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ANALYSIS ON THE CORROSION RATE CHANGES OF AISI 410 STAINLESS STEEL SUBMITTED TO ABRASION-CORROSION IN SIMULATED MARINE CONDITIONS

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Abstract: Due to its diversity of applications in mechanical components such as; turbines, valves and pumps, AISI 410 stainless steel is exposed to combined conditions of mechanical and electrochemical wear. Basic studies on the wear resistance of this martensitic stainless steel have already been carried out, but it is still necessary to delve into the tribocorrosion perspective, analyzing the effect of the combined wear forms since it is still been a phenomenon not completely understood. This work presents an analysis on the changes in the electrochemical response of AISI 410 stainless steel in marine abrasion-corrosion conditions, using a novel test rig based on ASTM G105-16 wet abrasion apparatus configuration, with an adapted electrochemical cell. The material was submitted to polarization resistance (R_p), and anodic potentiodynamic polarization tests, in both conditions; pure corrosion and abrasion-corrosion. Substitute ocean water (aqueous media), and silica sand (abrasive particles) were used to recreate the aggressive marine environment.

Potentiodynamic polarization test results do not show a passivation zone of the material when it is submerged in the media. The material does not present a good corrosion resistance under pure corrosion condition contrary to abrasion-corrosion. In addition SEM images analysis sample surface was carried out for each test. Micrograph shows the dominant wear mechanisms are produced by mechanical work.

Keywords: Tribocorrosion, martensitic, stainless, steel, abrasion-corrosion, AISI 410.

1. INTRODUCTION

Martensitic stainless steels are essentially Fe-Cr-C metallic alloys. These kinds of alloys are used in mechanical components that require a good mechanical performance and also a moderate corrosion resistance [1]. Stainless steel AISI 410 is the martensitic steel with

greater availability in the market and the easiest to obtain, also has a low cost compared with other stainless steels. This alloy is commonly used in applications such as pump axis and valve parts for the hydrocarbon extraction industry, aircraft engines parts, gas turbines, chemical plants, energy generation equipment, and some components for the

marine industry [2]. Due to its diverse uses and applications it is easy to find AISI 410 stainless steel exposed to tribocorrosion.

Tribocorrosion is defined as the transformation process of a material due to electrochemical degradation (corrosion) and mechanical wear simultaneously happening in contacting surfaces with relative motion between them. Rarely the tribocorrosion effect is just the sum of mechanical wear plus corrosive wear, but generally it is higher (synergistic interaction) or lower (antagonistic interaction) [3]. Two main forms of tribocorrosion can be found in literature: erosion-corrosion and abrasion-corrosion, and can be generated by various mechanisms like sliding, fretting, rolling, or impingement. Every one of these mechanisms can have its own variations [4].

To evaluate corrosion rate when a metallic material is probed in tribocorrosion conditions, generally electrochemical techniques are applied (i.e. Open circuit potential, TAFEL plot, polarization resistance, and anodic potentiodynamic polarization) in combination with standard tribological tests [5].

Martensitic steels, including AISI 410, have been probe in different conditions, for example: Pure corrosion [1], [2], erosion [6], and also in some tribocorrosion conditions like erosion-corrosion [7]. In previous works abrasion-corrosion has been evaluated in martensitic stainless steels using the pin on disk and the ball on disk tribometer configuration (two body unidirectional sliding to generate mechanical wear in a corrosive media) combined with the electrochemical techniques to evaluate accelerated corrosion [8], [9]. But even though the AISI 410 martensitic stainless steel has application in components used in marine environments, there are not enough information available about its performance when is submitted to tribocorrosion conditions similar to marine ones.

This work focus on the analysis on the corrosion rate changes of stainless steel AISI 410 when it is exposed to abrasion-corrosion (three-body unidirectional

sliding) compared with pure corrosion in a simulated marine environment, in order to evaluate the material performance, and using a novel tribocorrosion test rig developed by the IPN ESIME Zacatenco tribology group to simulate the mentioned work conditions.

2. TEST RIG AND MATERIALS

Elements used during experimentation to reproduce work conditions in marine environment were: a potentiostat, an abrasion-corrosion test rig, substitute ocean water as corrosive media, silica sand particles as abrasive agent, and as work material: samples of commercial AISI 410 stainless steel.

In the following subjects, the most important aspects of each element are detailed.

2.1 Experimental arrengment and abrasion-corrosion tribotester details

Experimental arrengment used in this work consist in a test rig design, with some characteristics based in the machine configuration called “wet sand/rubber wheel” that is used to perform wet abrasion tests [10], but adapted to a work cell that allows to perform electrochemical tests to evaluate corrosion rate using a potentiostat-galvanostat (Fig. 1).

Figure 1. Test rig components and configuration: 1. Electrochemical cel; 2. Abrasive-corrosive aqueous media; 3. Counter body; 4. Sample holder and load applier; 5. Weight; 6. Media mixer; 7. Metallic sample; 8. Electrode cables; 9. Potentiostat-galvanostat; 10. Data processing software.

Similar machine configurations, where a sample (work body) is presented against a

sliding counter body in the presence of an abrasive agent between (third body), have been used in previous works [11][12].

Figure 2. Schematic representation of contact configuration: 1. Work body; 2. Rubber wheel (softer unidirectional sliding body); 3. Silica sand particles suspended in synthetic seawater (abrasive slurry).

For the present work the counter body is a rubber wheel that has a softer surface than the metallic sample so the contact does not produce any damage in the work body; the only function of the counter body is to apply a load and move the silica sand particles in one direction to evaluate their effect in the corrosion rate (Fig. 2).

2.2 Metallic samples

Samples were obtained from a round bar of commercial AISI 410 stainless steel with a 210 HV vickers hardness. The material was analyzed by electron diffraction spectrometry (EDS) to determine if chemical composition corresponds to the proposed steel (Table 1).

Table 1. Chemical composition of AISI 410 stainless steel according to data sheet [13].

Element	Maximum Concentration (%)
C	0.08 – 0.15
Mn	1.0
S	.030
P	.040
Si	1.0
Cr	11.5 – 13.5
Ni	0.75
C	0.08 – 0.15

Results of EDS analysis indicate that the obtained material corresponds to AISI 410 martensitic stainless steel as shown in Fig. 3 and Table 2.

Table 2. Element concentration according to EDS analysis of samples.

Element Line	Weight %	Atom %
Si K	0.49	0.96
S K	0.03	0.12
Cr K	12.10	12.81
Mn K	0.39	0.39
Fe K	86.95	85.71
Total	100.00	100.00

Geometry of the metallic sample (working electrode) was determined with the aim of obtaining a 1 cm² work surface, to have a better control of parameters during electrochemical measurements. Instead of the commonly used Saturated Calomel (KCl), and graphite electrodes; two metallic rings made of the same working material (AISI 410 stainless steel) were assigned as reference electrode and counter electrode [14].

Figure 3. Spectre obtained from EDS analysis of AISI 410 stainless steel.

Figure 4. Schematic representation of sample and electrodes mounted on polyester resin.

Electrodes were mounted in polyester resin as shown in Fig. 4 in order to let the test rig counter body to maintain sliding contact with the working electrode, without affect the reference and counter electrodes [15].

2.3 Abrasive particles

Silica sand (SiO_2) was used to represent seaground abrasive particles. Characterization of sand particles was made using scanning electron microscopy (SEM) to determine morphology, laser annalysis to calculate average size, and nano indentation to calculate hardness. Results of particle characterization shows a sharp edges particles, with average size of 176 μm , and hardness of 789.5 Vickers.

Figure 5. SEM image of SiO_2 particles.

2.4 Corrosive aqueous media

Substitute ocean water was used as corrosive media to simulate marine conditions. It is a

solution with content of inorganic salts in representative proportions and concentrations of seawater. Its preparation is normalized by ASTM International [16]. Table 3 shows concentration of chemical compounds used to prepare substitute ocean water. Aqueous media was stabilized in an 8.2 pH.

Table 3. Chemical compounds in substitute ocean water according to norm ASTM D1141-98(2013).

Compound	Concentration (gr/l)
NaCl	24.53
MgCl_2	5.20
Na_2SO_4	4.09
CaCl_2	1.16
KCl	0.695
NaHCO_3	0.201
KBr	0.101
H_3BO_3	0.027
SrCl_2	0.025
NaF	0.003

3. Methodology

Two samples of AISI 410 were tested with three electrochemical techniques to evaluate corrosion. Techniques used in this experimental procedure were: Open circuit measurement to determine corrosion potential (E_{Corr}), Polarization resistance (R_p) to calculate corrosion rate, and potentiodynamic anodic polarization to analyse and compare the characteristic sample polarization plot generated. Each technique was performed in two conditions: Pure corrosion, and abrasion-corrosion. Both conditions were recreated in 1 L of substitute ocean water. Parameters controlled to recreate each work conditions were: Abrasive particle concentration (Apc, gr), Counter body load (load, N), and sliding velocity (Sv, m/min). Table 4 shows parameter values established for each test.

Table 4. Test parameters

Sample ID	Performed Test	Tests condition	Parameters value	
AISI410-1	Ocm	Pure corrosion	No abrasive particles or sliding contact.	
	R_p			
	Pap			
AISI410-2	Ocm	Abrasion-corrosion	150 gr	Apc
	R_p		2.5 N	Load
	Pap		30 m/min	Sv

Polarization resistance technique serves to measure corrosion rates and generally is expressed in mill-inches per year (mpy). This technique consist in perform a scanning trough a potential range very close to the (E_{Corr}). The potential range used for the experiment was ± 20 mV. Resulting current is plotted versus potential, and then is related to the corrosion rate as can be seen in Equation 1:

$$(mpy) = \frac{0.13 I_{corr} (E.W.)}{d} \quad (1)$$

were " I_{corr} " is the measured corrosion current density ($\mu A/cm^2$), "E.W." is the equivalent weight of the corroding specie, and "d" is the density of the material (gr/cm^3).

Potentiodynamic anodic polarization tests also consist in a potential scanning were the potential is plotted against the current density but with a wider range of voltage. This tests generate a polarization plot that can yield information such as: ability of the material to passivate, potential region in which the material remains passive, identify potential regions of the material and calculate corrosion rate in a certain one [17]. For this work the potential sweep was -200 mV to +1600 mV from the E_{Corr} .

After the tests both samples were analysed using SEM to determine prevalent wear mechanisms.

4. RESULTS AND DISCUSSION

Comparison of open circuit measurements, as can be observed in Fig. 6, shows how in abrasion-corrosion condition, with the presence of the abrasive slurry generated by the substitute ocean water mixed with SiO_2 particles, the open circuit potential gets a value between -0.359 and -0.059 mV showing instability in its behaviour, while in the pure corrosion condition values are stables between -0.357 and -0.441 mV. This is an indicator of reactivity decrease in the sample-media interface due to the presence of abrasive slurry in the sample surface.

The Rp tests results confirm a decrease on the corrosion rate in a 87 % taken it into 1.4 mpy (miles per year). Decreasing of corrosion rate value

confirm the difficult to made the electron exchange between electrodes when the mechanical wear is occurring. The corrosion rate is an average of four "Rp" technique repetitions in each sample and it can be observed in Fig. 7.

Figure 6. Open circuit plots of AISI 410 stainless steel in both conditions.

Figure 7. Corrosion rate comparison between work conditions.

Potentiodynamic anodic polarization plots, showed in Fig. 8, are graphic representations of material electrochemical response in media. In pure corrosion condition, it cannot be seen a well-marked passivation zone. This is an indicator of a low corrosion resistance in seawater. By the other hand an unstable behavior can be observed in the abrasion-corrosion condition. This can be attributed to the interference produced by the abrasive slurry present between electrodes. Decrease in the corrosion rate in this condition can be confirmed by the low current density observed in the plot.

Figure 8. Anodic potentiodynamic polarization plot comparison between work conditions.

Wear mechanisms occurring during potentiodynamic anodic polarization (in both work conditions) can be observed in the next images. Figure 9 shows zones where, the increase of electric potential (1.2 Volts over the open circuit potential), caused a detachment of material from the sample surface. In a close up of one of the pitting holes, produced by detach of material, signs of intergranular corrosion can be seen. This can be caused by sensitization of the oxide layer in grain boundaries, phenomenon that have been correlated with pitting corrosion of martensitic stainless steels in previous studies [18].

Figure 9. SEM View of wear scars generated in pure corrosion condition.

The last micrograph, showed in Fig. 11, presents the mechanisms found in abrasion-corrosion tests. As can be observed the pitting corrosion traces are no longer visible; instead, only scars produced by the mechanical action of

abrasive particles can be appreciated. This is an evidence of the corrosion rate decrease measured with the polarization resistance tests.

Figure 10. SEM view of intergranular corrosion mechanism, occurring during pure corrosion test.

Figure 11. SEM view of wear scars generated in abrasion-corrosion condition.

Figure 12. Close up of ploughing trace.

Ploughing and scratching are the main forms of wear presents in the sample surface, generating material accumulation in the edges of the scars. Also some incrustations of abrasive particles were found as can be seen in Fig. 12.

5. CONCLUSIONS

Results indicate that:

AISI 410 steel does not have good resistance to corrosion in an aggressive environment such as seawater, so its use is not recommended under these conditions.

Steel did not present a passivation zone in the analyzed graphs, but media mixed with abrasive particles inhibited the effect of corrosion; this is an antagonistic effect of the abrasion-corrosion phenomenon.

When AISI 410 stainless steel is subjected to the phenomenon of 'wet abrasion-corrosion', using synthetic seawater as a medium and SiO₂ as an abrasive particle, mechanical wear predominates over corrosion.

It becomes a priority to implement chemical tests for the identification of corrosion products and also determinate the mechanisms that are causing the reduction in corrosion rate.

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