EUROPEAN COMMISSION

ECSC Research Project RFS-PR-09032
Executive Committee TGS8

"STRUCTURAL APPLICATIONS OF FERRITIC STAINLESS STEELS"

Report on laboratory electrochemical tests (Deliverable WP7.4)

December, 2012

EUROPEAN COMMISSION

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Title of Research Project:	Structural Application of Ferritic Stainless Steels
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Report on laboratory electrochemical tests (Deliverable WP7.4)

SAFSS-WP7.4 : Report on laboratory electrochemical tests

1 INTRODUCTION

A comparative study is carried out in the project named SAFSS (Structural Applications of Ferritic Stainless Steels). The project intends to develop technical information about some grades of ferritic stainless steels in order to spread its use in construction. A large variety of tests are performed to characterize these materials.

Acerinox participates as the leader of the corrosion work package (WP7). Three tests make up this work package: exposure fields (atmospheric test), accelerated tests (climatic chamber) and electrochemical tests.

This document has been prepared to include electrochemical tests. By means of these assessments comparative information about resistance to pitting and uniform corrosion from the different ferritic grades is obtained.

2 TEST MATERIALS

The stainless steels have been delivered by the three industrial partners involved in the project (Aperam, Outokumpu and Acerinox).

In table 1 the identification in electrochemical test of the ferritic stainless steels is shown. The grade, origin, line, finish and thickness are specified.

Ferritic Stainless Steel	Line	Finish	Thickness (mm)	Identification
EN 1.4003	Hot rolled	1D	4.0	1
	Hot rolled	1D	6.0	2
	Cold rolled	2B	0.8	3
	Cold rolled	2B	1.0	4
EN 1.4509	Hot rolled	1D	3.5	5
	Hot rolled	1D	6.0	6
	Cold rolled	2B	0.6	7
	Cold rolled	2B	1.0	8
EN 1.4521	Cold rolled	2B	1.2	9
	Cold rolled	2B	0.8	10
EN 1.4621	Cold rolled	2M	1.0	11
EN 1.4016	Cold rolled	2B	1.2	12
	Cold rolled	BA	1.0	13
EN 1.4509	Cold rolled	2B	1.0	14
	Cold rolled	BA	1.0	15
	Cold rolled	BA	0.8	16
EN 1.4521	Cold rolled	BA	0.7	17
EN 1.4301	Cold rolled	2B	0.7	18

Table 1. - Stainless steels identification

Samples with electrochemical identification from 1 to 11 (table 1), take part on the atmospheric tests on the four test stations of the project, Seville (urban), Isbergues (industrial), Ljubljana (rural) and Tornio (marine). The ferritic EN 1.4016 is tested, because it is a ferritic grade widely used and studied. The austenitic stainless steel (EN 1.4301) has been included as a reference material. The grade EN 1.4509 in 2B and BA finishes has been included in order to check the repeatability of the test and evaluate the BA finish in this grade and finally the EN 1.4521 grade in BA finish has been included so as to improve the information gathered from the test. The inclusion of more specimens improves the repeatability and the information obtained from the test.

In order to check materials, by means of x-Ray fluorescence spectroscopy and Leco automatic detectors (carbon, nitrogen and sulphur) the chemical composition has been analysed (table 2).

	Weight %										
	C	**Si**	**Mn**	**Sn**	**Ni**	**Cr**	**Mo**	**Ti**	**Nb**	**S**	**N**
1	0.011	0.29	1.40	0.011	0.55	11.02	0.03	0.004	0.017	0.003	0.0146
2	0.019	0.29	1.40	0.011	0.55	11.05	0.03	0.003	0.017	0.002	0.0124
3	0.024	0.46	0.59	0.009	0.53	10.80	0.03	0.004	0.007	0.001	0.0154
4	0.014	0.26	1.42	0.010	0.48	11.05	0.01	0.004	0.002	0.002	0.0111
5	0.016	0.43	0.26	0.010	0.27	17.85	0.01	0.170	0.475	0.001	0.0210
6	0.017	0.57	0.32	0.010	0.26	17.64	0.01	0.149	0.402	0.002	0.0143
7	0.015	0.46	0.26	0.009	0.39	17.65	0.04	0.135	0.464	0.001	0.0255
8	0.019	0.52	0.44	0.015	0.32	18.14	0.03	0.120	0.443	0.001	0.0176
9	0.027	0.55	0.54	0.004	0.24	17.78	1.92	0.156	0.408	0.001	0.0237
10	0.066	0.37	0.64	0.007	0.41	18.02	1.98	0.138	0.395	0.003	0.0241
11	0.017	0.29	0.26	0.009	0.29	20.36	0.02	0.003	0.452	0.002	0.0230
12	0.066	0.37	0.64	0.011	0.35	16.35	0.01	0.003	0.008	0.003	0.0321
13	0.050	0.37	0.34	0.010	0.26	16.26	0.01	0.003	0.005	0.002	0.0352
14	0.019	0.54	0.31	0.010	0.39	17.76	0.01	0.174	0.470	0.001	0.0160
15	0.022	0.48	0.37	0.011	0.47	17.98	0.03	0.185	0.459	0.002	0.0164
16	0.025	0.60	0.29	0.017	0.28	17.71	0.02	0.152	0.446	0.002	0.0176
17	0.022	0.66	0.28	0.007	0.34	17.88	1.84	0.137	0.351	0.002	0.0142
18	0.048	0.33	1.73	0.009	8.07	18.12	0.22	0.005	0.012	0.001	0.0564

Table 2. - Chemical Composition

The correct composition selection is confirmed in each stainless steel.

3 ELECTROCHEMICAL TEST

The test is based on ASTM standards G3-94 "Conventions Applicable to Electrochemical Measurements in corrosion testing" and G5-94 "Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements". The procedure consists of a simple potentiodynamic test, where an electric variable is controlled and the response of a related one is registered. In this case potential is modified by a positive scan and current is measured by the same device, a potentiostat. The specimen potential is scanned in the positive-going direction and therefore acts as an anode such that it corrodes or forms an oxide coating.
The test is carried out in a flat cell as figure 1 shows. The flat cell has a controlled temperature water bath, and several holes to permit the introduction of electrodes,

inert gas inlet, salt bridge, agitator and thermometer. The test equipment is completed with a potentiostat (EG&G PARC model 263), and a computer with the software "Princeton Applied Research. Power suite 2.58" (figure 2).

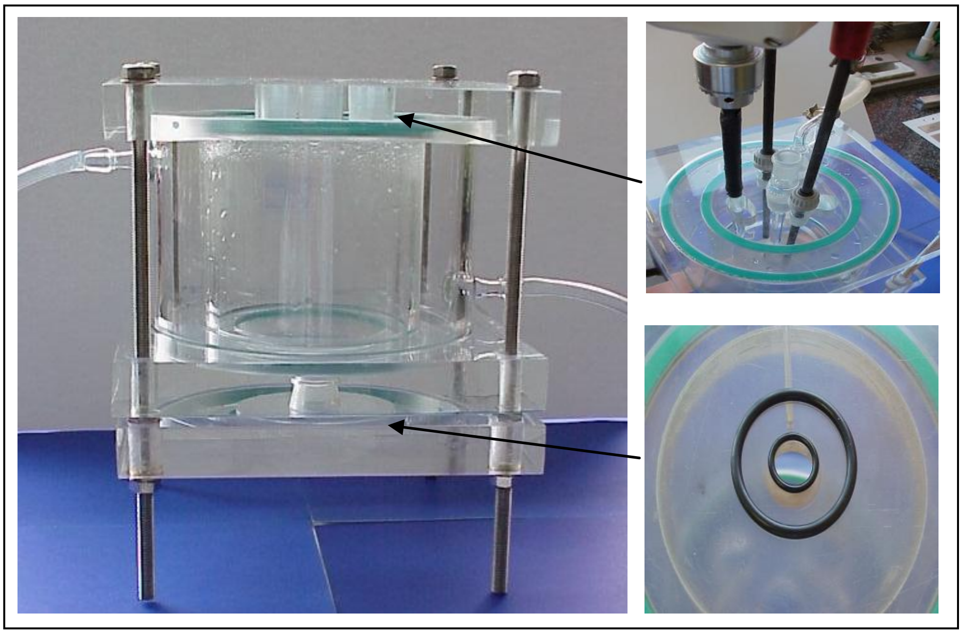

Figure 1. - Electrochemical test cell

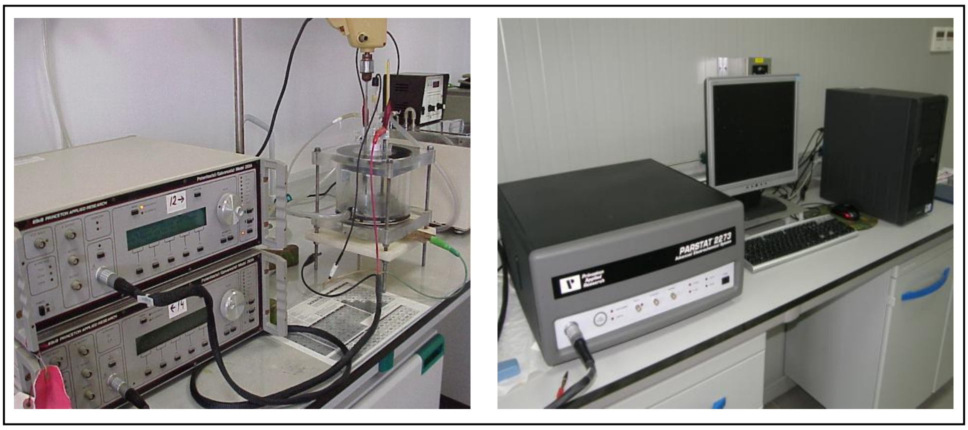

Figure 2. - Electrochemical test equipment

3.1 PITTING CORROSION

An indication of the susceptibility to initiation of localized corrosion is given by the potential which the anodic current suddenly increases rapidly. The nobler this potential, the lower susceptible the alloy to the initiation of localized corrosion in this environment. The procedure is a comparative test of resistance from different stainless steel in the applied conditions.

The demanded value is pitting potential (Ep). This fact means the minimal potential at which the first pitting nucleus occurs (figure 3).

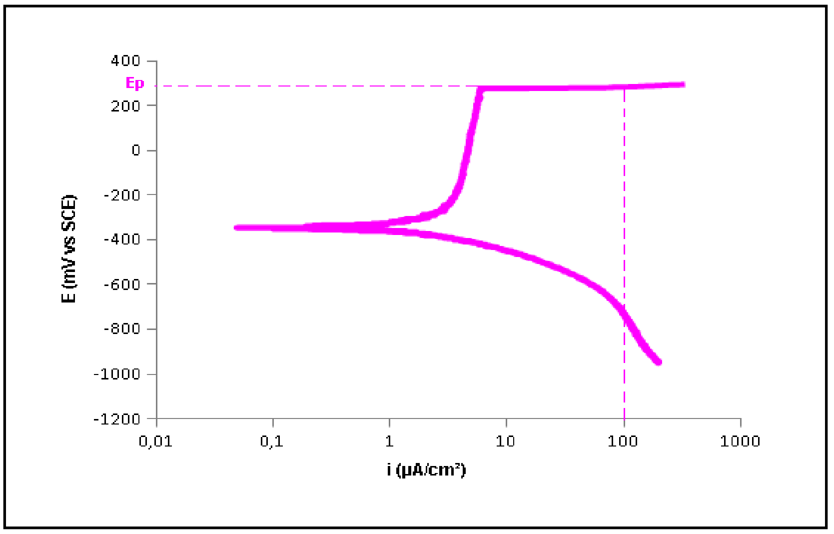

Figure 3. - Polarization curves - Pitting corrosion

3.1.1 Test conditions

Test solution, 300 ml of 35 g/L NaCl, is poured into the cell shown in figure 1. The test specimen is placed on the bottom side of the cell. The device is provided with an inlet of distilled water so as to avoid crevice corrosion (figure 4).

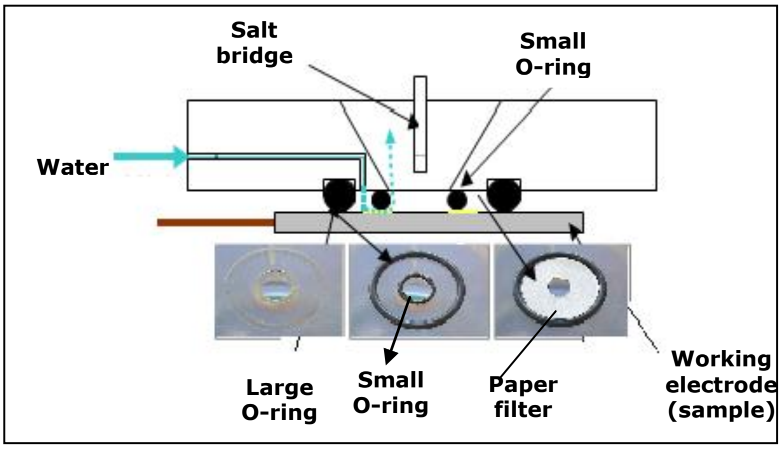

Figure 4. - Sample position in flat cell

The oxygen level in the solution is reduced by bubbling N_2 (0,8 L/min) 20 minutes before the start of the test and throughout the test period. The solution is stirred during the test to homogenize their composition. The test is carried out in a potentiostat by means of software. In table 3, the conditions that the software applies can be seen.

Conditioning potential	**-1,3 mV vs. SCE**
Conditioning time	**180 s**
Start potential	**-1,1 V vs. SCE**
Final potential	**1,6 V vs. SCE**
Rate scan	**0,17 mV/s**
Test area	**1 cm^2**
Temperature	**30 ºC ± 1**

Table 3. - Test conditions

3.1.2 Test materials

Table 4 shows a code which relates the results to the tested samples. The specimens are tested in two surface conditions, 600-grit polished and supply conditions.

Stainless Steel	Finish	Polish	Pitting Identification
EN 1.4003	1D	Yes	P_{P1}
		No	P_{S1}
	1D	Yes	P_{P2}
		No	P_{S2}
	2B	Yes	P_{P3}
		No	P_{S3}
	2B	Yes	P_{P4}
		No	P_{S4}
EN 1.4509	1D	Yes	P_{P5}
		No	P_{S5}
	1D	Yes	P_{P6}
		No	P_{S6}
	2B	Yes	P_{P7}
		No	P_{S7}
	2B	Yes	P_{P8}
		No	P_{S8}
EN 1.4521	2B	Yes	P_{P9}
		No	P_{S9}
	2B	Yes	P_{P10}
		No	P_{S10}
EN 1.4621	BA	Yes	P_{P11}
		No	P_{S11}
EN 1.4016	2B	Yes	P_{P12}
		No	P_{S12}
	BA	Yes	P_{P13}
		No	P_{S13}
EN 1.4509	2B	Yes	P_{P14}
		No	P_{S14}
	BA	Yes	P_{P15}
		No	P_{S15}
	BA	Yes	P_{P16}
		No	P_{S16}
EN 1.4521	BA	Yes	P_{P17}
		No	P_{S17}
EN 1.4301	2B	Yes	P_{P18}
		No	P_{S18}

Table 4. - Identification of samples

3.1.3 Sample preparation

The sample dimensions are $40x40mm^2$. In order to get as wide information as possible, they are tested by two different surface treatments.

In one of them, the working electrode surface (sample) is polished up to a fine-grained finish by 120, 180, 320 and 600-grit SiC paper until previous coarse scratches are removed. The surface is rinsed by means of distilled water and dried by cellulose paper. A support is glued in order to make easier the polishing procedure and the assembly of the sample.

The other treatment consists of rinsing the sample surface, washing with neutral soap and drying by cellulose paper. In this case a support may be glued like in polished samples or it may be used an isolated piece as it is shown in figure 6.

A copper wire is welded to the specimen as electrochemical contact. So, the specimens are prepared to be tested.

The final view of the sample is shown in figures 5 and 6.

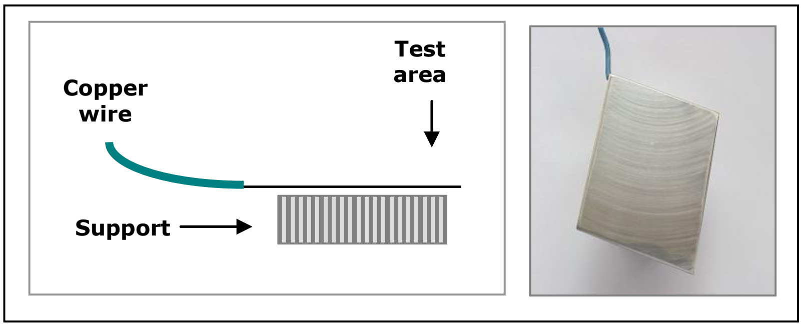

Figure 5. - Sample ready to be tested

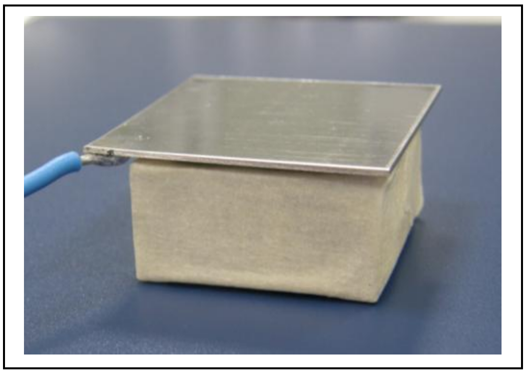

Figure 6. – Example of test specimen

3.1.4 Results and discussion

3.1.4.1. Polished surface

The results from the test and the comparison among stainless steels are shown and analysed by means of tables and graphs.

The following results are obtained from samples with a polished surface as above it has been mentioned.

The obtained graphic for each stainless steel, besides their pitting potential, are shown in figures (7 – 24).

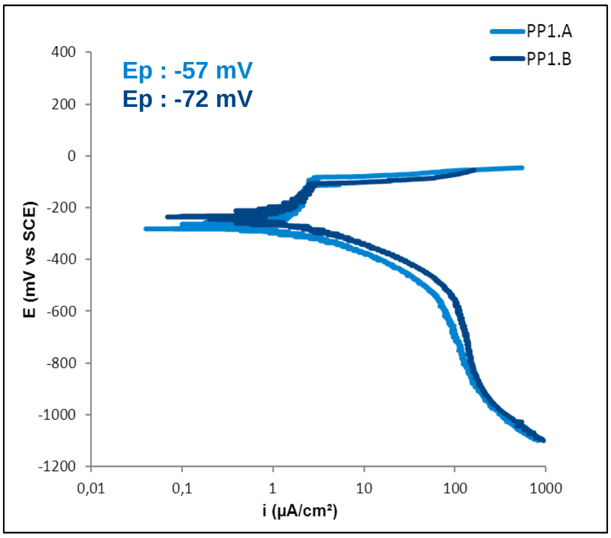

Figure 7.- EN 1.4003. P_{P1} samples

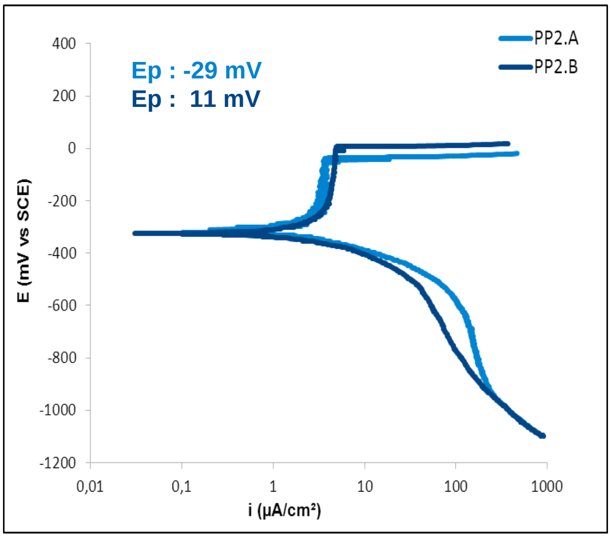

Figure 8.- EN 1.4003. P_{P2} samples

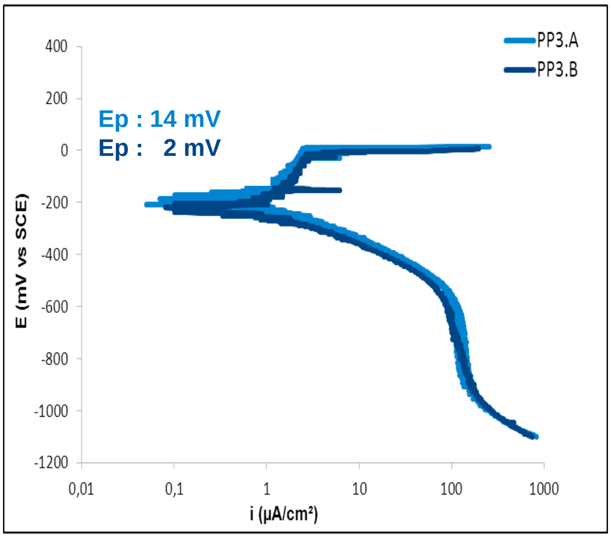

Figure 9. - EN 1.4003. P_{P3} samples

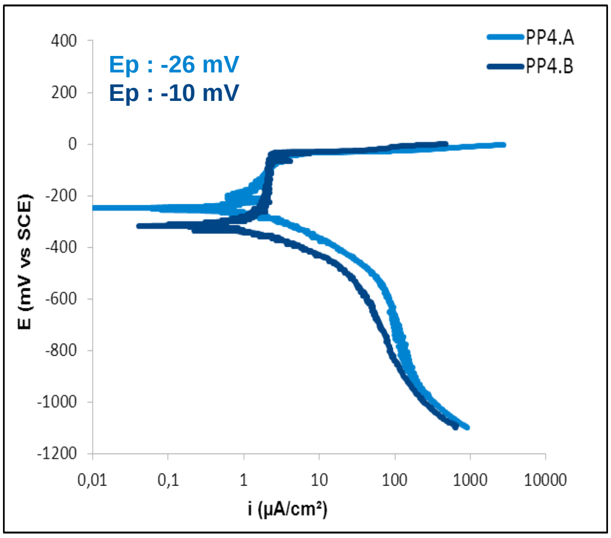

Figure 10.- EN 1.4003. P_{P4} samples

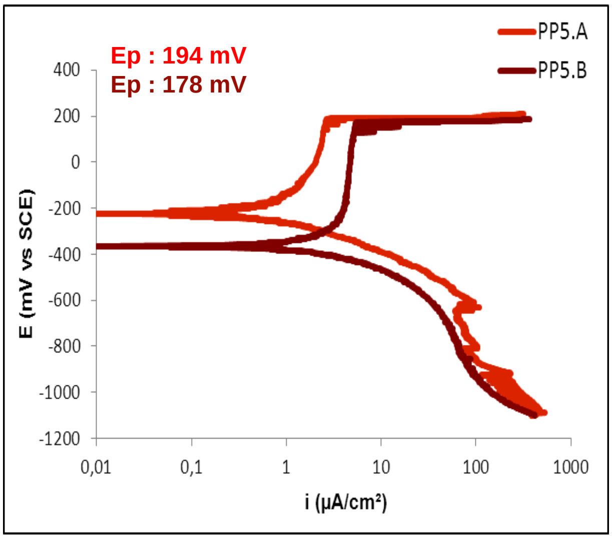

Figure 11.- EN 1.4509. P_{P5} samples

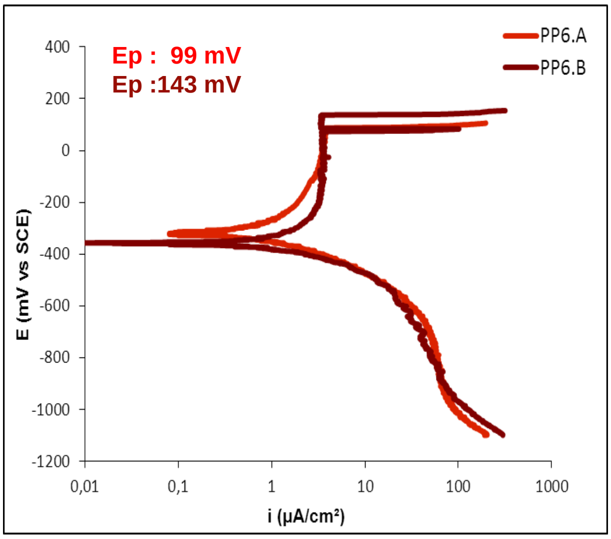

Figure 12.- EN 1.4509. P_{P6} samples

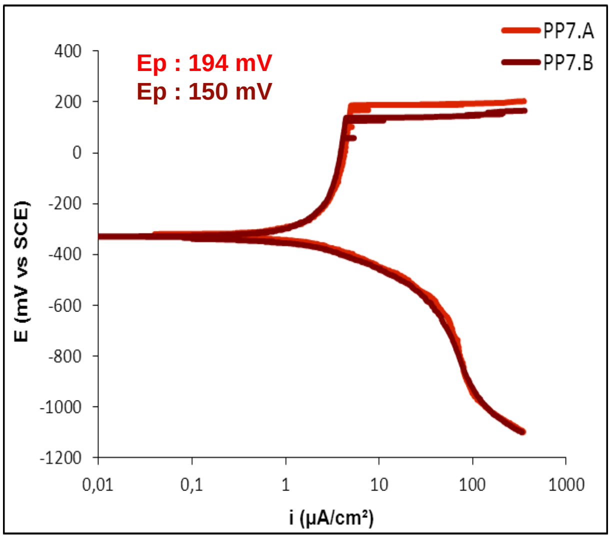

Figure 13.- EN 1.4509. P_{P7} samples

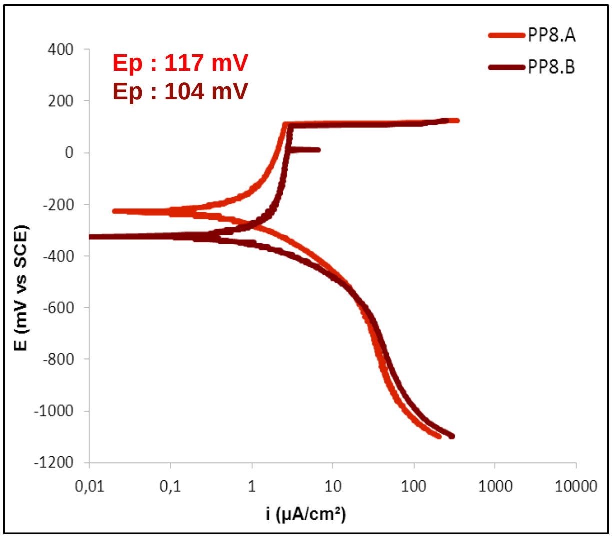

Figure 14.- EN 1.4509. P_{P8} samples

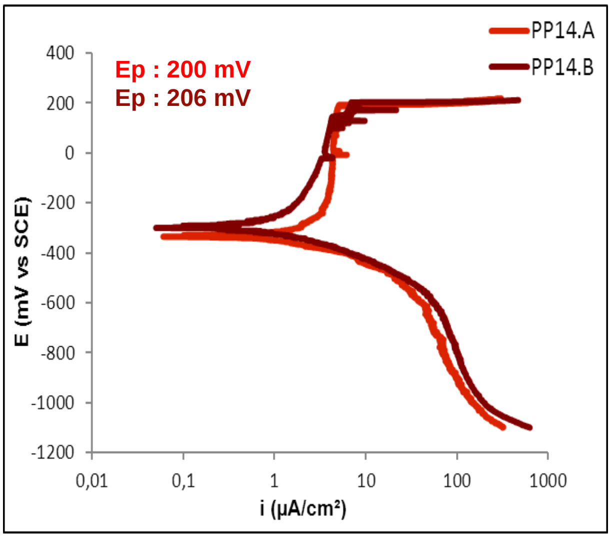

Figure 15.- EN 1.4509. P_{P14} samples

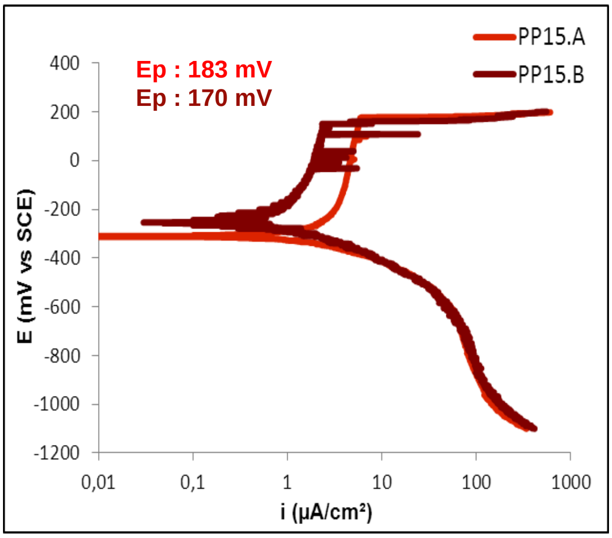

Figure 16.- EN 1.4509. P_{P15} samples

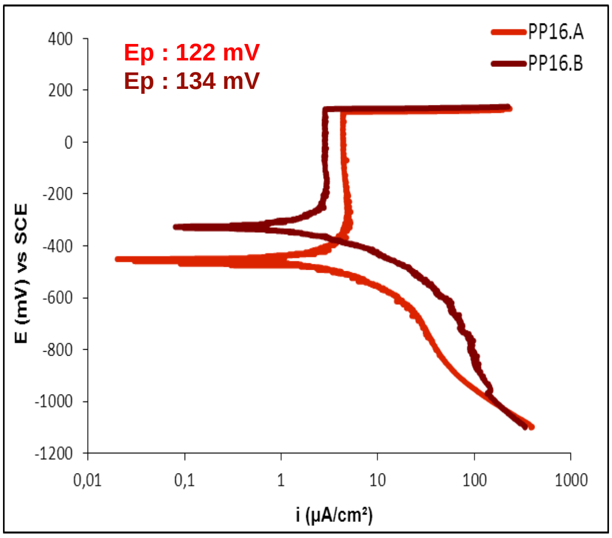

Figure 17.- EN 1.4509. P_{P16} samples

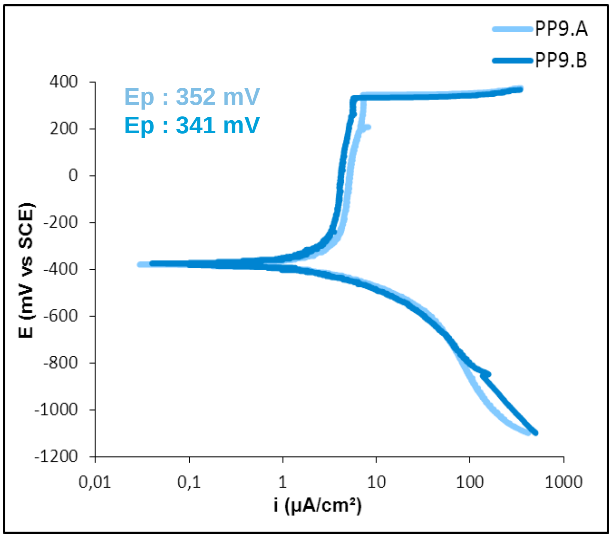

Figure 18.- EN 1.4521. P_{P9} samples

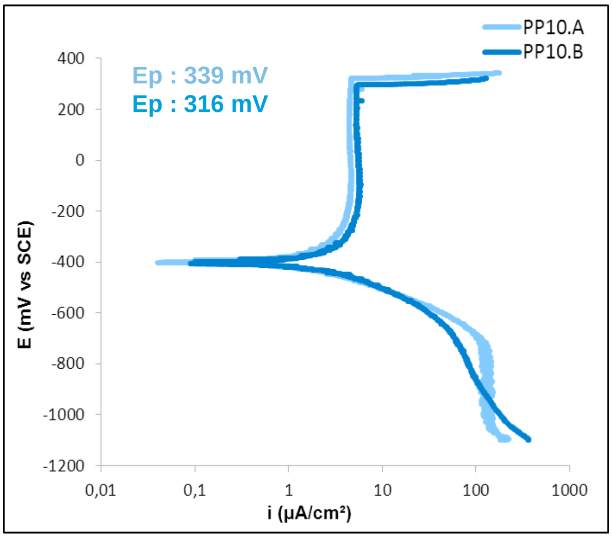

Figure 19.- EN 1.4521. P_{P10} samples

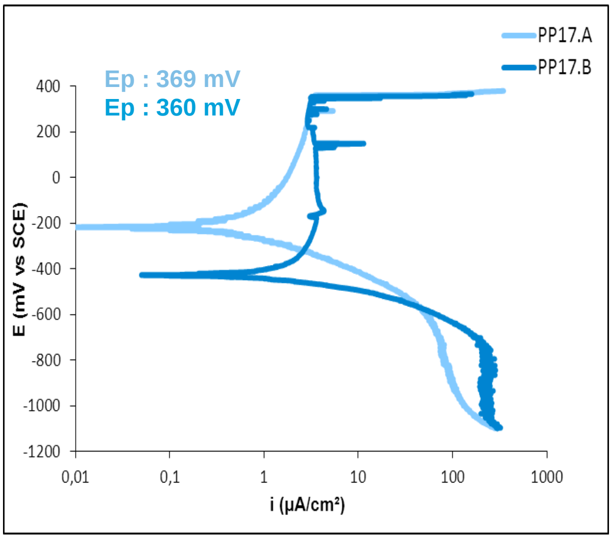

Figure 20.- EN 1.4521. P_{P17} samples

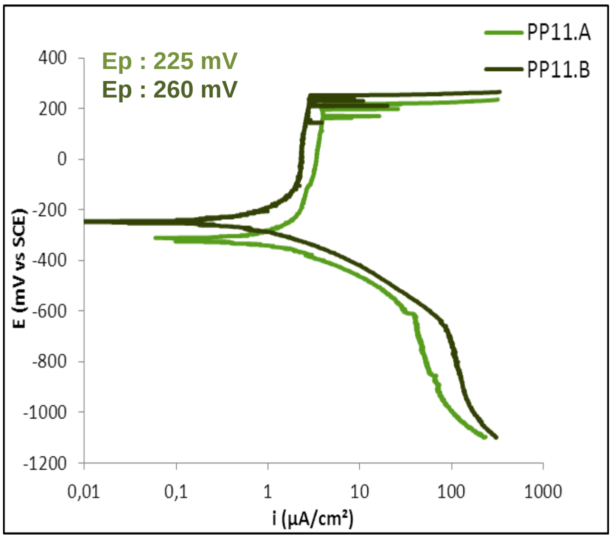

Figure 21.- EN 1.4621. P_{P11} samples

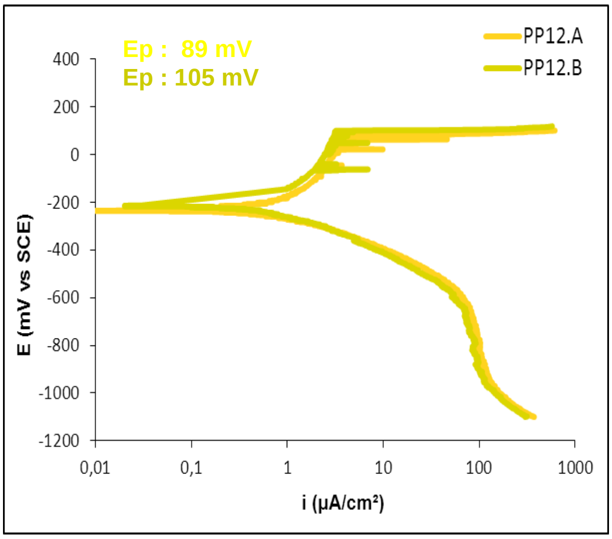

Figure 22.- EN 1.4016. P_{P12} samples

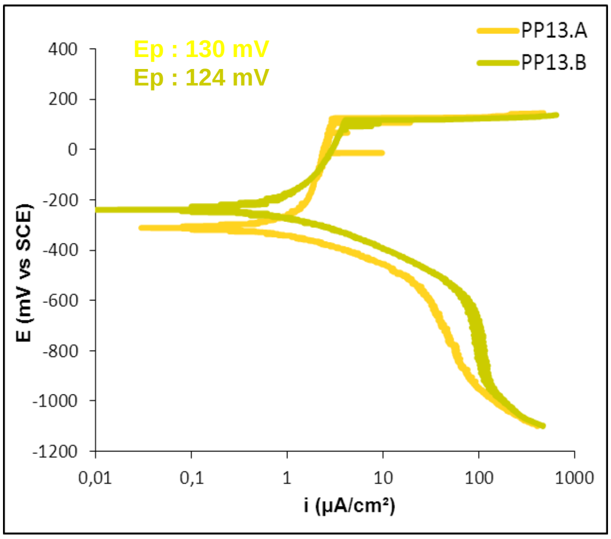

Figure 23.- EN 1.4016. P_{P13} samples

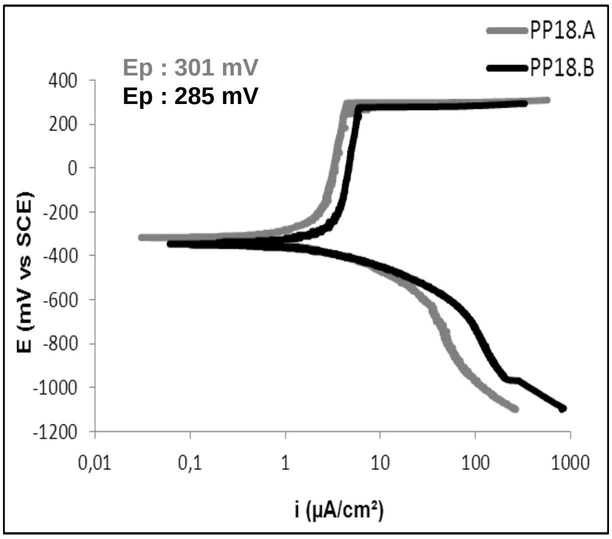

Figure 24.- EN 1.4301. P_{P18} samples

It can be observed that all graphs have the same shape with appearance of a passive area ended by the pitting potential. The only difference among samples is the value of this pitting potential (Ep) and the range of potentials in the passive area. The repeatability in samples A and B for each material must be outlined.

An interesting parameter to evaluate pitting corrosion resistance is PRE value, Pitting Resistance Equivalent. PRE relates the chromium, molybdenum and nitrogen content of a stainless steel, with its resistance to pitting corrosion. The equation to calculate PRE value is the following.

$$\mathbf{PRE = \% Cr + 3.3 \cdot \% Mo + 30 \cdot \% N}$$

In table 5 are included the values of the PRE and Ep parameters for every sample.

Stainless Steel	**Sample**		**PRE**	**Ep (mV vs. SCE)**	**Ep_{media} (mV vs. SCE)**
EN 1.4003	P_{P1}	A	11,56	-57	-65
		B		-72	
	P_{P2}	A	11,52	-29	-9
		B		11	
	P_{P3}	A	11,36	14	8
		B		2	
	P_{P4}	A	11,42	-29	-18
		B		-10	
EN 1.4509	P_{P5}	A	18,51	194	186
		B		178	
	P_{P6}	A	18,10	99	121
		B		143	
	P_{P7}	A	18,55	194	172
		B		150	
	P_{P8}	A	18,77	117	111
		B		104	
EN 1.4521	P_{P9}	A	24,73	352	347
		B		341	
	P_{P10}	A	25,28	339	328
		B		316	
EN 1.4621	P_{P11}	A	21,12	225	243
		B		260	
EN 1.4016	P_{P12}	A	17,35	89	97
		B		105	
	P_{P13}	A	17,38	130	127
		B		124	
EN 1.4509	P_{P14}	A	18,27	200	203
		B		206	
	P_{P15}	A	18,57	183	177
		B		170	
	P_{P16}	A	18,30	122	128
		B		134	
EN 1.4521	P_{P17}	A	24,38	369	365
		B		360	
EN 1.4301	P_{P18}	A	20,54	301	293
		B		285	

Table 5.- PRE and Ep values (polished)

In order to ease the analysis of data, in figure 25 the pitting potential from ferritic grades against their PRE value can be seen.

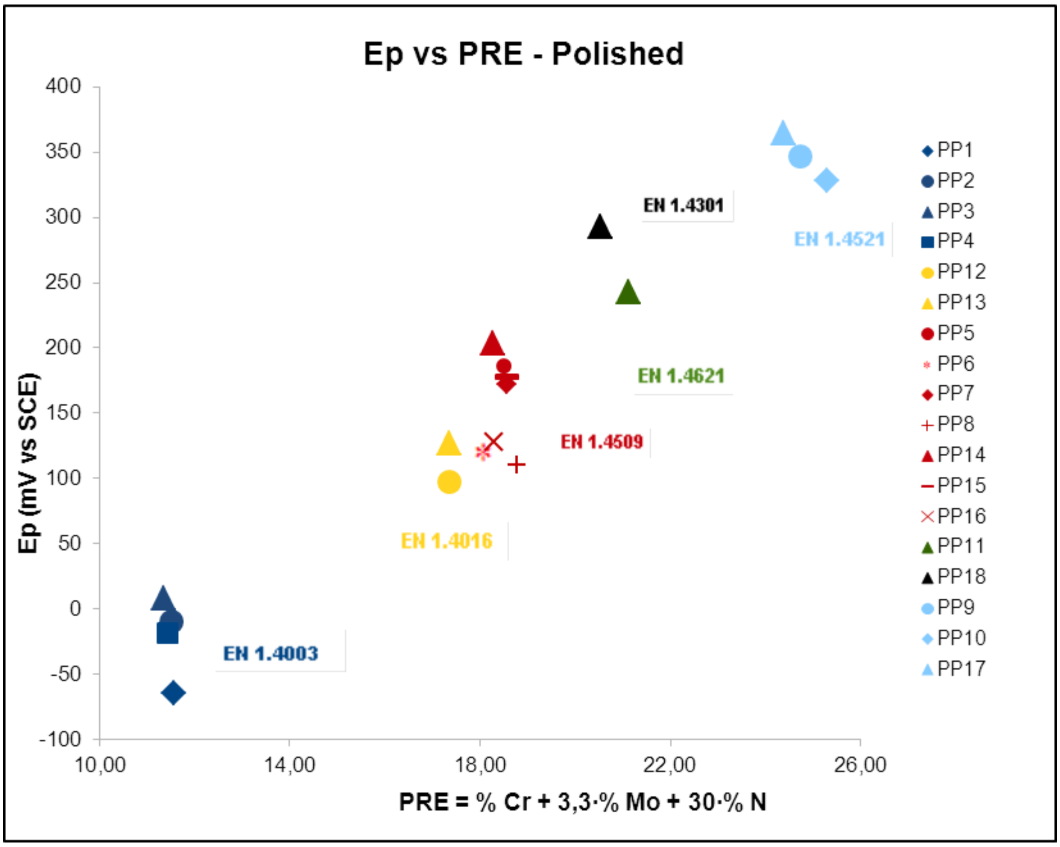

Figure 25.- Pitting corrosion - Ferritic grade

According to data illustrated on figure 25, it can be mentioned that exists a relation between PRE and Ep, a higher PRE value means a higher Ep result.

3.1.4.2. Supply surface

In figures 26 - 43 are represented the graphs and pitting potentials from every stainless steel in supply surface.

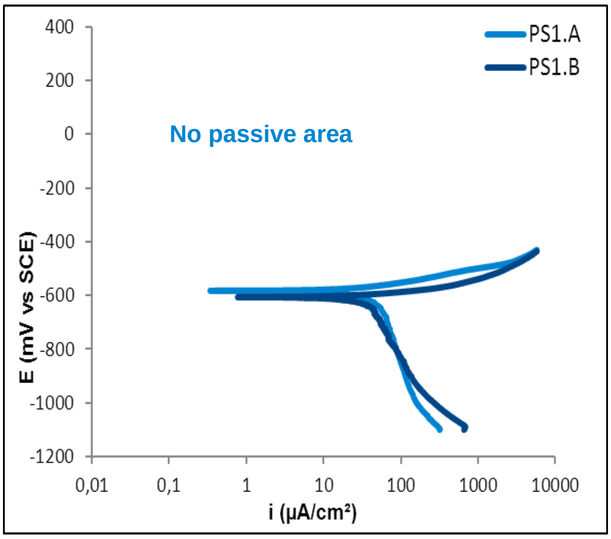

Figure 26.-EN 1.4003. P_{S1} samples (1D)

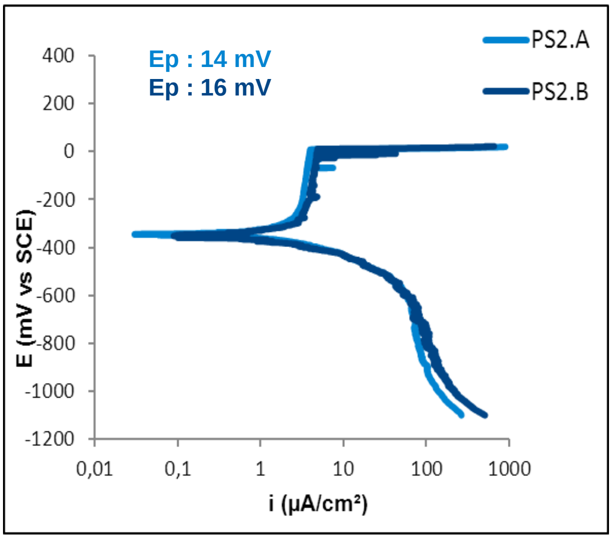

Figure 27.-EN 1.4003. P_{S2} samples (1D)

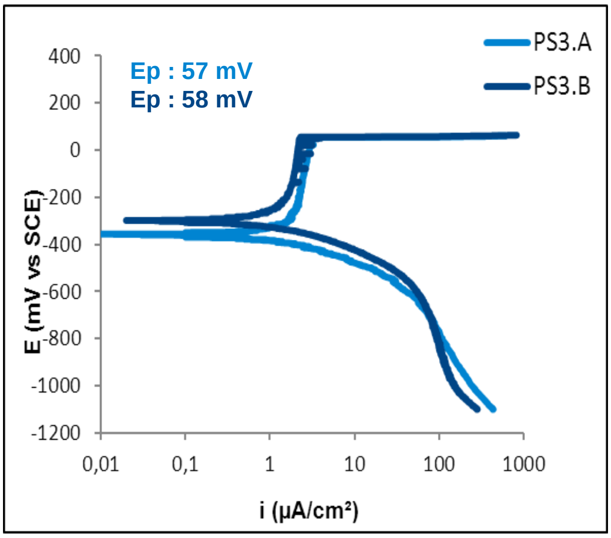

Figure 28.-EN 1.4003.P_{S3} samples (2B)

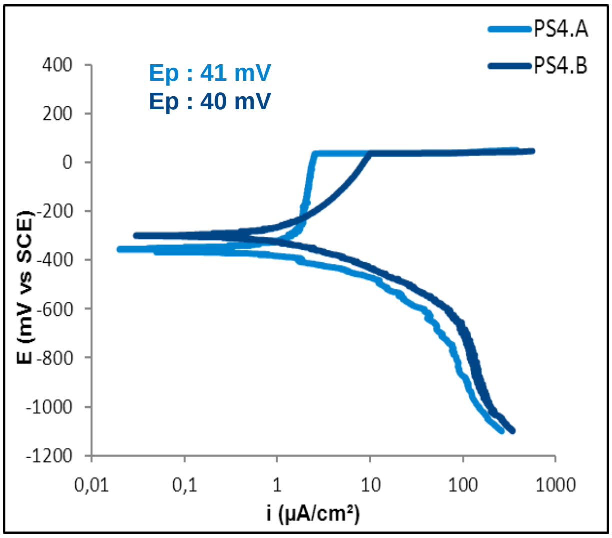

Figure 29.-EN 1.4003.P_{S4} samples (2B)

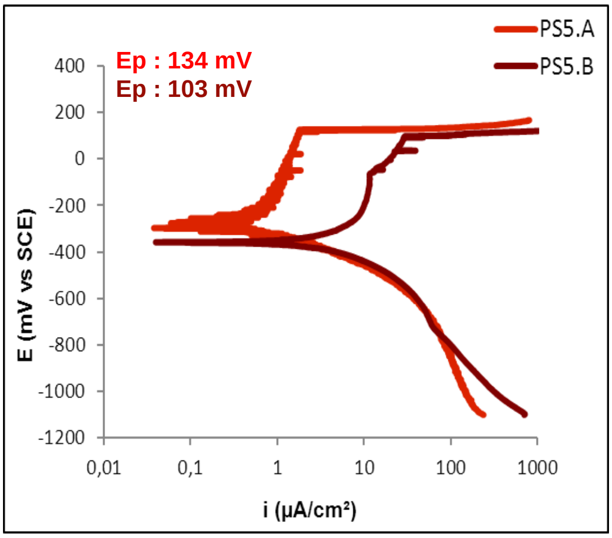

Figure 30.- EN 1.4509. P_{S5} samples (2B)

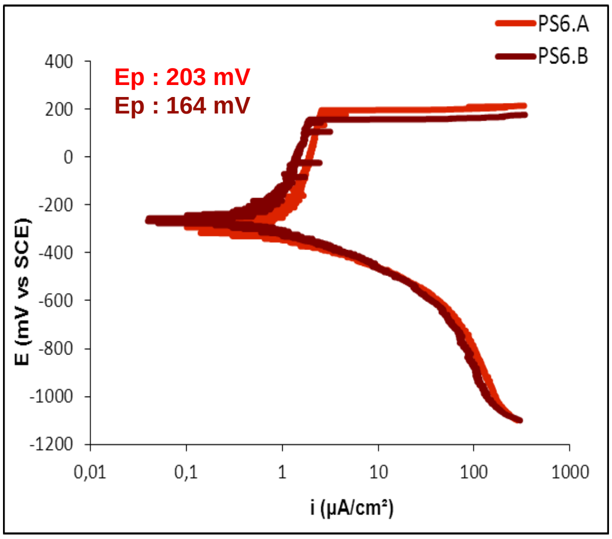

Figure 31.-EN 1.4509. P_{S6} samples (2B)

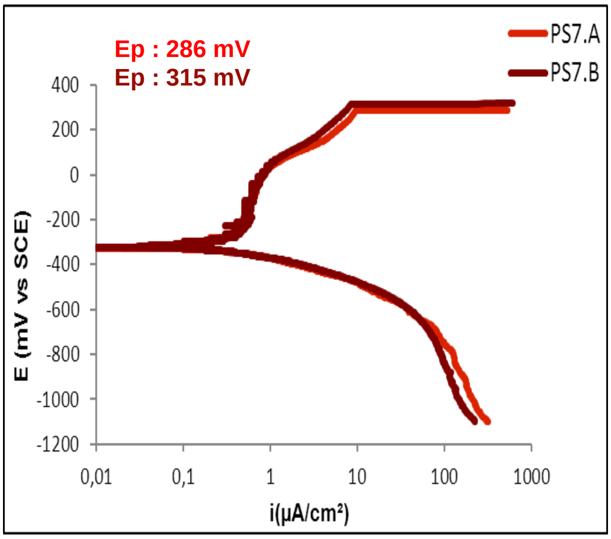

Figure 32.- EN 1.4509. P_{S7} samples (2B)

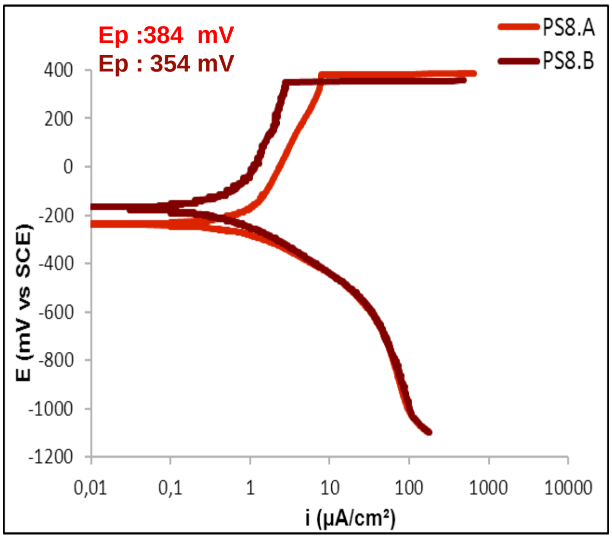

Figure 33.-EN 1.4509. P_{S8} samples (2B)

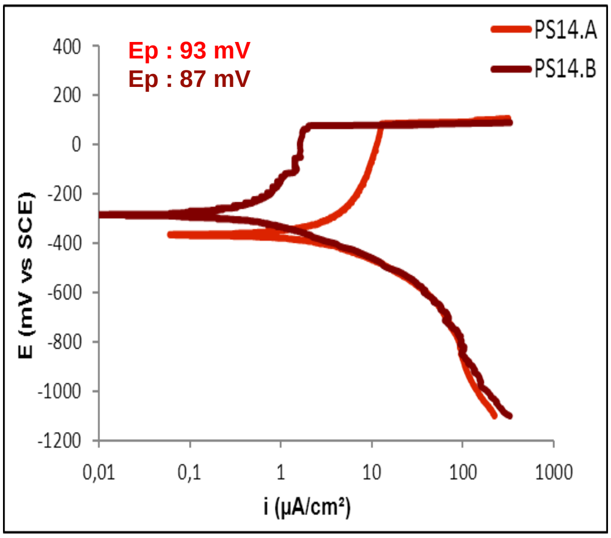

Figure 34.- EN 1.4509. P_{S14} samples (2B)

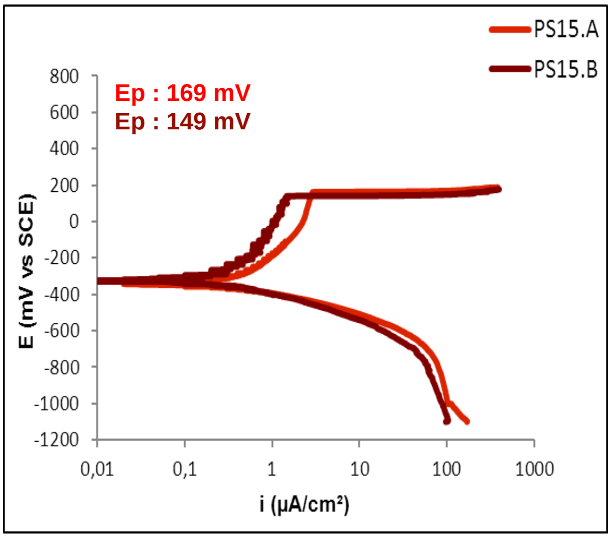

Figure 35.- EN 1.4509. P_{S15} samples (BA)

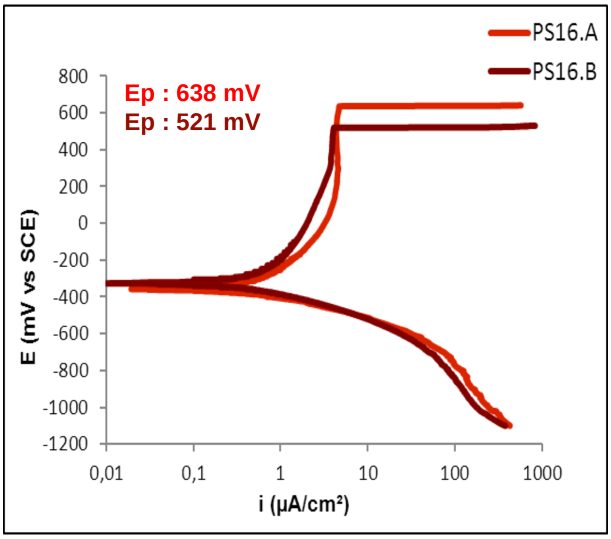

Figure 36.-EN 1.4509. P_{S16} samples (BA)

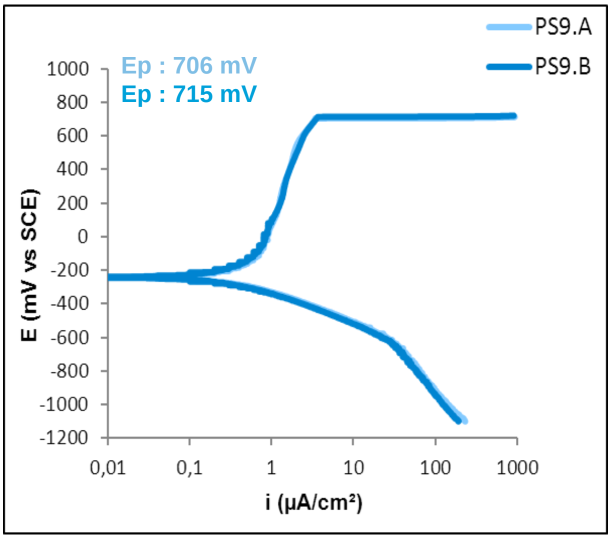

Figure 37.- EN 1.4521. P_{S9} samples (2B)

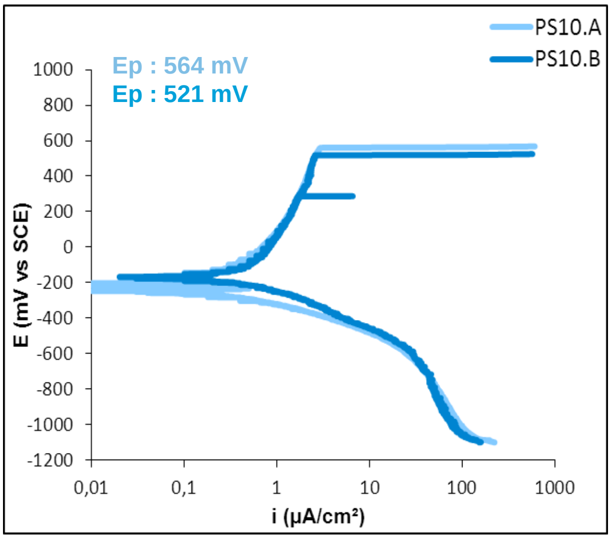

Figure 38.- EN 1.4521. P_{S10} samples (2B)

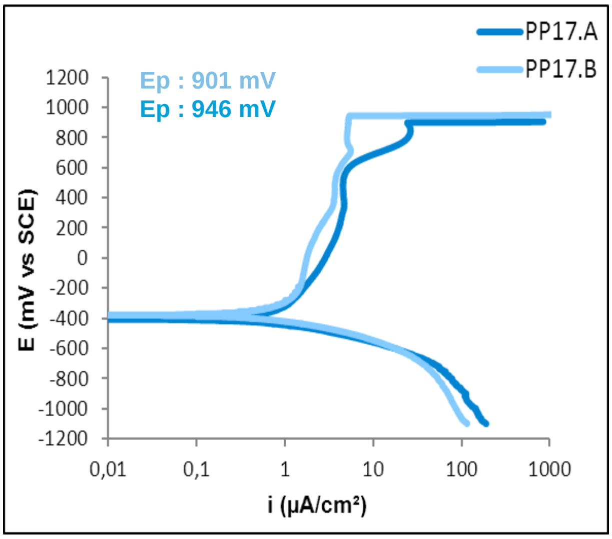

Figure 39.- EN 1.4521. P_{S17} samples (BA)

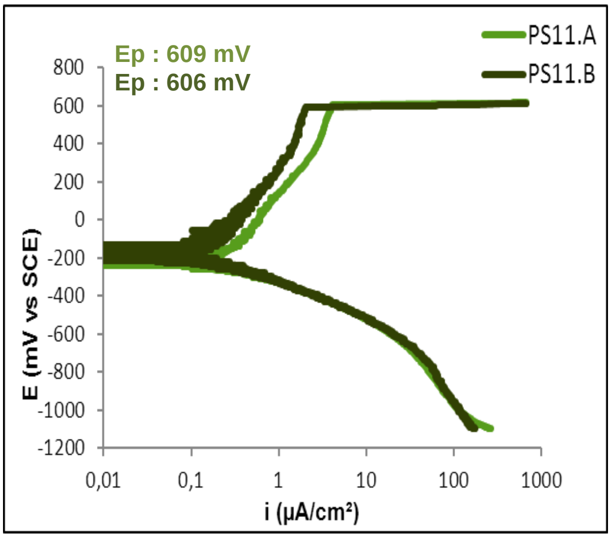

Figure 40.- EN 1.4621. P_{S11} samples (2M)

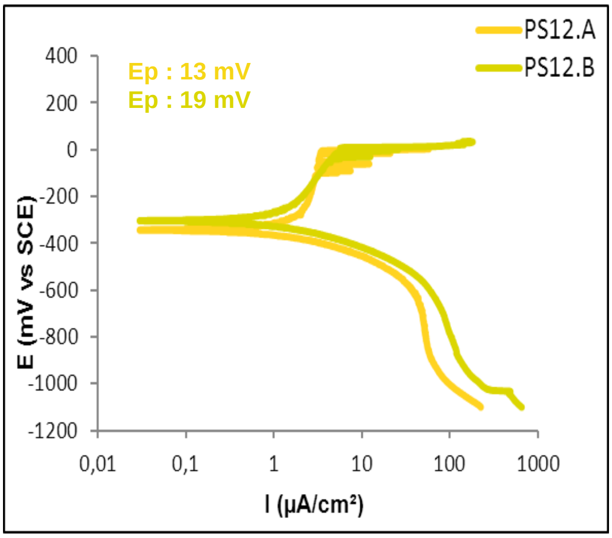

Figure 41.- EN 1.4016. P_{S12} samples (2B

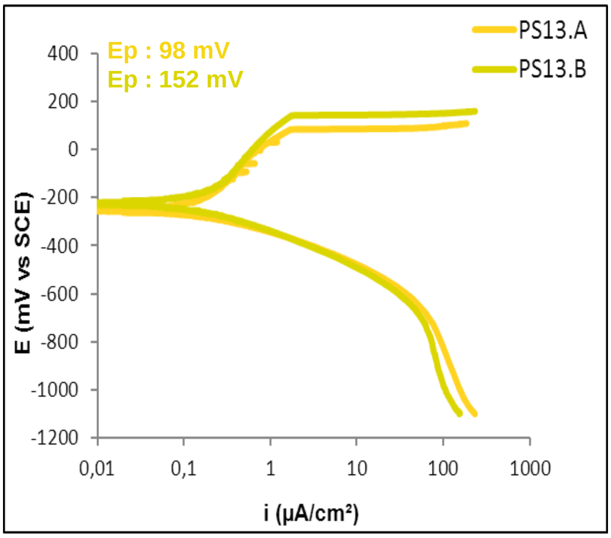

Figure 42.- EN 1.4016. P_{S13} samples (BA)

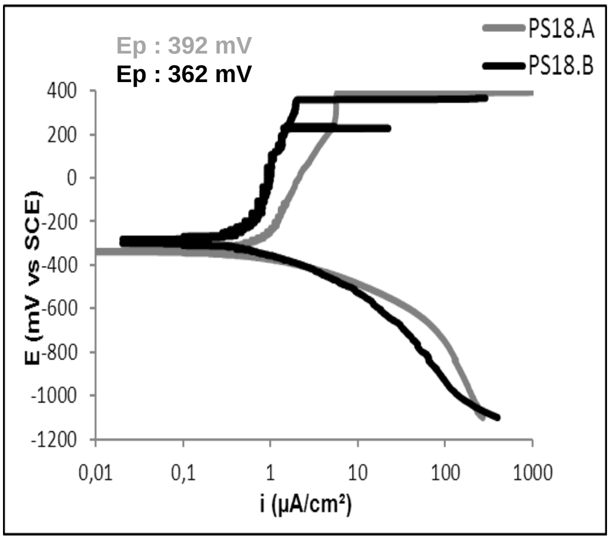

Figure 43.- EN 1.4301. P_{S18} samples (2B)

In this case, most graphs have the same shape, with passive area and a break in the passive layer with an increase in current density when a pit appears (pitting potential). Nevertheless, sample P_{S1} (EN 1.4003 – 1D) does not show a passive area, this means, during the positive-going of potential sweep the surface is not able to create a homogeneous enough passive layer to protect the material.

Table 6 shows the values collected from the curves and its corresponding PRE value.

Stainless Steel	Sample		Finish	PRE	Ep (mV vs. SCE)	$\overline{Ep}$ (mV vs. SCE)
EN 1.4003	P_{S1}	A	1D	11,56	--	--
		B				
	P_{S2}	A	1D	11,52	14	15
		B			16	
	P_{S3}	A	2B	11,36	57	58
		B			58	
	P_{S4}	A	2B	11,42	41	41
		B			40	
EN 1.4509	P_{S5}	A	1D	18,51	134	119
		B			103	
	P_{S6}	A	1D	18,10	203	184
		B			164	
	P_{S7}	A	2B	18,55	286	301
		B			315	
	P_{S8}	A	2B	18,77	384	369
		B			354	
EN 1.4521	P_{S9}	A	2B	24,73	706	711
		B			715	
	P_{S10}	A	2B	25,28	564	543
		B			521	
EN 1.4621	P_{S11}	A	2M	21,12	609	608
		B			606	
EN 1.4016	P_{S12}	A	2B	17,35	13	16
		B			19	
	P_{S13}	A	BA	17,38	98	125
		B			152	
EN 1.4509	P_{S14}	A	2B	18,27	93	90
		B			87	
	P_{S15}	A	BA	18,57	169	159
		B			149	
	P_{S16}	A	BA	18,30	638	580
		B			521	
EN 1.4521	P_{S17}	A	BA	24,38	901	924
		B			946	
EN 1.4301	P_{S18}	A	2B	20,54	392	377
		B			362	

Table 6.- PRE and Ep values (supply)

Figure 44 represents Ep data as a function of PRE values in supply surface conditions.

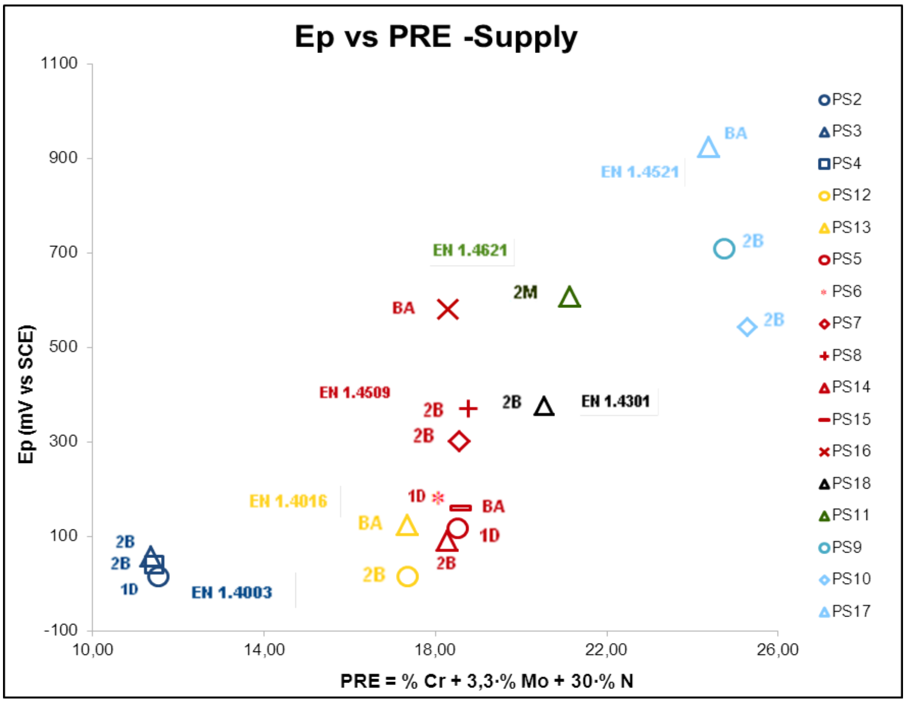

Figure 44. - Pitting corrosion - Finishes

According to data illustrated in figure 44, a relation between PRE and Ep values appears, but the results do not show the same repeatability than in polished sample surface.

BA finish seems to have better resistance than 2B finish in the same ferritic grade.

3.1.4.3. Comparison polished - supply surface

A comparison of behaviour between samples in supply conditions and polished up to 600 grit is represented in figure 45 and 46.

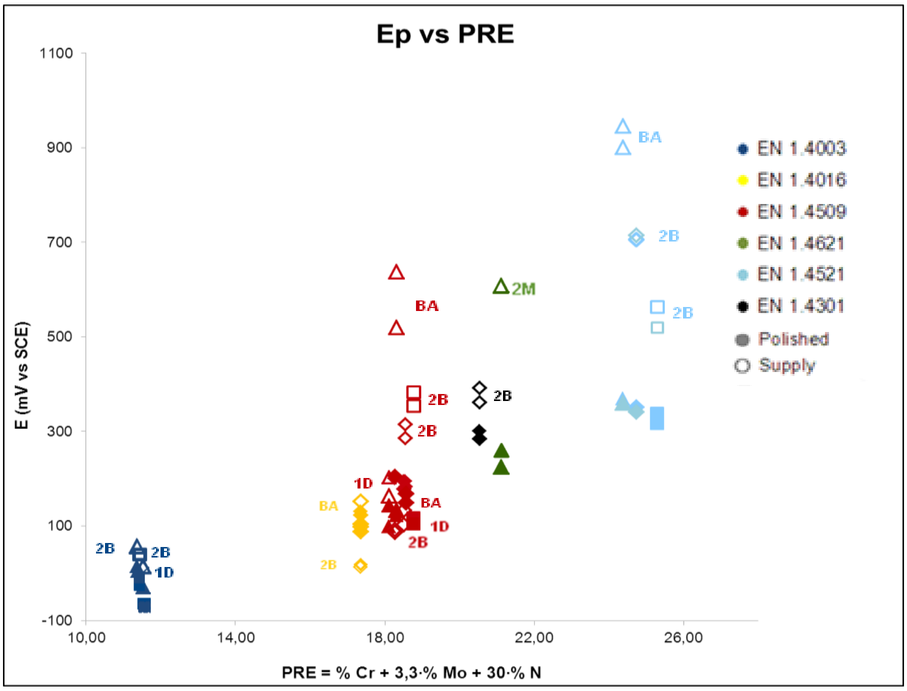

Figure 45. - Polished – supply surface comparison

In figure 45 an increase of the pitting potential with the increase in PRE value in all cases is observed. In samples with supply surface conditions, it seems that, Ep values are higher than in polish ones, but a low repeatability in these cases is observed.

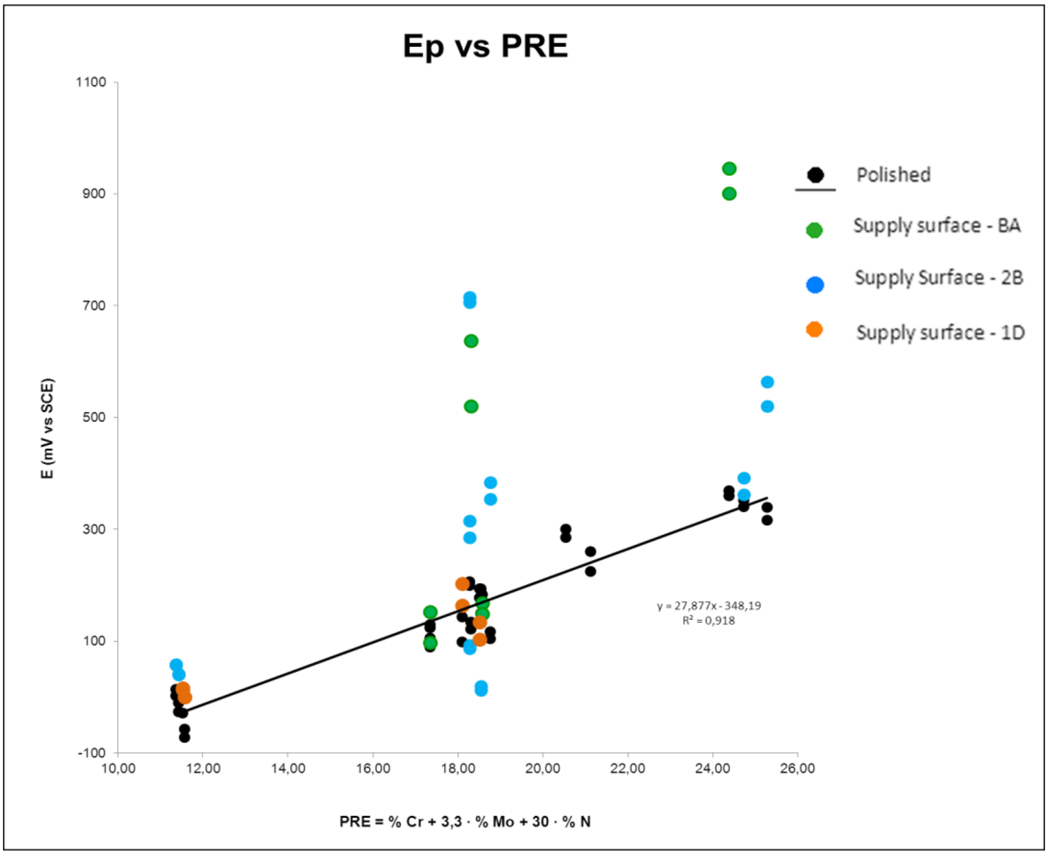

Figure 46. - Comparison from correlations

Only a good fit to a line has been obtained in the case of polished samples (figure 46). BA and 2B finishes have shown very scattered results. In the case of 1D, there are very few results in order to obtain a tendency.

The wet polish with 600-grit SiC paper homogenizes the surface, removing the variable finish and improving the repeatability of the test.

3.2 UNIFORM CORROSION

The uniform corrosion test takes place in a solution 1N H_2SO_4 and is de-aerated by means of bubbling N_2 (0,8 L/min) in the solution.

Polarization curves and parameters are obtained to compare from different ferritic grades (figure 47). Some critical parameters and its meanings are the following:

- Ecorr : Potential when the steady state is reached in a corrosive media
- icorr: Current that circulates between anode and cathode in the Ecorr.
- Epp : Primary passive potential.
- icr_1 : Maximum of current density over there is a region where the metal is in passive state.
- Eps : Potential which a second passive process takes place in metal surface after a small loss of passivity. This parameter does not appear in all the materials.
- icr_2 : Second maximum of current density over there is a region where the metal is in passive state (current density to Eps).
- Ep: Passive potential in polarization curve to minimal current density in the second passive zone.
- ip: Minimum of current density in the second passive zone.

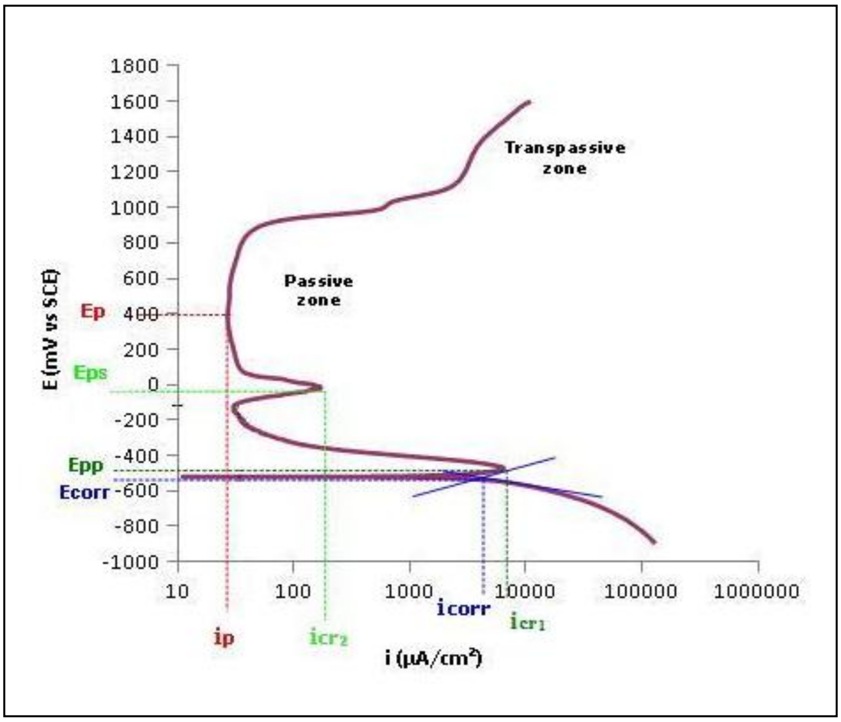

Figure 47. - Polarization curve - Uniform corrosion

The data are used to compare behaviour to uniform corrosion of the different ferritic grades.

3.2.1 Test conditions

The test medium is a de-aerated solution 1N H_2SO_4. The gas used to de-aerated is N_2 (0,8 L/min). The sample is placed in the flat cell device. A potential scan is applied to the working electrode (sample), and through a reference electrode (saturated calomel electrode) the conductivity is measured. The test conditions applied by the potentiostat are shown in table 7.

Start potential	**-0,9 V vs. SCE**
Final potential	**1,6 V vs. SCE**
Scan rate	**1,6 mV/s**
Test area	**1 cm^2**
Temperature	**30 ºC ± 1**

Table 7.- Test conditions - uniform corrosion

3.2.2 Test materials

Table 8 shows the code which relates results with samples. The specimens are tested in two surface conditions, 600 grit polishing and supply.

Stainless Steel	Finishes	Polish	Pitting Identification
EN 1.4003	1D	Yes	U_{P1}
		No	U_{S1}
	1D	Yes	U_{P2}
		No	U_{S2}
	2B	Yes	U_{P3}
		No	U_{S3}
	2B	Yes	U_{P4}
		No	U_{S4}
EN 1.4509	1D	Yes	U_{P5}
		No	U_{S5}
	1D	Yes	U_{P6}
		No	U_{S6}
	2B	Yes	U_{P7}
		No	U_{S7}
	2B	Yes	U_{P8}
		No	U_{S8}
EN 1.4521	2B	Yes	U_{P9}
		No	U_{S9}
	2B	Yes	U_{P10}
		No	U_{S10}
EN 1.4621	2M	Yes	U_{P11}
		No	U_{S11}
EN 1.4016	2B	Yes	U_{P12}
		No	U_{S12}
	BA	Yes	U_{P13}
		No	U_{S13}
EN 1.4509	2B	Yes	U_{P14}
		No	U_{S14}
	BA	Yes	U_{P15}
		No	U_{S15}
	BA	Yes	U_{P16}
		No	U_{S16}
EN 1.4521	BA	Yes	U_{P17}
		No	U_{S17}
EN 1.4301	2B	Yes	U_{P18}
		No	U_{S18}

Table 8.- Identification of samples

3.2.3 Sample preparation

It is carried out the same procedure as in pitting corrosion evaluation.

The sample dimensions are 40x40mm^2. In order to get as wide information as possible the samples were tested by two different surface treatments.

In one of them, working electrode surface (sample) is polished up to a fine-grained surface finish by 120, 180, 320 and 600-grit SiC paper. The resulting scratches of the polishing are rinsed by means of distilled water and dried by cellulose paper. The other treatment surface consists only of rinsing the surface, washing with neutral soap and drying by cellulose paper in order to evaluate the different surface finishes.

A copper wire is welded to specimen as electrochemical contact. So, the specimens are prepared to be tested.

The final view of the sample is shown in figure 48.

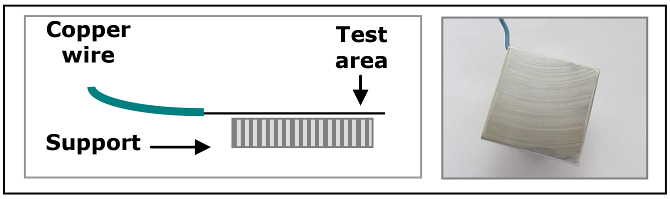

Figure 48.- Sample ready to be tested

3.2.4 Results and discussion

The results from the test are shown and analysed by means of tables and graphs. Below, the comparison among stainless steel and conclusions are commented.

3.2.4.1. Polished surface

The polished surface samples have a finish reached by treatment with 600 grit SiC paper. The graphs from every stainless steel in the aforementioned conditions are shown in figures 49 - 66.

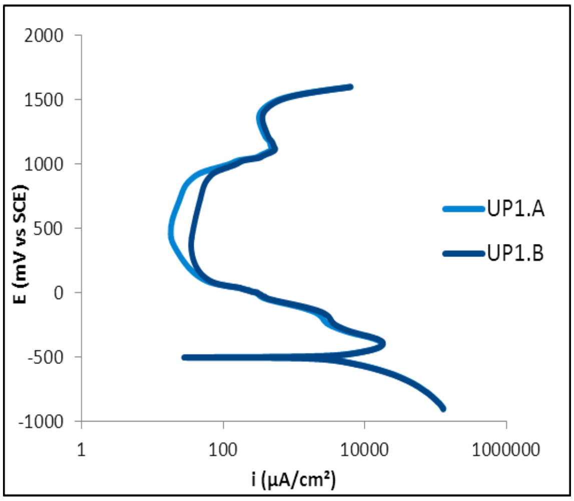

Figure 49.- EN 1.4003. U_{P1} samples

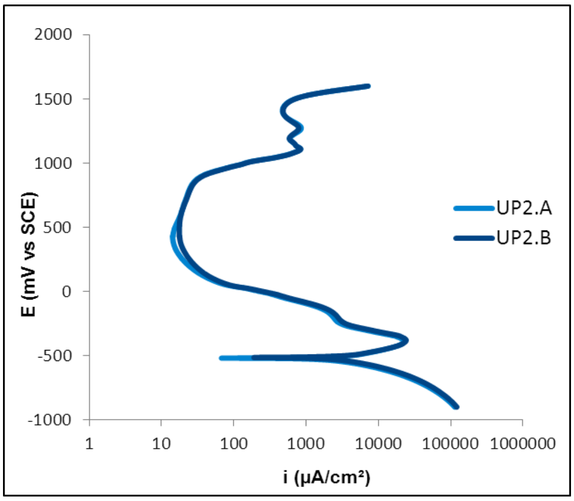

Figure 50.-EN 1.4003. U_{P2} samples

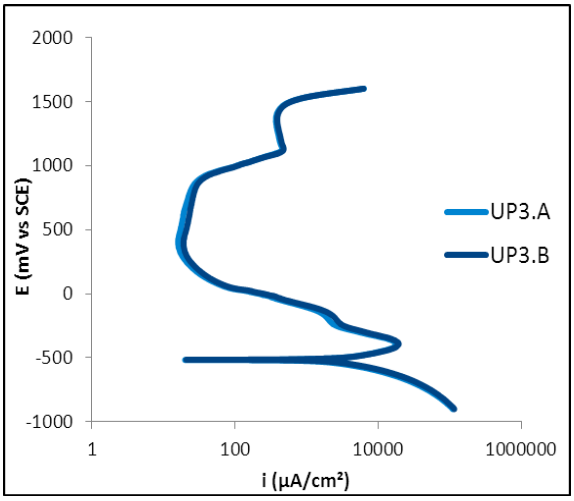

Figure 51.- EN 1.4003. U_{P3} samples

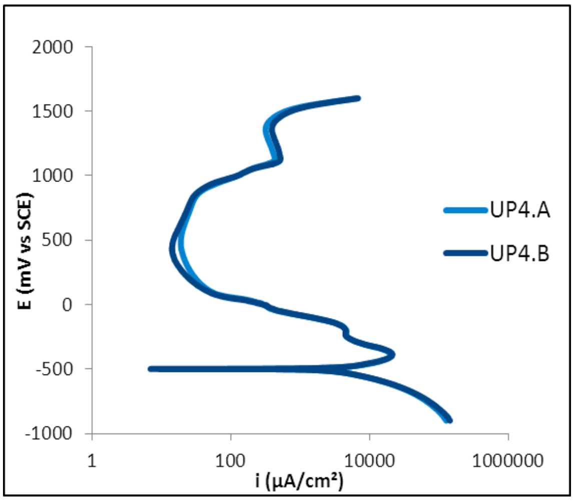

Figure 52.- EN 1.4003. U_{P4} samples

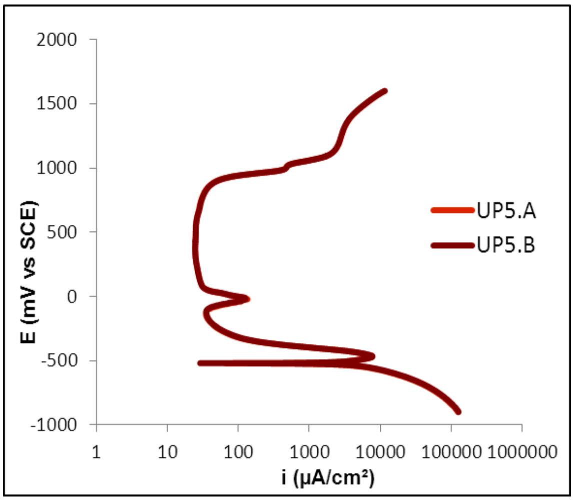

Figure 53.- EN 1.4509. U_{P5} samples

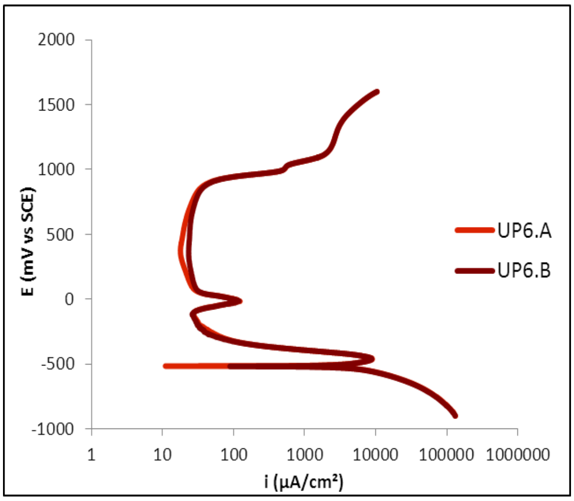

Figure 54.- EN 1.4509. U_{P6} samples

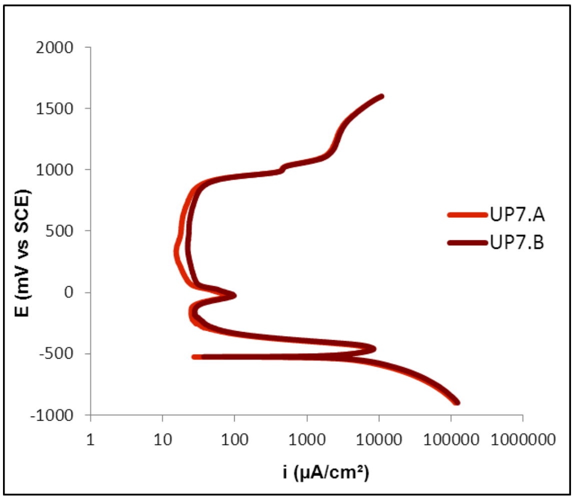

Figure 55.- EN 1.4509. U_{P7} samples

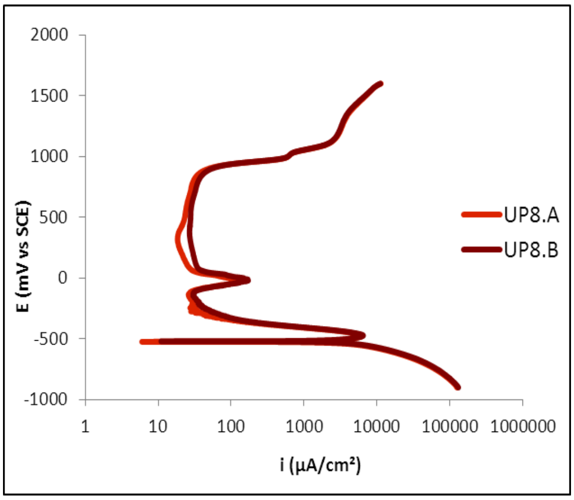

Figure 56.- EN 1.4509. U_{P8} samples

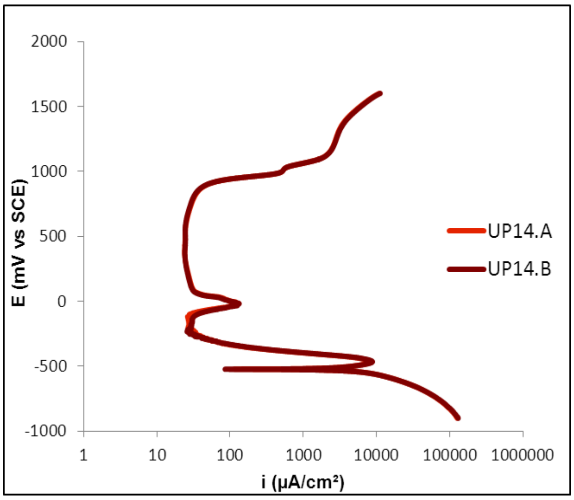

Figure 57.- EN 1.4509. U_{P14} samples

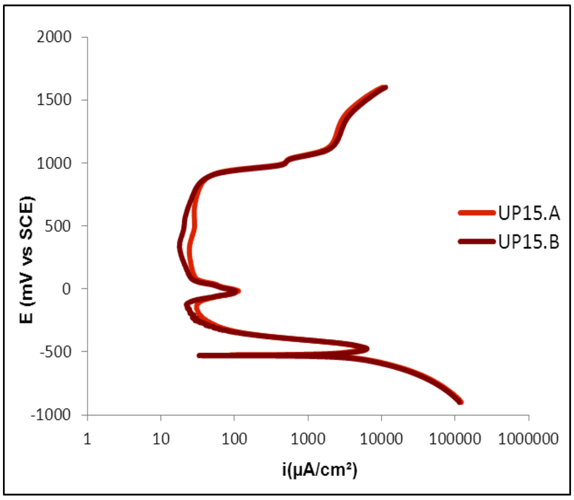

Figure 58.-EN 1.4509. U_{P15} samples

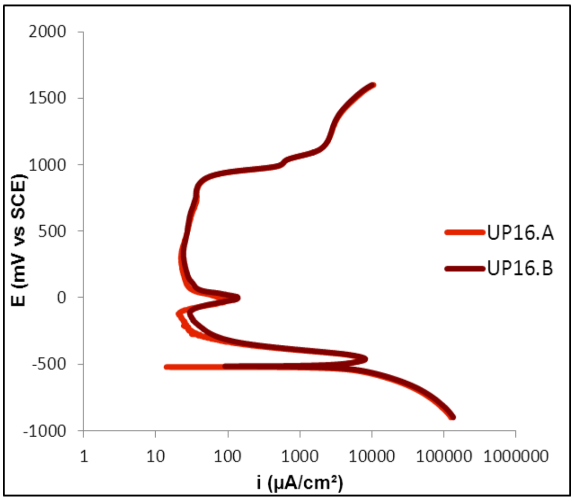

Figure 59.- EN 1.4509. U_{P16} samples

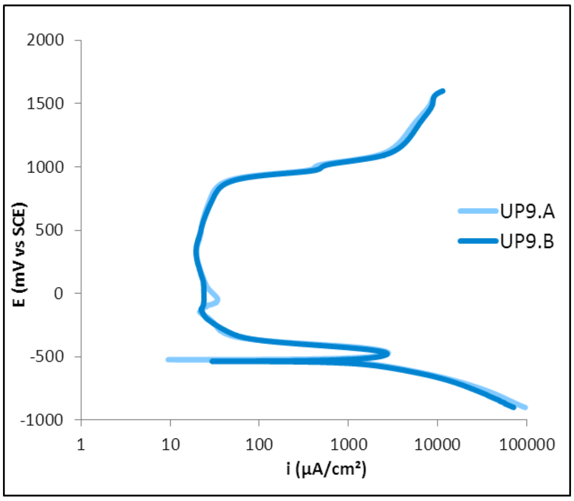

Figure 60.-EN 1.4521. U_{P9} samples

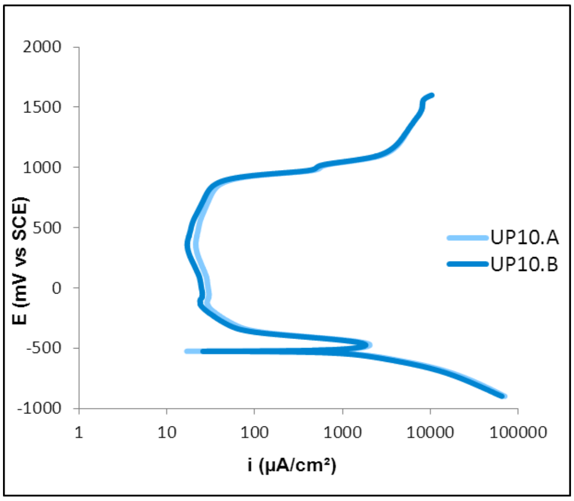

Figure 61.- EN 1.4521. U_{P10} samples

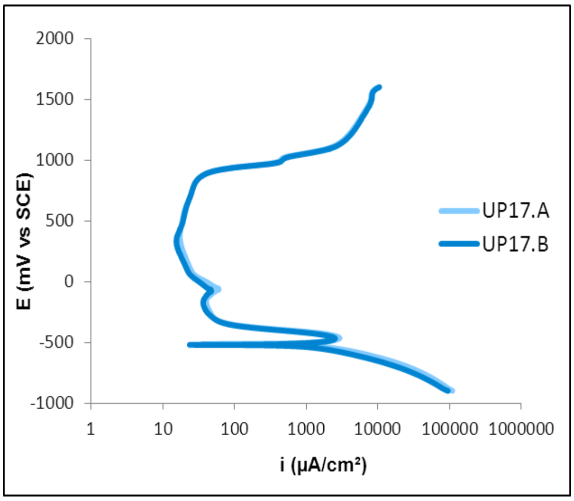

Figure 62.-EN 1.4521. U_{P17} samples

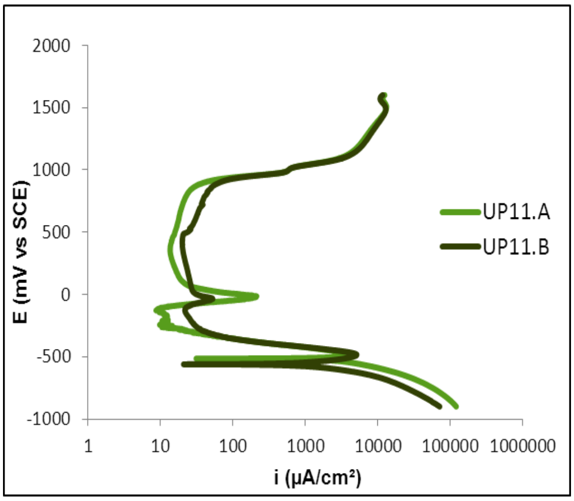

Figure 63.- EN 1.4621. U_{P11} samples

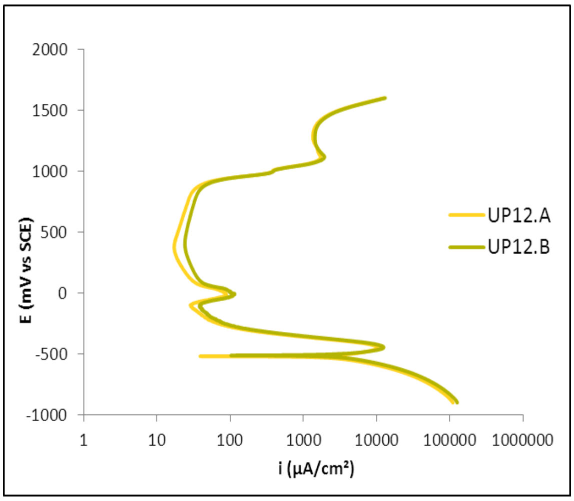

Figure 64.-EN 1.4016. U_{P12} samples

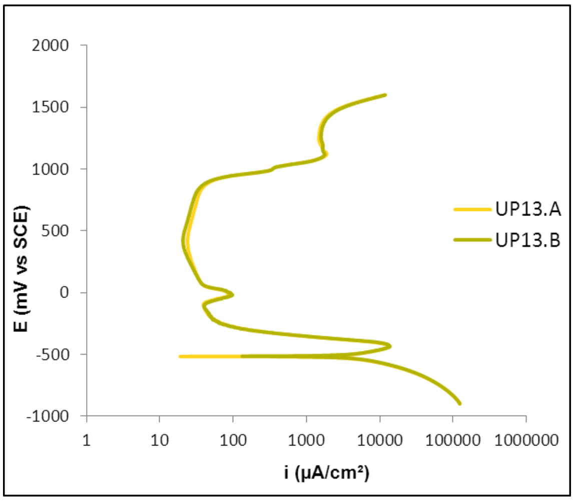

Figure 65.- EN 1.4016. U_{P13} samples

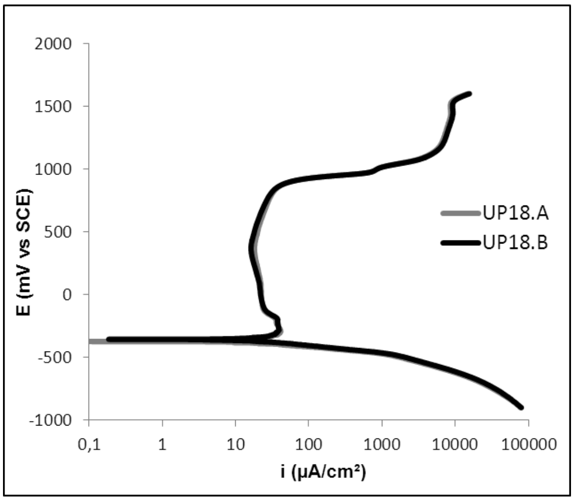

Figure 66.-EN 1.4301. U_{P18} samples

In the graphs, it can be observed as the shape of the curves is similar from the different ferritic grades. The appearance of the icr_2 peak in most ferritic grades has to be outlined. The austenic grade, EN 1.4301 (Figure 66) has a different curve, typical from austenitics.

The most useful points to compare the behaviour of stainless steel to uniform corrosion are: "icr_1" and "ip". According to data obtained from polarization curves, the appearance of the icr_2 and Eps values in polished samples may be another characteristic to underline, although this aspect is not widely known so far.

In general, the more resistant stainless steel in a defined media, the lower value of "icr_1" and "ip" and the wider range of potentials in passive zone.

To evaluate the resistance to uniform corrosion in a comparative form the parameter URE (Uniform Resistant Equivalent) is used. This term relates the percentage of some influential chemical elements like chromium, molybdenum, nitrogen and the addition of the content in nickel, with the resistance to uniform corrosion.

URE = % Cr + 3.3 · % Mo + 30 · % N + %Ni

The URE value, and the different parameters obtained from every stainless steel polarization curves are shown in table 9.

Stainless Steel	Sample		URE	icr_1 (µA/cm²)	$\overline{icr_1}$ (µA/cm²)	icr_2 (µA/cm²)	$\overline{icr_2}$ (µA/cm²)	ip (µA/cm²)	$\overline{ip}$ (µA/cm²)
EN 1.4003	U_{P1}	A	12,11	17340	17725	--	--	18	27
		B		18110		--		35	
	U_{P2}	A	12,07	22500	23350	--	--	14	16
		B		24200		--		18	
	U_{P3}	A	11,89	18020	18710	--	--	16	17
		B		19400		--		19	
	U_{P4}	A	11,90	21500	21050	--	--	14	16
		B		20600		--		19	
EN 1.4509	U_{P5}	A	18,78	7570	7685	135	132	35	35
		B		7800		128		35	
	U_{P6}	A	18,36	8960	8865	123	121	27	27
		B		8770		119		26	
	U_{P7}	A	18,94	7760	8110	79	88	25	26
		B		8460		97		28	
	U_{P8}	A	19,09	6280	6370	142	157	26	28
		B		6460		171		30	
EN 1.4521	U_{P9}	A	24,97	5800	4255	34	29	21	21
		B		2710		24		22	
	U_{P10}	A	25,69	2050	1946	--	--	21	19
		B		1843		--		17	
EN 1.4621	U_{P11}	A	21,41	4110	4590	211	132	14	15
		B		5070		52		20	
EN 1.4016	U_{P12}	A	17,70	10620	11600	89	103	29	33
		B		12580		116		38	
	U_{P13}	A	17,61	13390	13610	91	95	39	39
		B		13830		98		40	
EN 1.4509	U_{P14}	A	18,66	8630	8740	133	134	26	26
		B		8850		134		26	
	U_{P15}	A	19,04	5850	6105	114	109	31	26
		B		6360		104		22	
	U_{P16}	A	18,58	7770	7935	102	120	21	25
		B		8100		138		30	
EN 1.4521	U_{P17}	A	24,72	2930	2735	60	54	40	39
		B		2540		47		37	
EN 1.4301	U_{P18}	A	28,61	42	41	--	--	18	17
		B		40		--		16	

Table 9.- PRE , icr_1, icr_2 and ip of polished samples.

Figure 67 shows the value of "icr_1" of every stainless steel. They are represented as a function of URE in order to analyse and compare the performance of the different stainless steel grades.

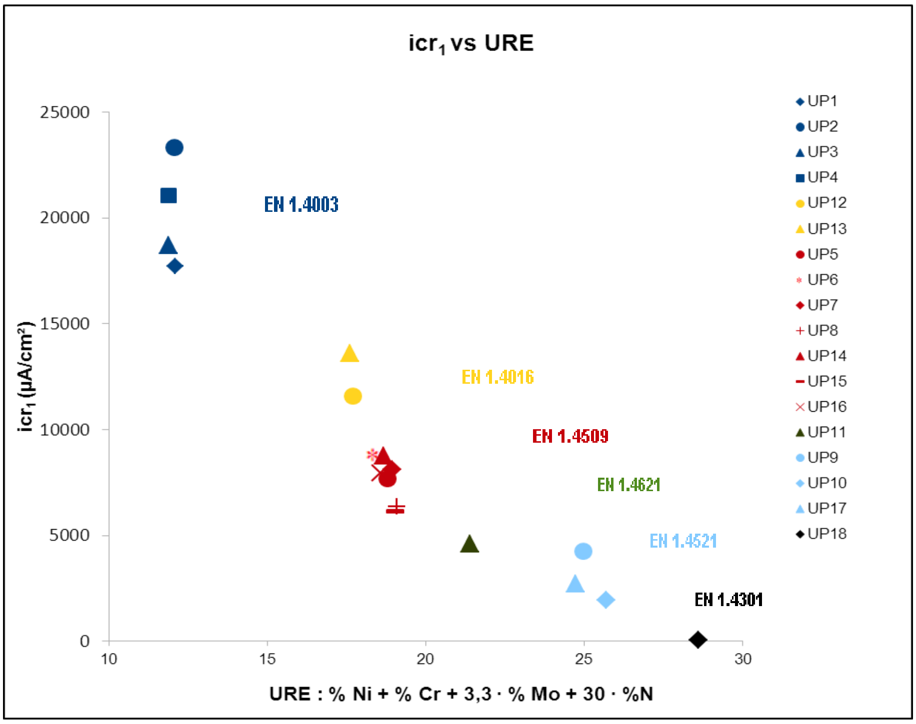

Figure 67. – icr_1 vs. URE, polished samples

In figure 67, the inverse linear fit that exists between URE and "icr_1"is observed. This relation is expected. It may be noted the highest icr_1 value of EN 1.4003 which means the poor resistance to uniform corrosion that this stainless steel has in the tested medium.

The icr_2 parameter obtained from graphs has a variation about microamperes from the different stainless steel grades as figure 68 shows. So this parameter does not contribute significantly to obtain comparative information about corrosion resistance behaviour.

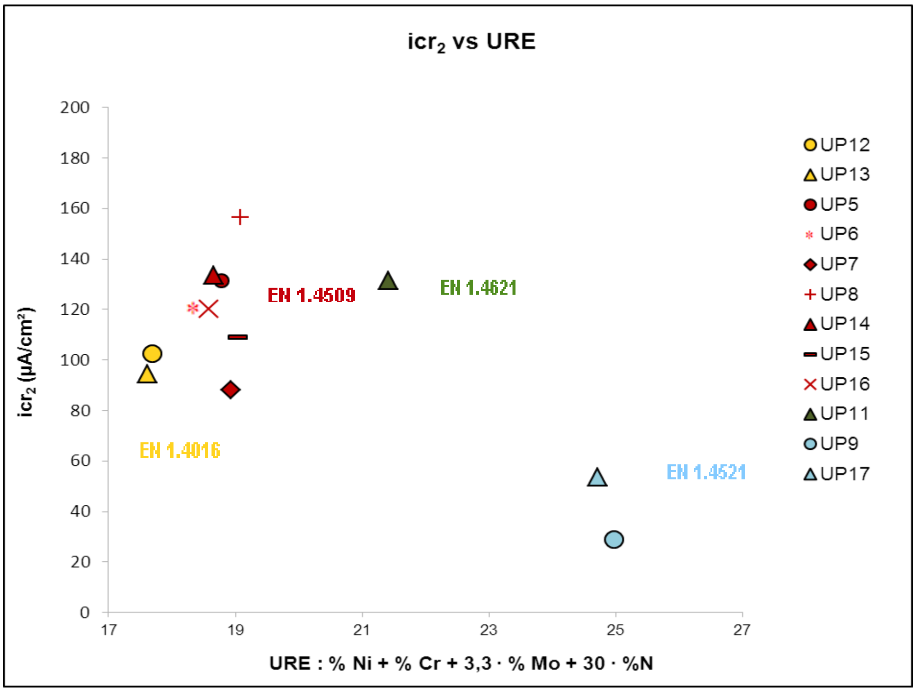

Figure 68.- icr_2 vs. URE, polished samples

Another value obtained from polarization curves is “ip”. In figure 69, the “ip” value of each stainless steel is represented as a function of its URE value.

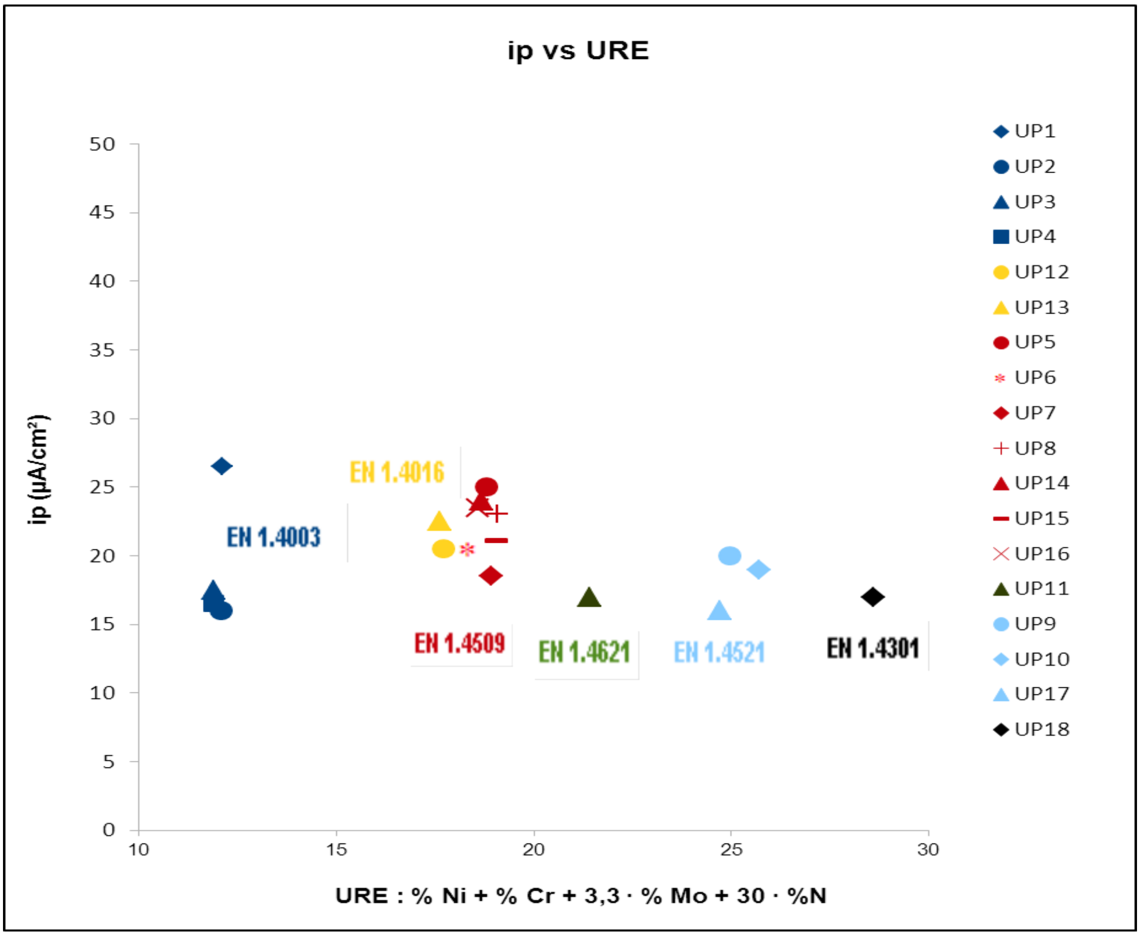

Figure 69. – ip vs. URE, polished samples

Although it seems that a tend to ip decrease whit URE value increase exists, it is clearly showed that samples have similar ip values, with a variation about microamperes from the different stainless steel grades.

3.2.4.2. Supply surface

The curve of every stainless steel in the above mentioned test conditions and supply surface, are shown in figures 70 – 87.

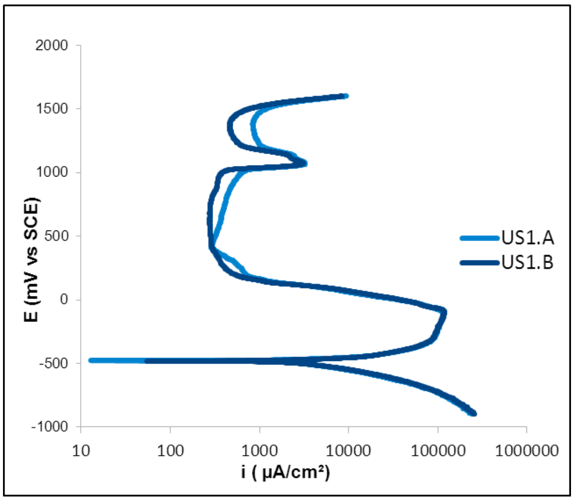

Figure 70.- EN 1.4003. U_{S1} samples (1D)

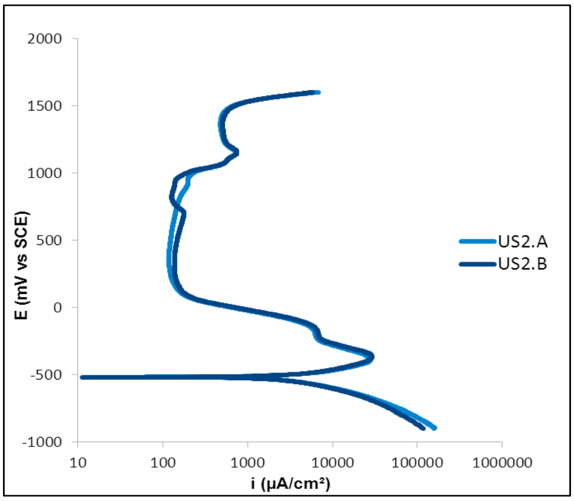

Figure 71.- EN 1.4003. U_{S2} samples (1D)

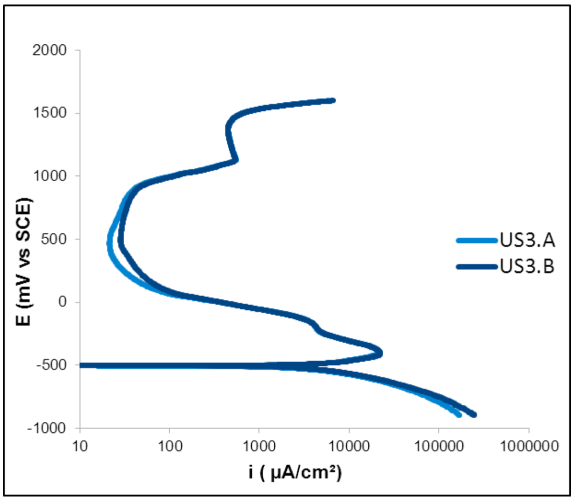

Figure 72.- EN 1.4003. U_{S3} samples (2B)

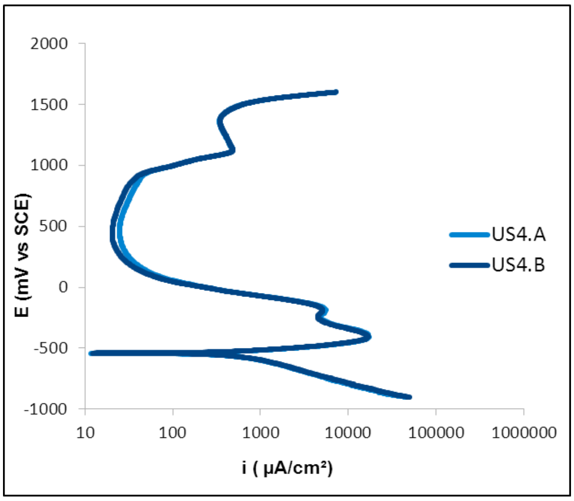

Figure 73.- EN 1.4003. U_{S4} samples (2B)

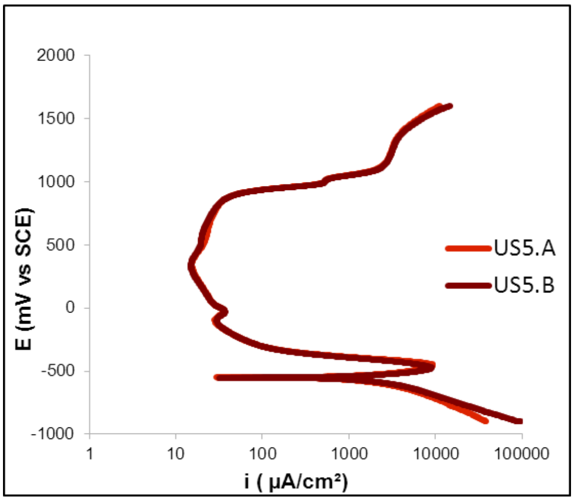

Figure 74.- EN 1.4509. U_{S5} samples (1D)

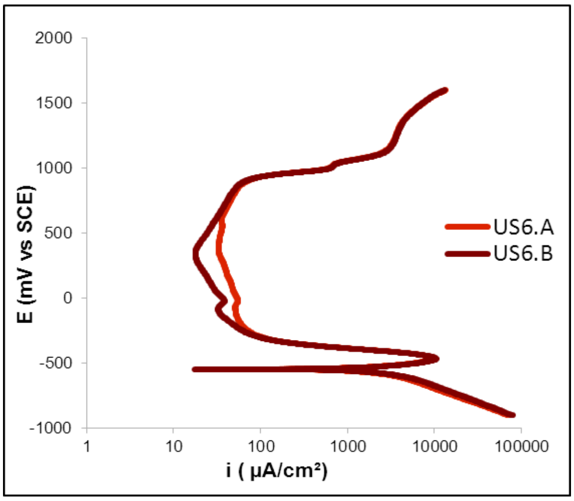

Figure 75.- EN 1.4509. U_{S6} samples (1D)

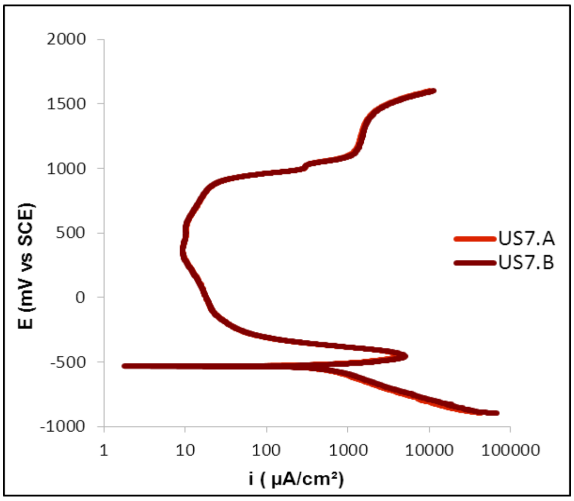

Figure 76.- EN 1.4509. U_{S7} samples (2B)

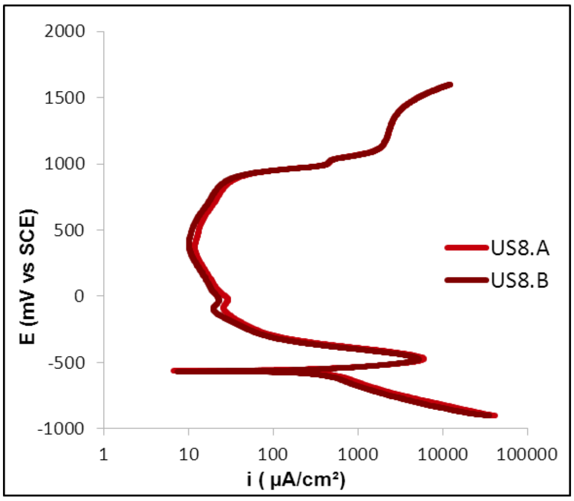

Figure 77.- EN 1.4509. U_{S8} samples (2B)

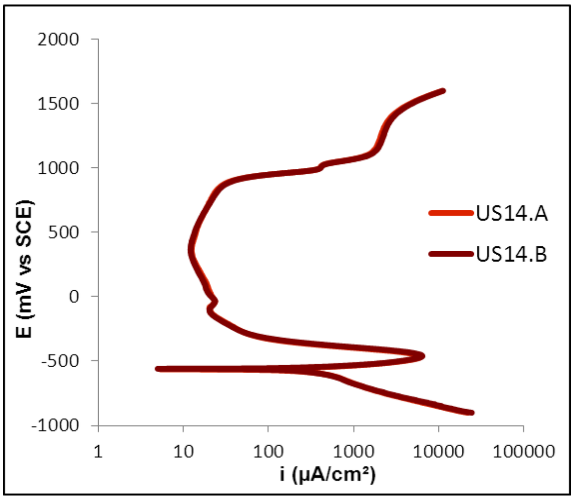

Figure 78.- EN 1.4509. U_{S14} samples (2B)

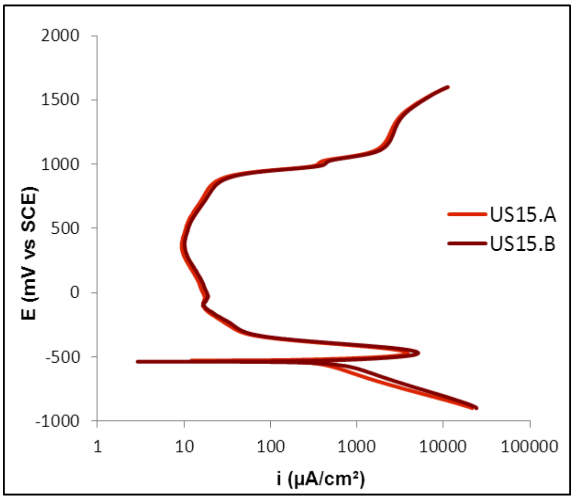

Figure 79.- EN 1.4509. U_{S15} samples (BA)

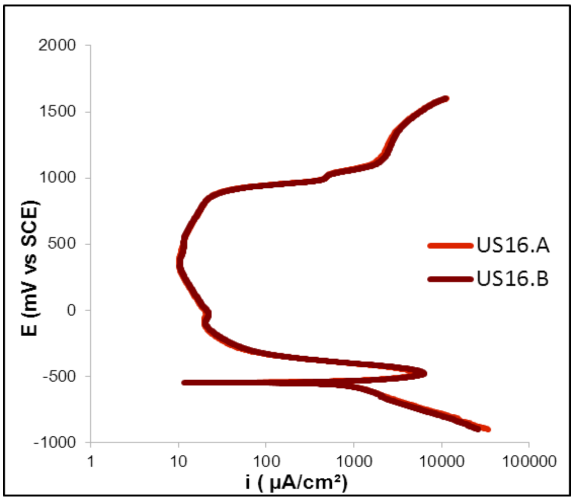

Figure 80.- EN 1.4509. U_{S16} samples (BA)

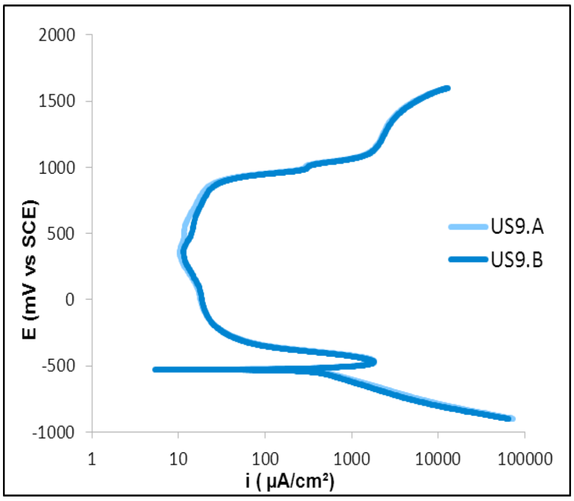

Figure 81.- EN 1.4521. U_{S9} samples (2B)

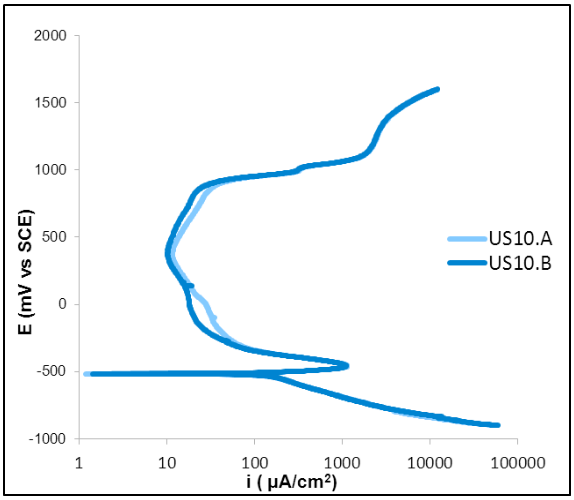

Figure 82.- EN 1.4521. U_{S10} samples (2B)

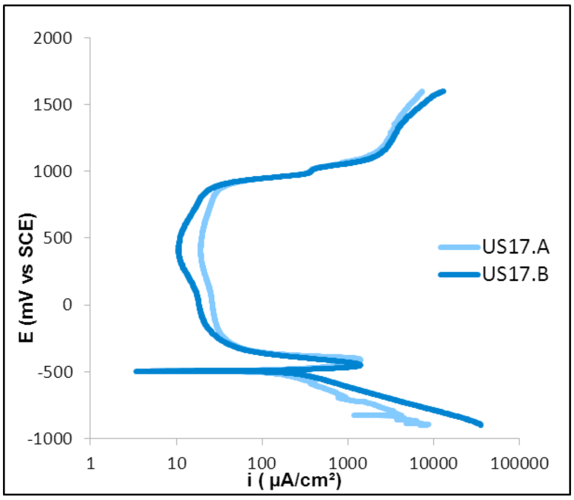

Figure 83.- EN 1.4521. U_{S17} samples (BA)

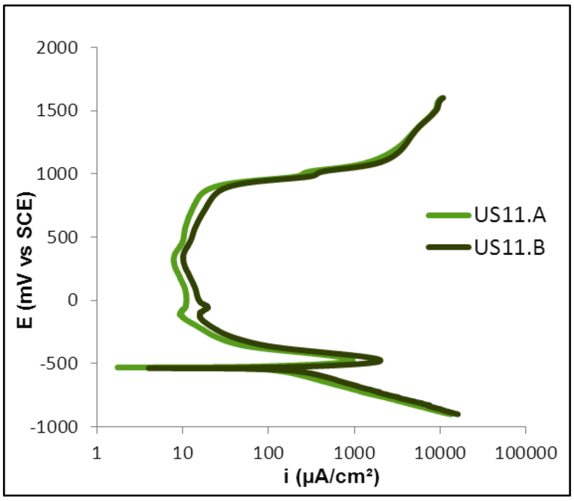

Figure 84.- EN 1.4621. U_{S11} samples (2M)

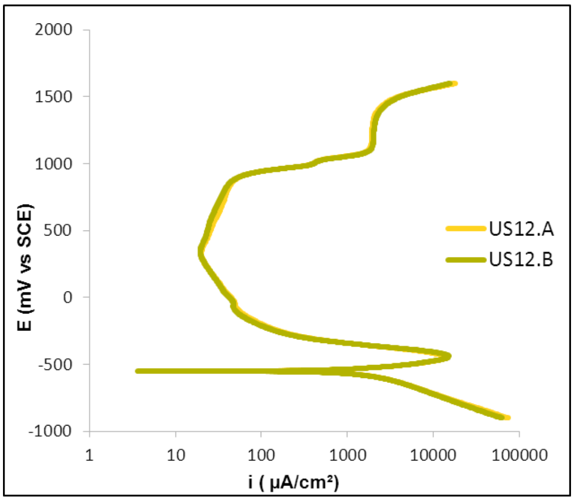

Figure 85.- EN 1.4016. U_{S12} samples (2B)

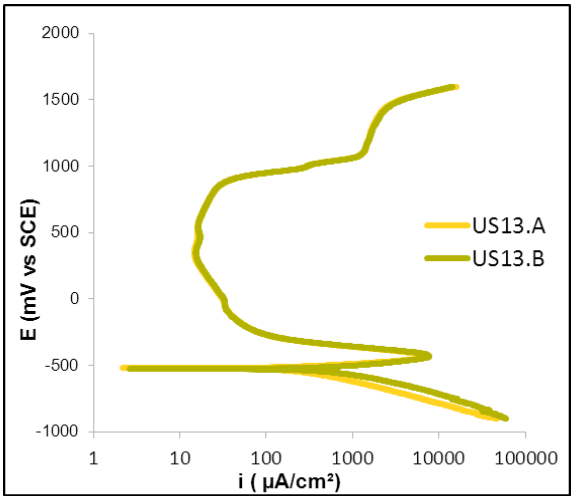

Figure 86.- EN 1.4016. U_{S13} samples (BA)

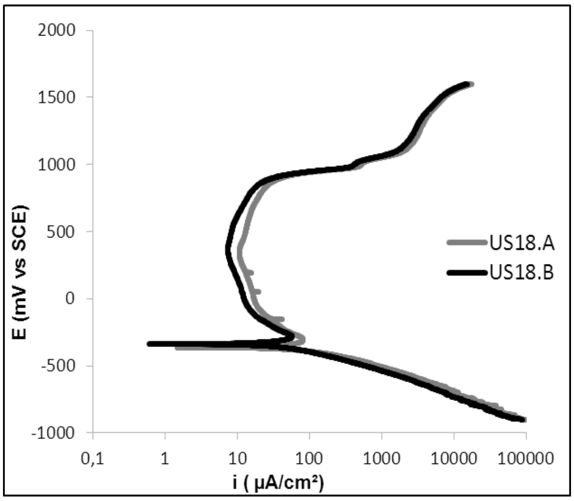

Figure 87.- EN 1.4301. U_{S18} samples (2B)

The EN 1.4003 stainless has slightly different graphs in transpassive area. This fact could be due to its lower content in chromium. Furthermore, the transpassive zone for this grade is different from 2B and 1D samples.

In some of the samples, the icr_2 peak is very soft, almost imperceptible.

In the austenic grade EN 1.4301 (figure 87), the curve is slightly different from the ferritic, typical from austenitic grades.

The icr_1, icr_2 and ip values of the samples in supply conditions are shown in table 10.

Stainless Steel	**Sample**		**Finish**	**URE**	**icr_1 (μA/cm²)**	**$\overline{icr_1}$ (μA/cm²)**	**icr_2 (μA/cm²)**	**$\overline{icr_2}$ (μA/cm²)**	**ip (μA/cm²)**	**$\overline{ip}$ (μA/cm²)**
EN 1.4003	U_{S1}	A	1D	12,11	115200	116250	--	--	286	281
		B			117300		--		277	
	U_{S2}	A		12,07	28400	28900	--	--	118	123
		B			29400		--		127	
	U_{S3}	A	2B	11,89	22300	21950	--	--	29	25
		B			21600		--		21	
	U_{S4}	A		11,90	17290	17090	--	--	25	23
		B			16890		--		20	
EN 1.4509	U_{S5}	A	1D	18,78	9310	9185	37	37	15	15
		B			9060		37		15	
	U_{S6}	A		18,36	10040	10260	39	47	33	25
		B			10480		55		18	
	U_{S7}	A	2B	18,94	4310	4695	--	--	9	9
		B			5080		--		9	
	U_{S8}	A		19,09	6050	5640	23	26	10	11
		B			5230		30		12	
EN 1.4521	U_{S9}	A	2B	24,97	1844	1833	--	--	10	11
		B			1821		--		11	
	U_{S10}	A		25,69	1139	1123	--	--	12	11
		B			1108		--		10	
EN 1.4621	U_{S11}	A	2M	21,41	953	1481	12	15	9	12
		B			2010		18		16	
EN 1.4016	U_{S12}	A	2B	17,70	13860	14515	--	--	20	20
		B			15170		--		19	
	U_{S13}	A	BA	17,61	6760	7230	--	--	15	15
		B			7700		--		15	
EN 1.4509	U_{S14}	A	2B	18,66	6150	6290	24	24	12	12
		B			6430		24		12	
	U_{S15}	A	BA	19,04	3890	4515	17	17	17	17
		B			5140		17		17	
	U_{S16}	A		18,58	5400	5890	21	22	10	10
		B			6380		22		10	
EN 1.4521	U_{S17}	A	BA	24,72	1419	1419	--	--	19	18
		B			1418		--		17	
EN 1.4301	U_{S18}	A	2B	28,61	83	70	--	--	11	9
		B			58		--		7	

Table 10.- PRE , icr_1, icr_2 and ip of supply samples.

In order to rank resistance to uniform corrosion, figure 88 shows the "icr_1" value as a function of URE.

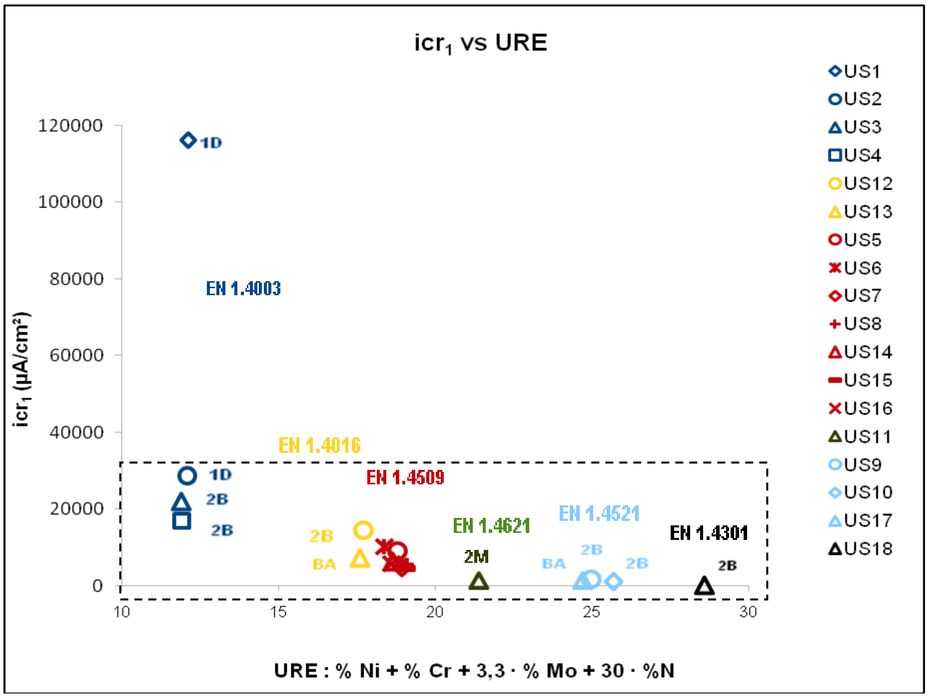

Figure 88. –"icr_1" vs. URE. Supply surface samples

Figure 88 shows an inverse relation between "icr_1" and URE, which is expected. Furthermore, the highest value of sample U_{S1} (EN 1.4003-1D) can be underlined, which means, a very low resistance to uniform corrosion in this media. If this result is removed and the outlined area is enlarged, the different behaviour related with finish may be noted (figure 89).

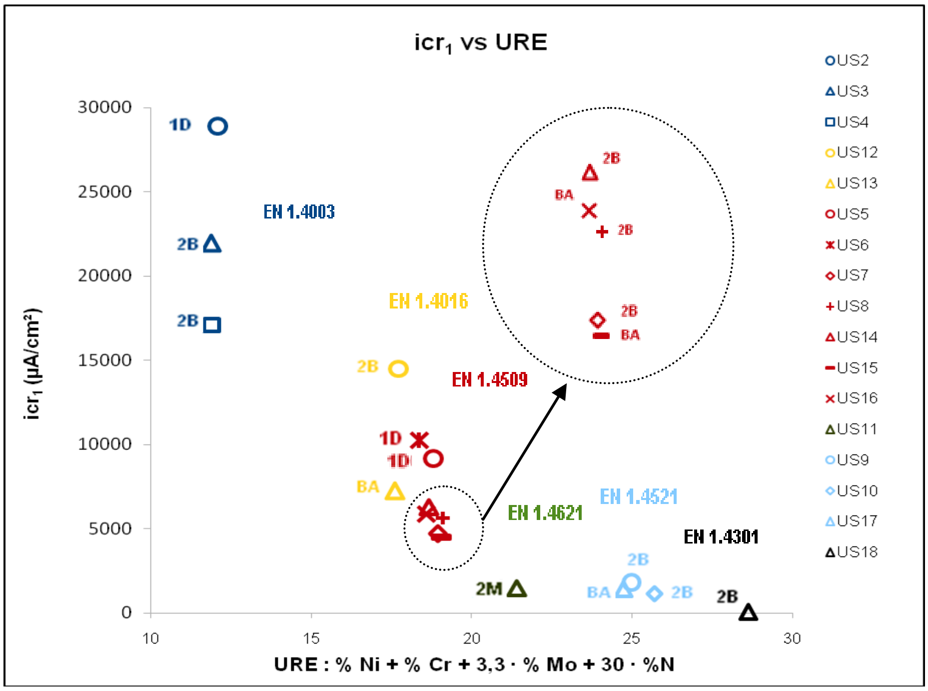

Figure 89. –"icr_1" vs. URE. Supply surface samples

In the new graph, the better performance of cold rolled (2B and BA) than hot rolled (1D) in EN 1.4003 and EN 1.4509 is shown, as well as the slightest difference between 2B and BA finishes in EN 1.4509 (enlarged area) and EN 1.4521. The fit to a line is clearer without the removed result.

The icr_2 parameter is represented as a function of URE, in order to evaluate the information obtained by this peak (figure 90).

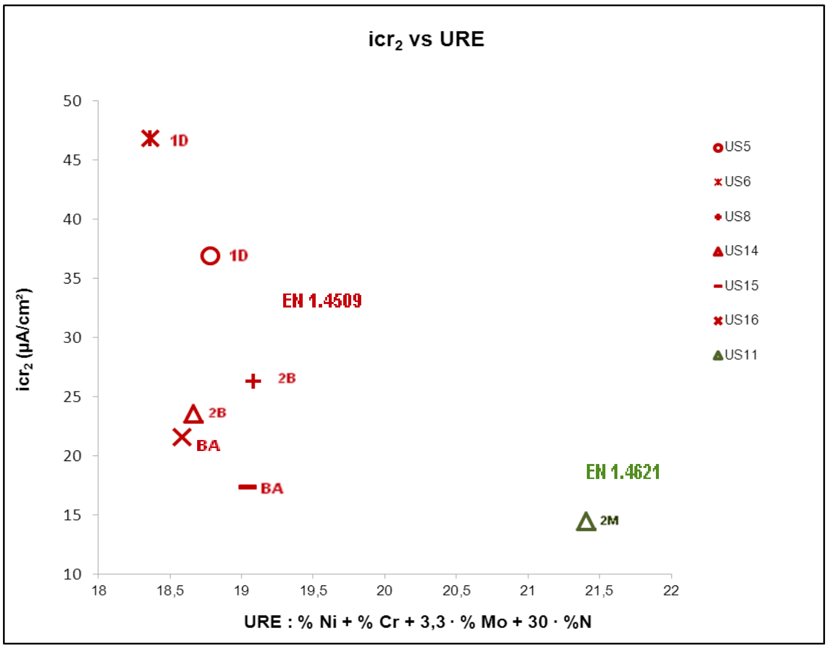

Figure 90. - icr_2 vs. URE, supply samples

With data shown in figure 90 it may be outlined the decrease in icr_2 value from 1D to BA in the grade EN 1.4509 although they are almost the same values, with a difference from several microamperes.

In figure 91 the current density variation in passive area from the tested materials can be observed.

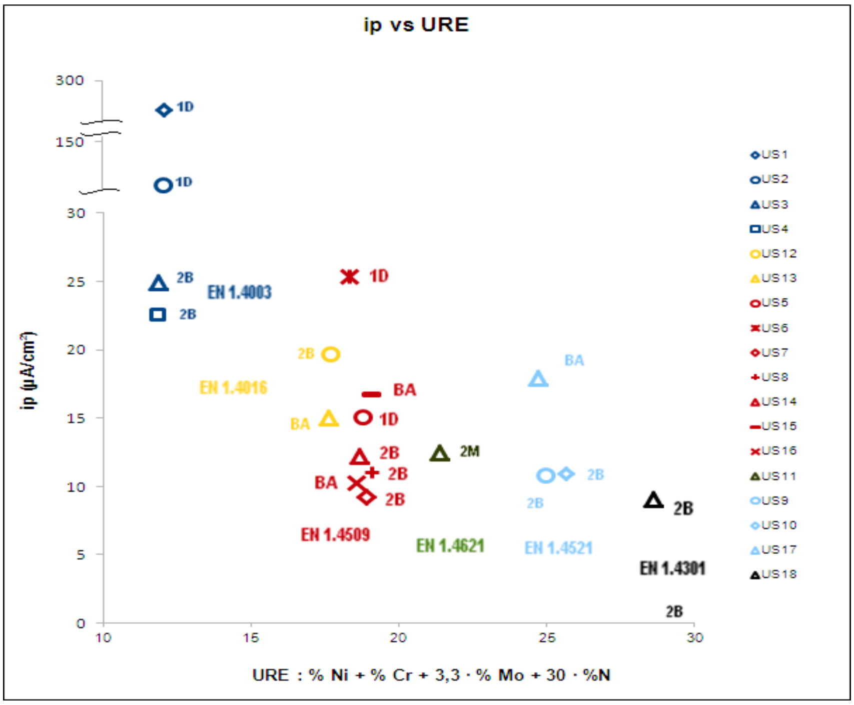

Figure 91. – “ip” vs. URE. Supply samples

In this case, the graph does not show a very clear linear correlation of "ip" with URE. Most ip values are rather similar. They have the same behaviour, low current density typical from stainless steel passive layer. Only U_{S1} and U_{S2} samples (EN 1.4003-1D) have higher "ip" values, which mean a worst material behaviour in these conditions.

3.2.4.3. Comparison polished - supply surface conditions

Finally, a comparison of results in both surface conditions, supply and polished with 600-grit SiC paper, is made. By means of the icr_1 parameter to compare the effect added by finish is pretended.

In figure 92 icr_1 vs. URE is represented. The sample EN 1.4003 in 1D finish (U_{S1}), is represented in a different scale because owns an icr_1 value too high.

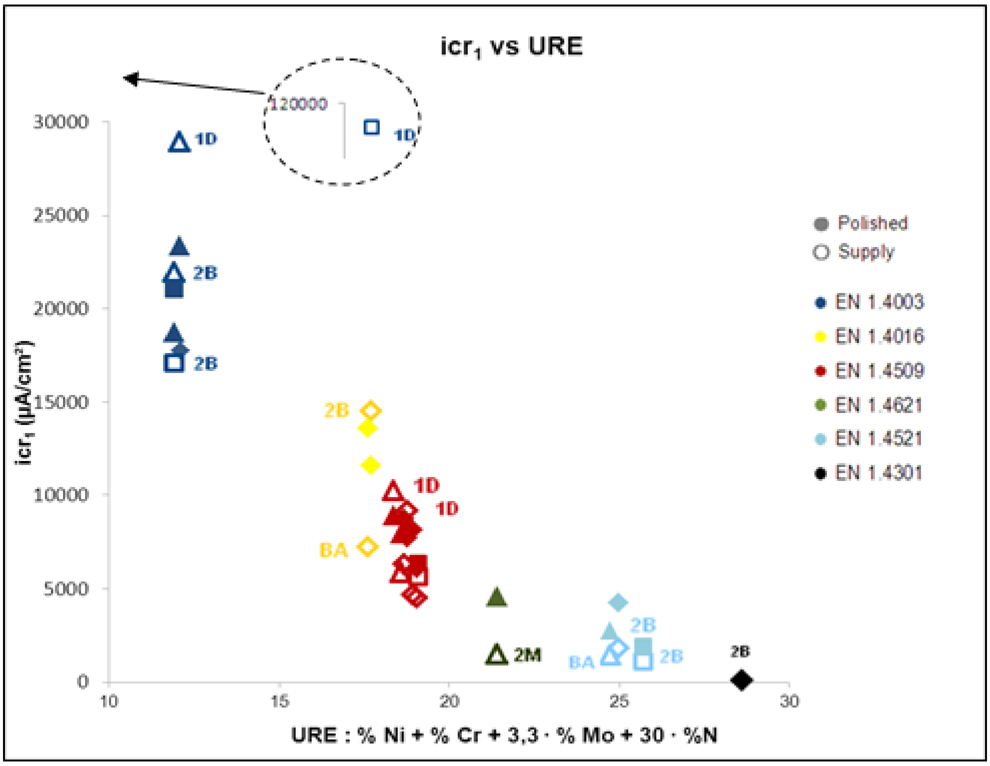

Figure 92. – "icr_1" vs. URE. Supply and polished samples

The comparison does not show relevant differences on uniform corrosion resistance of stainless steels due to the effect added by the finish. This means that their behaviour is nearly similar in supply conditions than in polished ones in these test conditions.

4 CONCLUSIONS

Ferritic stainless steel were exposed to electrochemical test in 35 g/L NaCl and 1N H_2SO_4 solutions, so as to evaluate the pitting corrosion resistance and the uniform corrosion resistance, respectively. Furthermore, in both tests, polished samples with 600-grit SiC paper and in supply conditions were tested in order to get as many information as possible.

In pitting corrosion test, the pitting potential, Ep, is obtained. This parameter means the lowest potential at which pitting nucleus occur. The more noble this potential, the lower susceptible is the alloy to initiation of localized corrosion in this environment.

By means of the pitting corrosion test on samples**,** the following resistant classification it has been obtained in this test conditions.

Less resistant   More resistant

EN 1.4003 < EN 1.4016 < EN 1.4509 < EN 1.4621 < EN 1.4301 < EN 1.4521

This result is closely related with the PRE (Pitting Resistance Equivalent) value of the samples. This parameter relates the content in chromium, molybdenum and nitrogen with the resistance to pitting corrosion.

When the test is carried out on supply surface samples, the repeatability of the test decreases, and a high improvement according pitting corrosion resistance is found in BA finish, less significant in 2B finish.

In uniform corrosion the lower value of icr_1, the more resistant a stainless steel in the defined corrosive conditions.

By means of the evaluation of icr_1 on samples, the following resistance classification in this test conditions has been obtained.

Less resistant   More resistant

EN 1.4003 < EN 1.4016 < EN 1.4509 < EN 1.4621 < EN 1.4521 < EN 1.4301

This result is closely related with its URE value (Uniform Resistance Equivalent). This parameter relates the content in chromium, molybdenum, nitrogen and nickel with the resistance to uniform corrosion.

By means of testing samples in supply and polished by 600-grit SiC paper, the improvement of the repeatability of the test in polished samples has been tested.

In uniform corrosion the effect by finish is not clear. It can be outlined that EN 1.4003 grade in the 1D finish shows a huge decrease in corrosion resistance in these corrosive conditions.