medium was selected for its suitability for the study of corrosion due to the presence of corrosion activators, including chloride ions (Hache, 1956) and simulating a physiological solution (Chaouki et al., 2005; Eschler et al., 2001; Hanawa, 2002; Lorsbach & Schmitz, 2018). The working electrode consisted of an AISI 316 (WE) stainless steel substrate associated with an Ag/AgCl (RE) reference electrode, while two graphite electrodes were used as counter-electrodes (CE). The open-circuit potential measurements (E_{OCP}) were performed with an Ag/AgCl reference electrode. The potentiodynamic polarization tests covered a range from -1500 mV to 1500 mV, with an acquisition rate of 60 mV/min. The current-potential curves were obtained after 1 hour and 8 days of immersion. The open-circuit potential and current-to-potential curves were recorded using an AUTOLAB potentiostat/galvanostat. The corrosion potential (Ecorr) and the polarization resistance (Rp) were determined from the obtained curves.

Results and Discussions

After subjecting the surface of 316 stainless steel, which contains a molybdenum content greater than 2.19% by weight, to a chemical attack in an Aqua Regia solution, we performed a scanning electron microscope analysis (see Figure 1). This observation revealed the presence of multiple distinct phases in our steel.

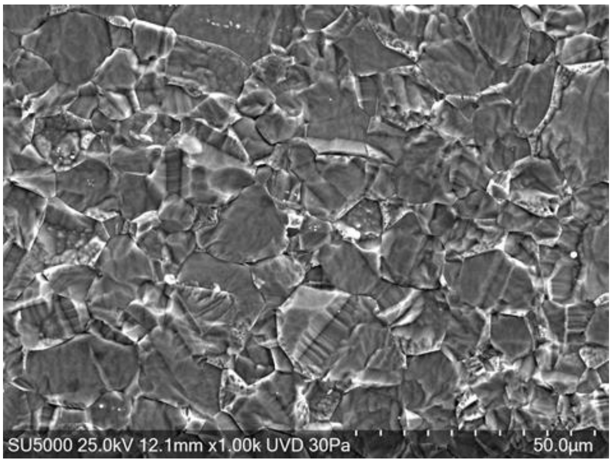
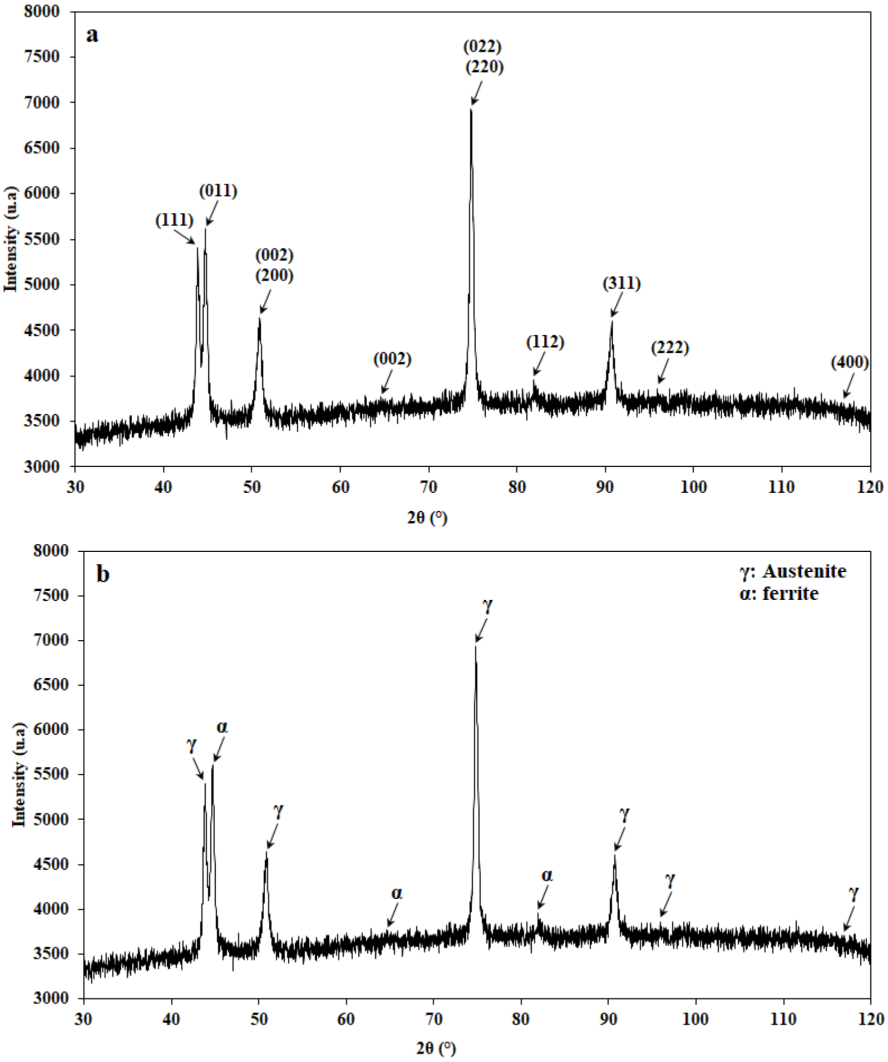


Figure 1. Scanning electron microscopic observation of 316 steel containing 2.19% molybdenum.

The results of the X-ray diffraction confirmed the previous observations, revealing the presence of several phases and highlighting the presence of austenitic and ferritic phases in the steel 316 studied. The peaks corresponding to austenite and ferrite are illustrated in Figure 2. The appearance of the ferritic phase on the diffractogram is attributed to the content of chromium (16.65%) and molybdenum (2.19%) in alloy 316, thus promoting the formation of this ferritic phase (Cunat, 2000; Leger, 1993; Sumita et al., 2004). The austenite content in the alloy is 73.3%, while the ferrite content is 18.1%, and the other phases represent 8.6% of the total composition, which classifies this steel as an austenitic type.



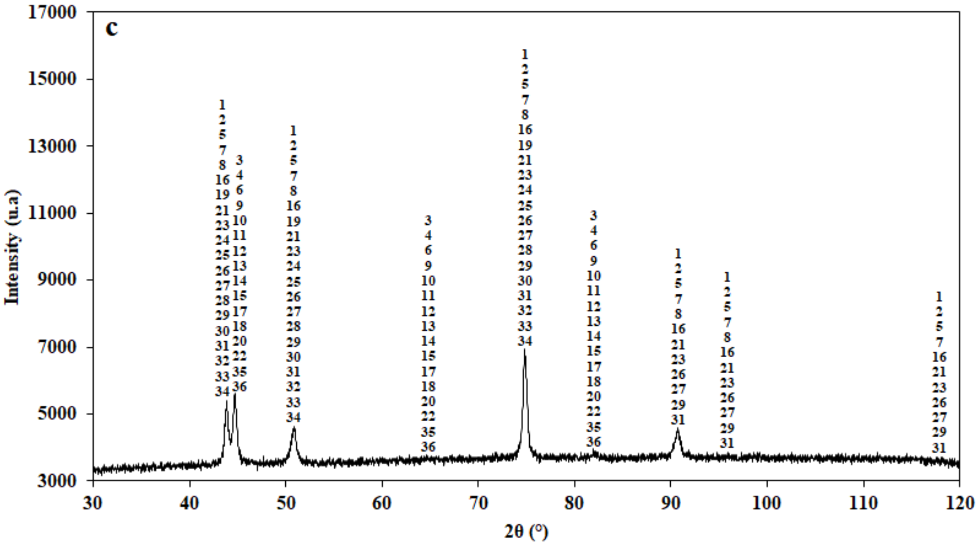


Figure 2. X-ray diffraction of austenitic stainless steel 316, **a-** Diffraction planes, **b-** Picks of austenitic phase and ferritic phase, **c-** All Thirty-six phases in the alloy.

Table 3. Thirty-six phases present in 316 stainless steel containing 2.19 % Mo.

Phase number	Chemical formula	Diffraction angle 2θ (°)	Diffraction plans (hkl)	PGCD
1	$C_{0.06}Cr_{0.29}FeNi_{0.16}$	43.583, 50.792, 74.699, 90.697, 95.968, 118.161.	(111), (002), (220), (311), (222), (400).	ICDD 00-033-0397.
2	$Nb_{0.1}Ni_{0.9}$	43.698, 50.901, 74.852, 90.899, 96.202, 118.514.	(111), (200), (220), (311), (222), (400).	ICDD 03-065-9420.
3	$Fe_{1.8}V_{0.2}$	44.484, 64.729, 81.932.	(011), (002), (122).	ICSD 98-063-4038
4	$Ce_{0.0045}Fe_{0.9955}$	44.696, 65.059, 82.384.	(011), (002), (112).	ICSD 98-010-2148.
5	$B_2Fe_3Ni_3$	43.507, 50.674, 74.487, 90.416, 95.671, 117.716.	(111), (200), (220), (311), (222), (400).	ICDD 03-065-8674.
6	$Fe_{0.984}W_{0.016}$	44.696, 65.059, 82.384.	(011), (002), (112).	ICSD 98-010-3696.
7	$C_{0.05}Fe_{0.95}$	43.473, 50.674, 74.679, 90.676, 95.944, 117.716.	(111), (200), (220), (311), (222), (400).	ICDD 00-023-0298.
8	$Fe_{0.64}Ni_{0.36}$	43.605, 50.795, 74.679, 90.633, 95.907.	(111), (200), (220), (311), (222).	ICDD 00-047-1405.
9	$Fe_{0.82}\ B_{0.18}$	44.779, 65.186, 82.559.	(011), (002), (112).	COD 96-151-1092.
10	$Fe_{1,98}Ta_{0,02}$	44.631, 64.957, 82.244.	(011), (002), (112).	ICSD 98-063-3793.
11	$Fe_{1.95}Ti_{0.05}$	44,581, 64,881, 82,140.	(011), (002), (112).	ICSD 98-063-3933.
12	$Fe_{0.991}Sn_{0.006}Zr_{0.003}$	44.647, 64.982, 82.279.	(011), (002), (112).	ICSD 98-016-8654.
13	$Fe_{1.8}Si_{0.2}$	44.779, 65.186, 82.559.	(011), (002), (112).	ICSD 98-063-3527.
14	$Al_{0.5}Cr_{0.5}Fe_1$	44.614, 64.931, 82.201.	(011), (002), (112).	ICSD 98-005-7655.
15	$Fe_{0.96}Ni_{0.03}Sb_{0.01}$	44.631, 64.957, 82.244.	(011), (002), (112).	ICSD 98-010-3570.
16	Fe_3Ni_2	43.530, 50.705, 74.535, 90.479, 95.742, 117.822.	(111), (200), (220), (311), (222), (400).	ICDD 03-065-5131.
17	$Fe_{2.00}$	44.680, 65,033, 82,349.	(011), (002), (112).	COD 96-900-

				6589.
18	$Cu_{0.3}Fe_{1.7}$	44.435, 64.653, 81.828.	(011), (002), (112).	ICSD 98-062-7297.
19	$Fe_{4.00}$	43.724, 50.932, 74.901.	(111), (002), (022).	COD 96-901-4592.
20	$Cr_{0.7}Fe_{0.3}$	44.581, 64.881, 82.140.	(011), (002), (112).	ICSD 98-010-2754.
21	$Al_{0.34}Co_{0.41}Cr_{0.21}W_{0,04}$	43.473, 50.674, 74.679, 89.934, 95.578, 117.716.	(111), (200), (220), (311), (222), (400).	ICDD 00-050-1290.
22	$Cr_{0.2}Fe_{0.8}$	44.680, 65.033, 82.349.	(011), (002), (112).	ICSD 98-010-2752.
23	$Cr_{1.7}Fe_{6.6}Mo_{0.1}Ni_{1.2}Si_{0.2}$	43.473, 50.674, 74.679, 89.934, 95.578, 117.716.	(111), (200), (220), (311), (222), (400).	ICDD 00-050-1293.
24	$Al_{0.05}Cr_{0.3}Ni_{0.65}$	43.943, 51.192, 75.320.	(111), (002), (022).	ICSD 98-010-7768.
25	$Cr_{0.23}Mn_{0.08}Ni_{0.69}$	43.749, 50.962, 74.950.	(111), (002), (022).	ICSD 98-010-8339.
26	$Al_{0.5}CNi_3Ti_{0.5}$	43.473, 50.644, 74.610, 90.676, 96.190, 118.353.	(111), (200), (220), (311), (222),(400).	ICDD 00-019-0035.
27	$Cu_{3.8}Ni$	43.473, 50.765, 74.748, 90.569, 95.944, 118.140.	(111), (200), (220), (311), (222), (400).	ICDD 00-009-0205.
28	$Cr_{0.4}Ni_{0.6}$	43.775, 50.993, 74.999.	(111), (002), (022).	ICSD 98-010-2821.
29	$Ni_{17}W_3$	43.680, 50.880, 74.818, 90.854, 96.153, 118.439.	(111), (200), (220), (311), (222), (400).	ICDD 03-065-4828.
30	Ni_4Zn_1	43.904, 51.146, 75.246.	(111), (002), (022).	ICSD 98-064-7139.
31	$Ni_{9.1}Sb_{0.9}$	43.608, 50.795, 74.682, 90.673, 95.953, 118.140.	(111), (200), (220), (311), (222), (400).	ICDD 03-065-4321.
32	$Ni_{0.92}Ta_{0.08}$	43.711, 50.917, 74.877.	(111), (002), (022).	ICSD 98-010-5393.
33	$Fe_{2.6}Mn_{1.2}Ni_{0.2}$	43.736, 50,947, 74.926.	(111), (002), (022).	ICSD 98-063-2501.
34	Ni_3Si	43.724, 50.932, 74.901.	(111), (002), (022),	ICSD 98-064-6580.
35	$Fe_{0.96}P_{0.04}$	44,729, 65,110, 82.454.	(011), (002), (112).	ICSD 98-010-8462.
36	$As_{0.2}Fe_{1.8}$	44.370, 64.553, 81.690.	(011), (002), (112).	ICSD 98-061-0476.

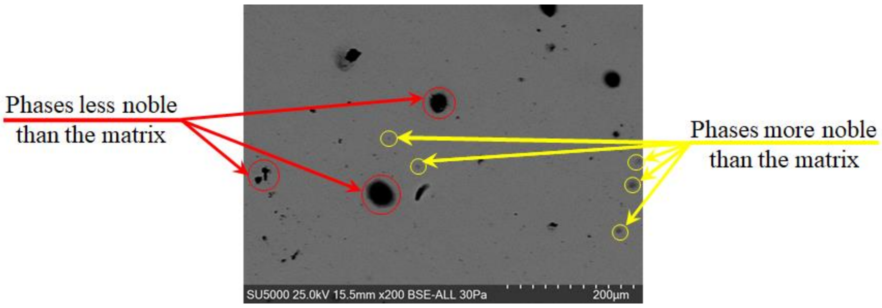


Figure 3. Scanning electron microscopic observation of 316 steel containing 2.19% molybdenum, after treatment in 65 wt% nitric acid.

After immersion of the surface of 316 stainless steel in a 65% nitric acid solution by weight for a period of 3 days, a scanning electron microscope analysis was performed (see Figure 3). This observation showed more pronounced corrosion in the less noble phases than the matrix, those with a lower corrosion potential than the matrix (austenite). On the other hand, phases with a higher potential than the matrix were relatively spared. These findings confirm the conclusions drawn from X-ray diffraction (XRD) analyses; our steel 316 is composed of several distinct phases.

After chemical treatment with nitric acid over a period of three days, electrochemical studies were conducted in physiological solutions of 0.9% NaCl aerated, to which different glucose concentrations (one, two, and four grams per liter) were added. These experiments were conducted at a constant temperature of 37°C. Figure 4 illustrates the variation of the open circuit potential (OCP) during one hour of immersion in a physiological solution of 0.9 % NaCl for austenitic stainless steel under different experimental conditions, namely (a) without treatment and (b) after nitric acid treatment. The results show that the corrosion potentials of nitric acid-treated samples are higher than those of untreated samples, which is consistent with previous research (Barbosa, 1983; Kannan et al., 2005; Noh et al., 2000b; Salvago & Fumagalli, 1994). At the time of immersion, the corrosion potential of sample 3 is highest, measured at approximately E = 0.092 V; this value decreases continuously to reach E = -0.069 V after one hour of immersion. In contrast, the corrosion potential of sample 2 is initially less noble than that of sample 3, measured at E = -0.015 V. However, it increases to E = 0.125 V after 360 seconds, then decreases to E = -0.154 V after 410 seconds, to finally increase again and reach a higher potential, measured at E = 0.042 V after one hour of immersion. Samples with the addition of one gram of glucose (1 and 4) have the lowest corrosion potentials, whether treated or not. Samples 2 and 5 have the highest corrosion potentials after one hour of immersion in the sodium chloride solution. It appears that the concentration of two grams of glucose in the saline solution has an optimal effect on the corrosion potential after one hour of exposure.

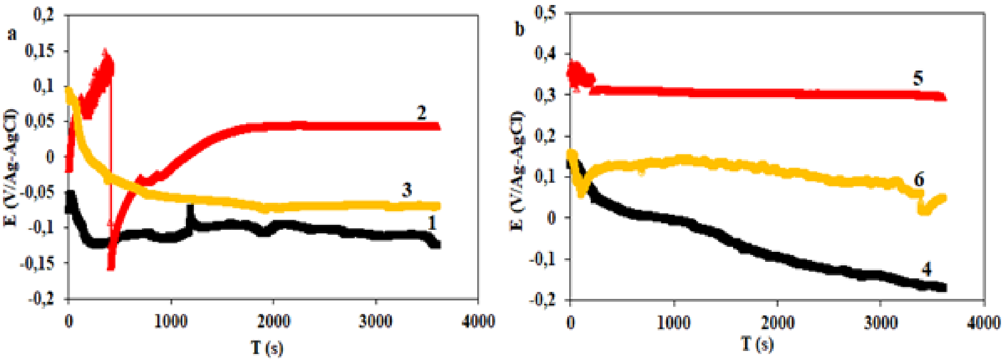


Figure 4. The open circuit potential (OCP) of austenitic steel 316 from samples, ■ samples 1 and 4 (one gram of glucose), ▲ samples 2 and 5 (two grams of glucose), ● samples 3 and 6 (four grams of glucose), in the physiological solution of 0.9% NaCl for one hour, (a) without treatment (b) after treatment.

In order to evaluate the effect of chemical treatment with nitric acid as well as the impact of glucose addition at different concentrations on the corrosion morphology of 316 stainless steel after one hour of immersion in a physiological solution of 0.9 % NaCl, the samples were examined using an optical microscope. The results of these observations are presented in Figure 5. Samples 1, 2, and 3, represented by (a), (b), and (c), respectively, were tested without treatment, while samples 4, 5, and 6, represented by (a'), (b'), and (c'), respectively, were subjected to chemical treatment.

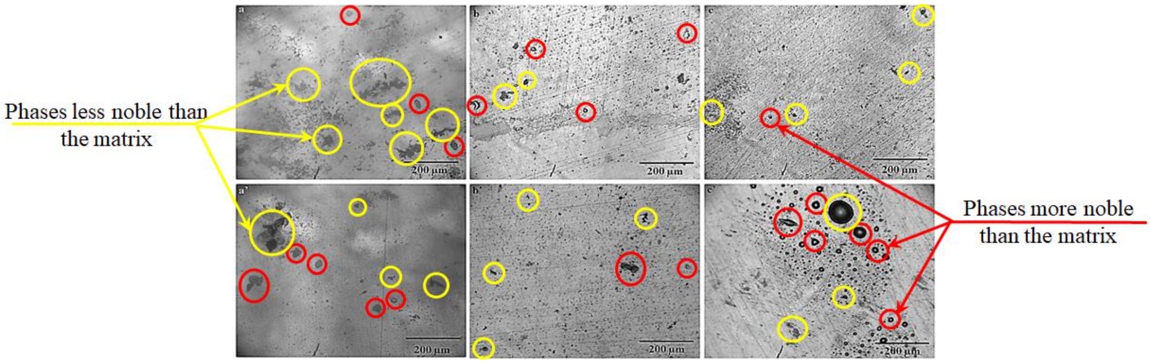


Figure 5. Corrosion morphology of austenitic steel 316, for different experimental conditions, samples 1, 2 and 3, represented by (a), (b) and (c) respectively, were tested without treatment. Samples 4, 5 and 6, represented by (a'), (b') and (c') respectively, were subjected to chemical treatment.

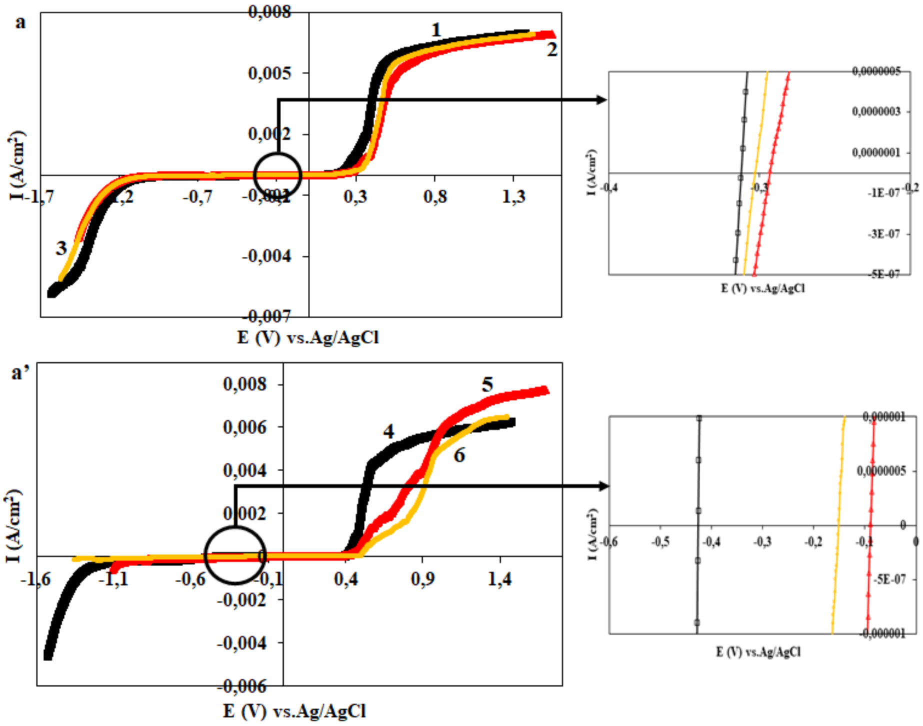
Localized corrosion was observed on all samples but was more pronounced on untreated samples. This can be explained by the passivation of the samples treated with nitric acid and the increase in chromium concentration in the passive film after surface treatment, as reported in references (Barbosa, 1983; Hultquist & Leygraf, 1980; Noh et al., 2000b). In addition, we observed that the corrosion rate decreases with an increase in glucose concentration. We found that some particles are completely corroded. In this case, these are less noble than the matrix (austenite). However, other particles remained intact; only their contours were corroded. These particles are more noble than the matrix.

In order to study the effect of nitric acid chemical treatment and the impact of glucose addition at different concentrations on polarization resistance and corrosion potential, we performed polarization tests in a 0.9% NaCl solution with the addition of one, two, and four grams/liter of glucose. These experiments were conducted at a constant temperature of 37°C. Figure 6 shows the polarization curves of 316 stainless steel, while Table 3 lists the values of corrosion potential and polarization resistance calculated from the polarization curves.

Figure 6 (a and a’) show the polarization curves (i=f(E)) and their magnification effect, while (b and b’) show the polarization curves (log (i)=f(E)) after one hour of corrosion (OCP) in the physiological solution 0,9% NaCl at different glucose concentrations. Figure 6 (a and b) without surface treatment; however, (a’ and b’) with nitric acid treatment. From these curves and the data in Table 3, we observed that the corrosion potentials of samples without treatment (1, 2, and 3) are very close compared to those of samples treated chemically (4, 5, and 6). In addition, the corrosion potentials of samples 5 and 6 are higher than those of samples without treatment 2 and 3, indicating that the addition of glucose (two and four grams) has an optimal effect on the corrosion potential (Ecorr) after chemical treatment with nitric acid. In contrast, samples 1 and 4 have the lowest potentials, confirming the results in Figure 4. However, the polarization resistance of chemically unprocessed samples is higher than that of treated samples (4, 5, and 6), and the polarization resistance decrease with surface treatment.

Table 4. Polarization resistance and corrosion potential of AISI 316 steel, after one hour of free corrosion (OCP), without and with nitric acid treatment.

Samples	Corrosion time	Rp (Ω cm^2)	Ecorr (v)
1	1 hour	7446	-0,3123
2	1 hour	19228	-0,2929
3	1 hour	10228	-0,3028
4	1 hour	2330	-0,4261
5	1 hour	7324	-0,0886
6	1 hour	8514	-0,1515



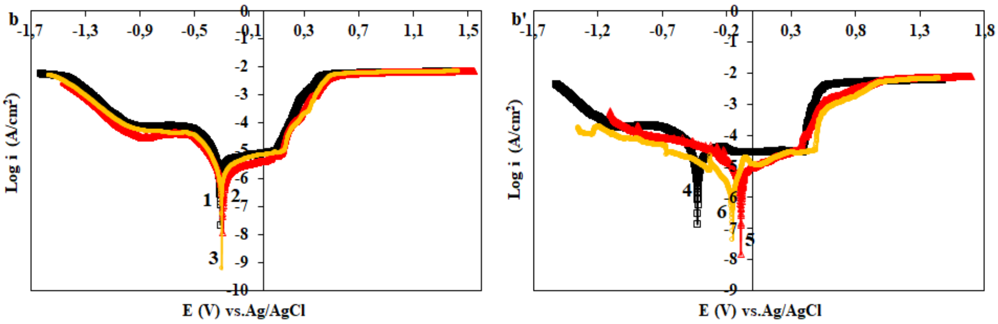


Figure 6. Polarization curves of austenitic steel 316, (a and a') shows the polarization curves (i=f(E)) and their magnification effect, (b and b') shows the polarization curves (log(i)=f(E)) after one hour of free corrosion (OCP) in physiological solution at different glucose concentrations, (a and b) without surface treatment, (a' and b') with nitric acid treatment.

Microscopic observations were made after each polarization test in a physiological solution after one hour of immersion. The results of these observations are presented in Figure 7. Samples 1, 2, and 3, noted respectively (a), (b), and (c), were tested without treatment, while samples 4, 5, and 6, noted (a'), (b'), and (c'), were subjected to pre-treatment.

Localized corrosion was observed on all samples but was more pronounced on untreated samples. This can be explained by the passivation of the samples by nitric acid (HNO_3) and the increase of the chromium concentration in the passive film after surface treatment, as indicated in references (Barbosa, 1983; Hultquist & Leygraf, 1980; Noh et al., 2000b). In particular, we noted that the corrosion rate decreases with an increase in glucose concentration, especially for samples that have undergone chemical treatment (HNO_3). We also observed that some particles are completely corroded, these are less noble than the matrix (austenite). On the other hand, other particles remained intact, only their contours having been corroded, the latter are more noble than the matrix.

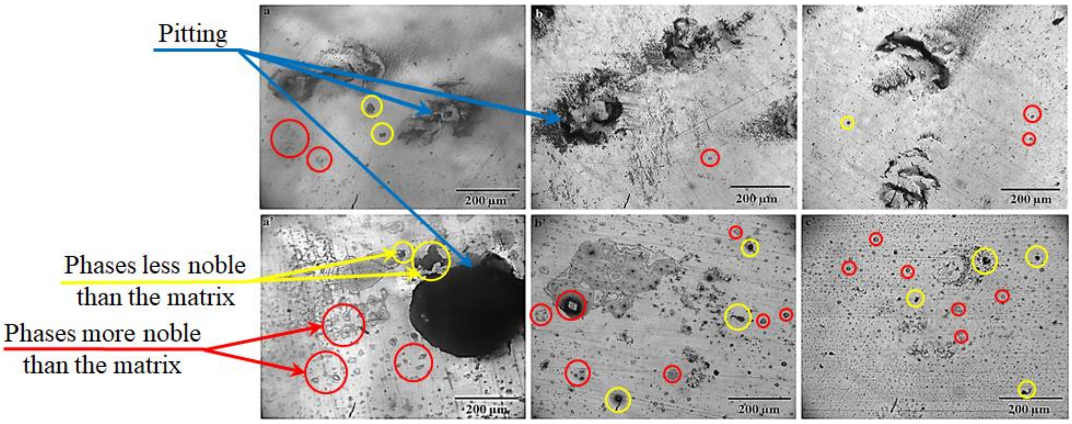


Figure 7. Corrosion morphology of austenitic steel 316 after each polarization test, after one week of corrosion, for different experimental conditions, samples without treatment 1, 2, and 3, designated by (a), (b), and (c) respectively. Samples with chemical treatment 4, 5, and 6, designated by (a'), (b'), and (c') respectively.

Figure 8 (a and b) show the evolution of the open circuit potential (OCP) during one week of immersion in a physiological solution for austenitic stainless steel under different experimental conditions, namely (a) without treatment and (b) after treatment with nitric acid. Contrary to the results observed after one hour of OCP and after one week, the potentials of samples not treated with nitric acid are higher than those of the treated samples, which means that the samples are passivated in the physiological solution of 0.9% NaCl in the presence of glucose. We noted that the potentials of the samples (8 and 9), subjected to the addition of two and four grams of glucose without treatment, are similar and nobler than those of sample 7, and similarly, for acid-treated samples (11 and 12), their potentials are close to and superior to those of sample 10. After eight days of corrosion, the potential is measured at approximately E = 0.64 V for sample 8 and E = 0.208 V for sample 9. It is virtually identical for samples with treatment (11 and 12), measured at approximately E = 0.064 V. Samples with the addition of one gram of glucose (7 and 10) have the lowest potentials, whether treated or not. It is obvious that the concentration of two and four grams of glucose in the saline solution exerts an optimal effect on the potential one week of immersion for the treated samples or not.

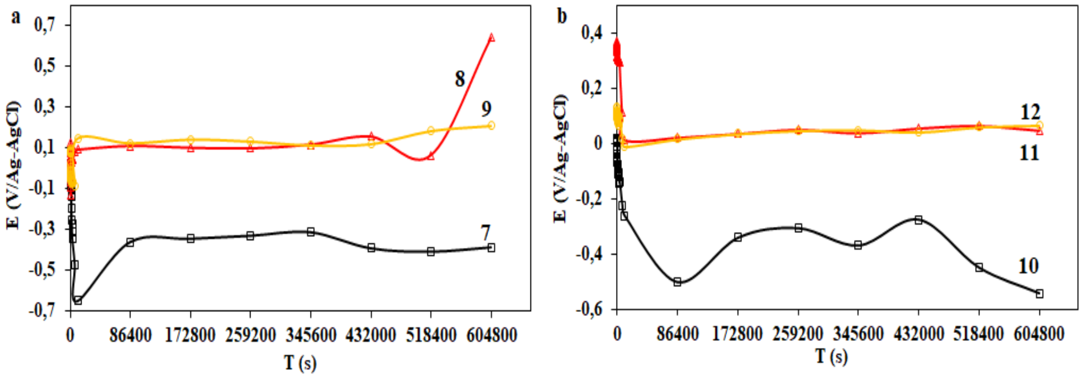


Figure 8. The open-circuit potential (OCP) of austenitic steel 316 from samples, ■ samples 7 and 10 (one gram of glucose), ▲ samples 8 and 11 (two grams of glucose), ● samples 9 and 12 (four grams of glucose), in the physiological solution of 0.9% NaCl for one week, (a) without treatment (b) after treatment.

In order to see the effect of nitric acid chemical treatment and the influence of glucose addition at different concentrations on 316 stainless steel corrosion morphology after one week of immersion in a physiological solution of 0.9% NaCl, we made microscopic optical observations. The results of these observations are shown in Figure 9. Samples 7, 8, and 9, represented by (a), (b), and (c) respectively, were tested without treatment, while samples 10, 11, and 12, represented by (a'), (b'), and (c') respectively, were subjected to chemical treatment. We found localized corrosion on all samples, but this corrosion is more pronounced on untreated samples. This can be explained by the passivation of the samples after 8 days of corrosion and the increase in chromium concentration in the passive film after surface treatment. Also, we found that the rate of corrosion decreases with an increase in glucose concentration, especially for samples treated with HNO_3 acid (a', b', and c'). Some particles were completely corroded, corresponding to the less noble particles than the matrix (austenite). On the other hand, other particles remained intact; only their contours were corroded, these particles are more noble than the matrix.

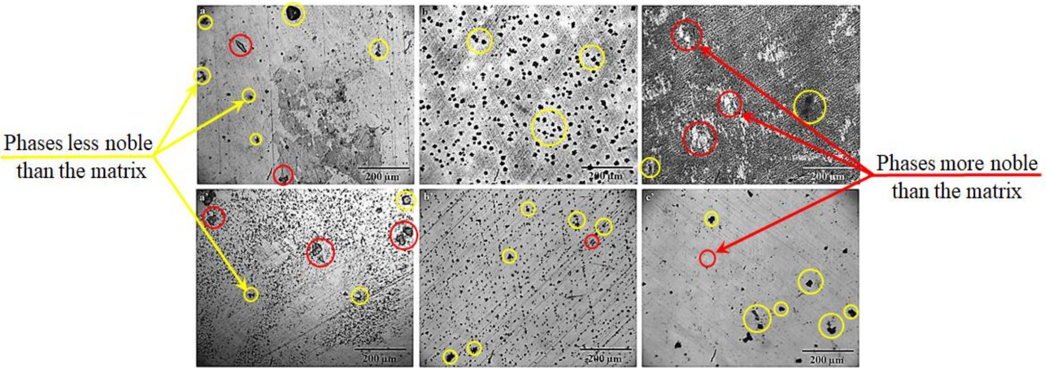


Figure 9. Corrosion morphology of austenitic steel 316, for different experimental conditions, untreated samples 7, 8 and 9, represented by (a), (b) and (c) respectively. Samples with chemical treatment 10, 11 and 12, represented by (a'), (b') and (c') respectively.

After one week of corrosion exposure (OCP), polarization tests were performed in a 0.9% NaCl solution with the addition of one, two, and four grams of glucose per liter. The polarization curves for 316 stainless steel are shown in Figure 10, while Table 4 summarizes the values of corrosion potential and polarization resistance calculated from these curves.

The polarization curves (i=f(E)) are illustrated in Figure 10 (a and a'), with their lope effect, while (b and b') show the polarization curves (log (i)=f(E)) after one week of corrosion exposure (OCP) in the physiological solution of 0.9% NaCl at different glucose concentrations. The samples in Figure 10 (a and b) are without surface treatment, while (a' and b') have been treated with nitric acid. Based on these curves and the data in Table 4, we found that the corrosion potentials of untreated samples (7, 8, and 9) are higher than those of chemically treated samples (10, 11, and 12). This phenomenon can be explained by the passivation of untreated samples after 8 days of corrosion in the solution saline. In addition, the polarization resistance and corrosion potentials of untreated samples increase with the increase in glucose concentration in the physiological solution. The polarization resistance values are respectively Rp = 2509 Ω/cm^2, Rp = 4022 Ω/cm^2, and Rp = 4598 Ω/cm^2, so the corrosion potentials are measured at about E = -0.3586 V, E = -0.2712 V, and E = -0.2301 V for one, two, and four grams of glucose per liter, respectively. These results indicate that the addition of two and four grams of glucose per liter has an optimal effect on polarization resistance and corrosion potential (Ecorr) after one week of corrosion. However, for chemically treated samples, Sample 11 has the highest corrosion potential, thus confirming the previous results (Figure 6 (a')). The nitric acid treatment and the addition of two grams of glucose to the solution of saline have a significant effect on the corrosion potential of stainless steel. In addition, the polarization resistance of chemically untreated samples (7, 8, and 9) is higher than that of treated samples (10, 11, and 12), indicating a decrease in polarization resistance with surface treatment.

Table 5. Polarization resistance and corrosion potential of AISI 316 steel, after one week of free corrosion (OCP), without and with nitric acid treatment.

Samples	Corrosion time	Rp (Ω cm^2)	Ecorr (v)
7	8 days	2509	-0.3586
8	8 days	4022	-0.2712
9	8 days	4598	-0.2301
10	8 days	75895	-0.6257
11	8 days	3489	-0.2748
12	8 day	2018	-0.4845

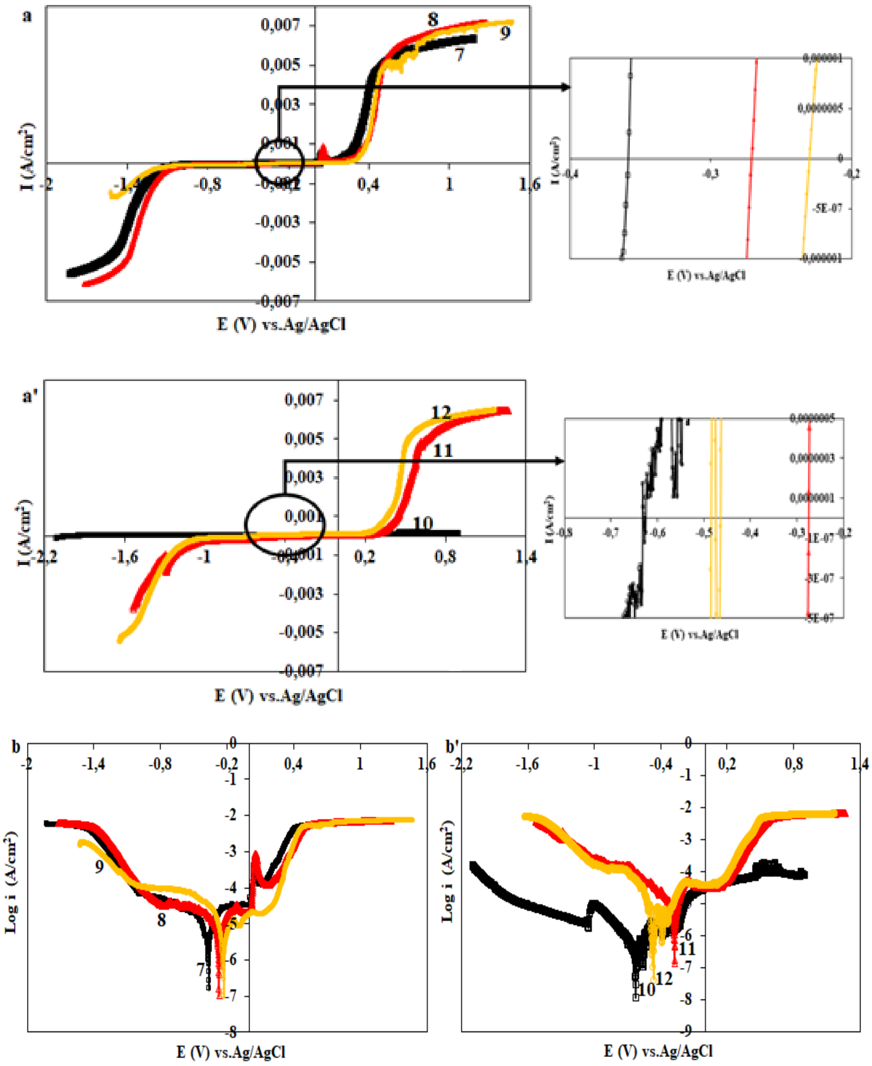


Figure 10. Polarization curves of austenitic steel 316, (a and a') shows the polarization curves (i=f(E)) and their magnification effect, (b and b') shows the polarization curves (log(i)=f(E)) after one week of free corrosion (OCP) in physiological solution at different glucose concentrations, (a and b) without surface treatment, (a' and b') with nitric acid treatment.

In order to evaluate the impact of HNO_3 nitric acid chemical treatment as well as the influence of glucose addition at different concentrations on the corrosion morphology of 316 stainless steel, microscopic observations were made after each polarization test in a physiological solution after one week of corrosion. The results of these observations are presented in Figure 11. Samples 7, 8, and 9, designated by (a), (b), and (c), respectively, were tested without treatment, while samples 10, 11, and 12, designated by (a'), (b') and (c'), were subjected to pre-treatment.

Localized corrosion was observed on all the samples; however, it is more pronounced on the treated samples. This fact can be explained by the passivation of the untreated samples after 8 days of free corrosion in the saline solution. In particular, we noticed that the corrosion rate decreased with the increase in glucose concentration, especially for untreated samples (glucose improves the passivation of austenitic steels, 316). We also found that some particles are completely corroded, corresponding to less noble particles than the matrix (austenite). On the other hand, other particles remained intact, only their contours having been corroded, these particles are more noble than the matrix.

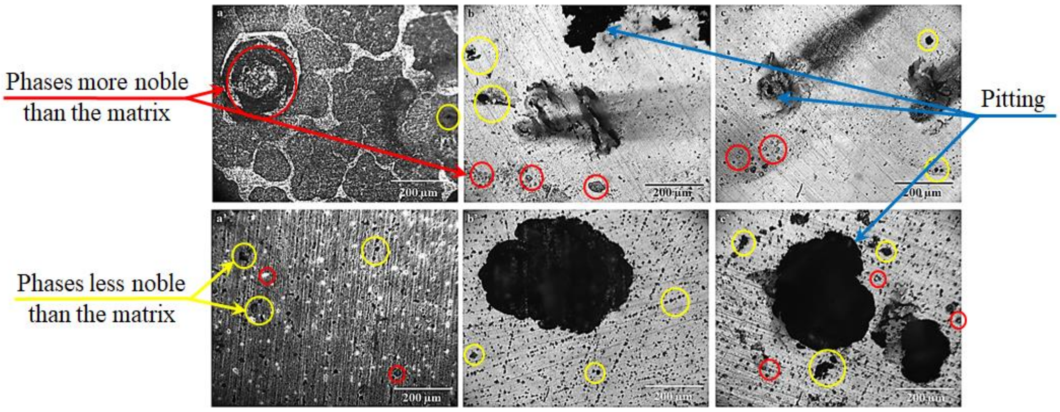


Figure 11. Corrosion morphology of austenitic steel 316 after each polarization test, after one week of corrosion, for different experimental conditions, samples without treatment 1, 2 and 3, designated by (a), (b) and (c) respectively. Samples with chemical treatment 4, 5 and 6, designated by (a'), (b') and (c') respectively.

Conclusion

The study examines the corrosion resistance of stainless steel 316 exposed to a 0.9% NaCl solution with different glucose concentrations following surface treatment with nitric acid. Through various analyses, including microscopic examination, X-ray diffraction, and electrochemical tests, several important conclusions are drawn:

Initially, the AISI 316 has a variety of distinct phases and inclusions. The corrosion potential increases after one hour of corrosion, while the polarization resistance decreases for treated samples. The impact of corrosion on AISI 316 is particularly marked, especially with the addition of 2 grams of glucose in the solution, while the pitting rate decreases for treated samples after one hour of corrosion. In addition, untreated samples show a significant increase in potential after one week of corrosion. The addition of glucose optimizes the polarization resistance and corrosion potential; the samples passivate in the NaCl solution in the presence of glucose. The corrosion behavior of AISI 316 is significantly influenced, especially with the addition of 2 grams of glucose to the solution after treatment with HNO_3 acid. In addition, the polarization resistance and corrosion potentials of untreated samples increase with increasing glucose concentrations, while the pitting rate decreases for these samples.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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