Review above Applying Active Anode Protection at Some Dynamic Petroleum Equipment's in Order to Reduce Wear

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The paper presents a synthesis of studies carried out to reduce wear in some petroleum dynamic equipment such as rod pumps and centrifugal pumps. Rod pumps and centrifugal pumps work in heavy conditions. Crude oil contains an important quantity of highly mineralized formation water, rich gases with a high percent of CO_2, grains of sand from petroliferous bed. The main causes of failure in rod pumps are abrasive and corrosive wear, and in centrifugal pumps erosive and corrosive wear. The developed tests are presented, which show that cathodic protection with active anode reduces wear and is possible to be applied. The influence of the temperature, pressure, CO_2 partial pressure, materials couples, sliding speed, impingement angles, etc. on wear was established. Also, the durability calculus of this equipment and the patents obtained as the results of studies are presented.

Keywords: *durability, rod pumps, centrifugal pumps, active anode, corrosion, wear laws, roughness.*

1. INTRODUCTION

Friction and wear cause different malfunctions in pumps. To raise durability of pumps, many technologies were developed in order to reduce friction and wear. When working medium is corrosive, applying cathodic protection is a solution to diminish wear [1-4]. In petroleum industry wear and corrosion represent major problems. These degradation forms lead to interrupting and production loses, continuous reduced efficiency and increased maintenance and replacing equipment expenses. These affect not only economic budget but lead directly to environment pollution. Corrosion is considered as a natural degradation process of metallic materials under the action of chemical agents. Metallic materials are metastable in aggressive mediums and have the tendency to pass into a more stable form. The maximum intensity of this process took place in electrolytic mediums. Wear removes material and corrosion products from material surfaces and degradation is accelerated and reliability is diminished. To prevent wear in electrolytic mediums, the recommendation goes to the materials recognized as resistant (noble) and to those which do not generate galvanic corrosion in friction couples, using corrosion inhibitors, diminishing electrochemical potential of materials in the Pourbaix immunity domain, etc. For the fixed materials couple a cathodic protection could reduce degradation process with the condition to not produce hydrogen embrittlement because hydrogen appears in cathode.

Pumps' good reliability, based on pumps construction and materials performances, is a demand of all users. To respond to this demand, we have first to know and control the mechanisms developed at the material-medium interfaces and then to develop and apply new techniques and technologies to increase wear resistance. To obtain good performances we have to use materials and technologies adequate to working conditions. Taking into account that in petroleum industry pumped fluids are highly corrosive and erosive, pumps' parts are manufactured of materials with high hardness and good corrosion resistance. To fulfill only these tasks, the pumps will become very expensive.

Durability of exploited pump equipment could be 25 years or longer (e.g. main pipes) and inspection costs, maintenance and repairing costs account for around 20 % of total costs of pump life time. By non-conventional measures such as cathodic protection it is possible to reduce these costs for different types of pumps [4,5].

To reduce costs and evaluate durability, first of all, we have to analyze technical solutions based on theoretical and experimental studies in the laboratory and then in real working conditions.

The paper presents a review of the tests and results obtained by the authors in order to raise durability of sucker rod pumps and centrifugal pumps by cathodic protection and by nitrating thermochemical treatment applied to austenitic stainless steels in centrifugal pumps.

2. SUCKER ROD PUMPS

An important percent of damages of production wells are caused by pump failure, and pump reliability depends on piston-cylinder and ball-valve couple durability [4]. For ceramics ball-valve couple, pump reliability depends only of piston-cylinder durability [4]. Crude oil contains an important quantity of highly mineralized water, rich gases with a great percent of CO_2, grains of sand from petroliferous bed.

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Piston slipping along the cylinder, theoretically, is made in the presence of, more or less, lubricate film. In fact, film thickness isn't constant. It's possible that piston slips directly on the cylinder and with abrasion wear to have adhesion wear. Materials for piston and cylinder are not proper for adhesion wear. Working fluid contains sand. Quantity and size of sand depends of the existence and quality of sand filter. Sand grains smaller than radial clearance pass through piston and cylinder and remove chips from both surfaces, [1,4-6].

Fluids have also a strong corrosive action on metallic materials. Electro-chemical reactions generate brittle and hard compounds. In static conditions these compounds realize a passivated coating. In dynamic conditions, friction tangential force between the piston and the cylinder locally remove oxide coating. Coating reconstruction needs time and sliding is continuous. Surface without coating oxide is exposed to corrosive action. Current density on non-coated area is much bigger than on coated area. In these conditions the corrosion rate on non-coated area is bigger.

In conclusion, in rod-pumps piston-cylinder couple there are three main wear tips, abrasive, corrosive and adhesive [1,4-6].

Corrosive wear participation in total wear is 25 – 50 %, [1,4-6] and if fluid contains H_2S even more.

The diminishing wear is possible result of diminishing corrosive wear.

To reduce corrosive wear, three possible methods can be applied:

- proper materials with high corrosion resistance;
- reduce fluid aggressiveness with corrosion inhibitors;
- electrochemical methods such as cathodic protection.

To increase the working life of rod pumps in abrasive and corrosive medium, it is recommended to use materials with high hardness and resistance to corrosion such as hard- chromium plating steel for cylinder or piston, carbonitrided and nitrided cylinder and metallic carbide layers of METCO types for pistons in order to resist heavy duty conditions [1,4-6]. The aim of the paper is to present the methodology used to establish wear laws in order to predict piston-cylinder durability and also to present the cathodic protection method with active anode.

2.1 Piston-cylinder corrosion laws

For static corrosion tests the prepared samples were manufactured from real pumps' pistons and cylinders. We used metal sprayed and hard chromium plated steel pistons and carbonitrided, nitrided and hard chromium plated steel cylinders which are the most used materials for piston-cylinder couples in sucker rod pumps in Romania oil fields. Also, specimens were prepared made of Al-Zn alloy as galvanic anode.

Each material surface was studied in order to establish the microgeometry parameters, microhardness and thickness of the coatings or nitrided or carbonitrided stratums.

Because many factors were involved, the experiments were conducted in order to establish each factor's influence.

In the first phase were established electrochemical parameters at 20 °C and at 60 °C in formation water with and without CO_2 barbotage. The results are presented in papers [1,4-9]. It was observed that corrosive medium temperature modifies corrosion potential. Temperature rising induces corrosion potential and corrosion current density rising, the barbotage of CO_2 rises corrosion potential and corrosion current density and different materials samples have different corrosion potential and corrosion current density and in couples will form galvanic cells.

In the second phase were tested in formation water at different temperatures (20, 30, 40 and 50 °C), CO_2 pressures (0, barbotage, 2, 3, 4 and 5 MPa) couples of materials in different combinations with and without active anode presence.

Corrosion rate [g/m^{2}h] was calculated using relation:

$$v_{\text{cor}} = \frac{\Delta M}{A \cdot \tau} \qquad (1)$$

where: ΔM is mass loss [g]; A is sample active area [m^2]; τ is time [h].

In Figure 1 it is presented the corrosion rate at the temperature of 20 °C in formation water with CO_2 barbotage with and without active anode [1,4].

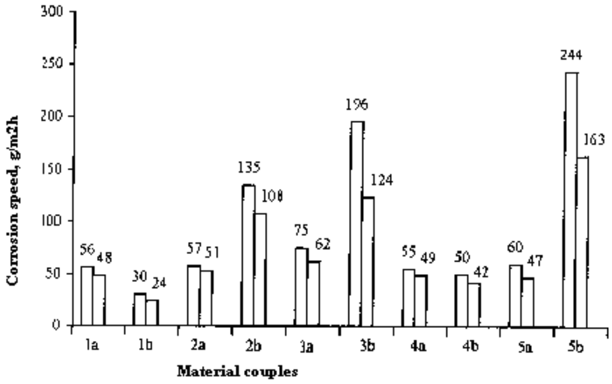

Figure 1. Corrosion rate at 20 °C and CO_2 barbotage; 1a – piston metal sprayed; 1b – skirt chromium; 2a – piston metal sprayed; 2b – skirt carbonitrided; 3a – piston metal sprayed; 3b – skirt nitrided; 4a – piston chromium-plated; 4b – skirt carbonitrided; 5a – piston chromium-plated; 5b – skirt nitrided

Analyzing the influence of parameters above the corrosion rate [g/m^{2}h] experimental results were formulated as a Weibull type relation which shows the temperature influence [4]:

$$v_{\text{cor}} = a_{\text{p,c}} - b_{\text{p,c}} \cdot e^{-c_{\text{p,c}} \cdot t^{d_{\text{p,c}}}} \qquad (2)$$

where: coefficients a_p, b_p, c_p, d_p are for piston material and a_c, b_c, c_c, d_c are for cylinder material.

In Figure 2 it is shown the corrosion rate variation with temperature for carbide sprayed piston in couple with hard chromium cylinder [4].

The CO_2 pressure influence on corrosion rate [g/m^{2}h] is expressed with polynomial relation [4]:

$$v_{\text{cor}} = a_{\text{p,c}} + b_{\text{p,c}} \cdot p + c_{\text{p,c}} \cdot p^2 + d_{\text{p,c}} \cdot p^3 + e_{\text{p,c}} \cdot p^4 \qquad (3)$$

where: $a_{p,c}$, $b_{p,c}$, $c_{p,c}$, $d_{p,c}$, $e_{p,c}$ are coefficients depending of tested materials couples and working medium.

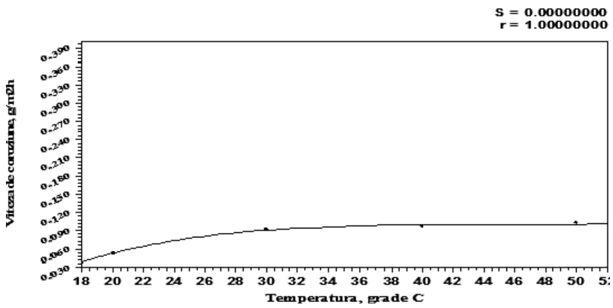

Figure 2. Corrosion rate vs. temperature for carbide sprayed piston in couple with hard chromium cylinder

In Figure 3 [4] it is exemplified the corrosion rate variation with CO_2 pressure for carbide sprayed piston in couple with hard chromium cylinder.

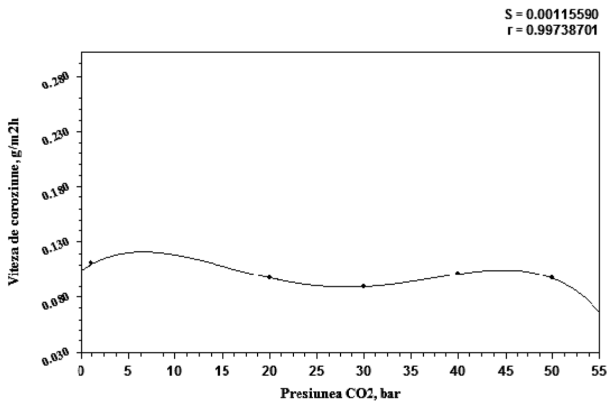

Figure 3. Corrosion rate vs. CO_2 pressure for carbide sprayed piston in couple with hard chromium cylinder

The temperature and CO_2 pressure influence on the corrosion rate [g/m^{2}h] relation obtained is [4]:

$$v_{cor} = a + \frac{b}{x_1} + c \cdot x_2 + \frac{d}{x_1^2} + e \cdot x_2^2 + f \cdot \frac{x_2}{x_1} \qquad (4)$$

where: a, b, c, d, e, f are coefficients depending of tested materials couples and working medium; x_1 is temperature [°C]; x_2 is pressure CO_2 [bar].

The corrosion rate curve depending of the temperature and corrosion rate is shown in Figure 4 [4], for carbide sprayed piston in couple with hard chromium cylinder.

In Figure 5 [4] it is shown the corrosion rate variation with temperature and CO_2 pressure for carbide sprayed piston in couple with hard chromium cylinder in active anode Al-Zn presence.

Corrosion tests proved that active anode Al-Zn presence reduces the corrosion rate, and diminishing efficiency depends of materials' couples and working parameters [1,2,4-9].

2.2 Piston-cylinder wear laws

Abrasive wear process was examined on a testing machine designed and completed for that purpose. In Figure 6 [4] it is presented the kinematic diagram of the device.

On a vertical rod (1) the sample type piston is fixed (2). A sample type cylinder (3) slotted is tightened on a piston with a flexible cable (4), tensioned with a weight set (5). Alternative movement of the piston is provided by the crank and connecting-rod assembly (6), driven by an electric motor (11). The piston-cylinder system is completely immersed in formation water from the tank (9). To maintain in suspension sand, we have a punched plate (10).

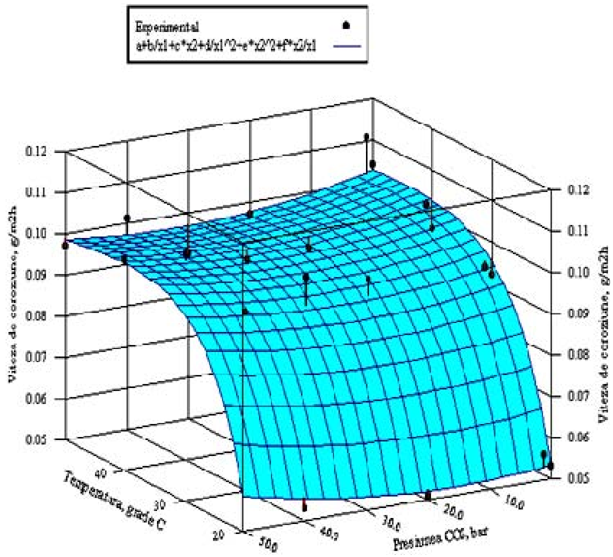

Figure 4. Corrosion rate vs. temperature and CO_2 pressure for carbide sprayed piston in couple with hard chromium cylinder

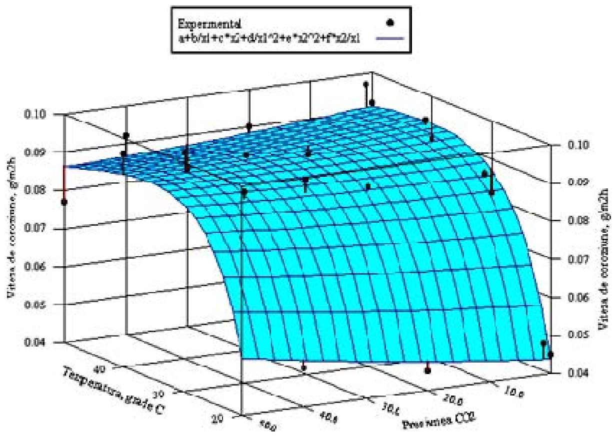

Figure 5. Corrosion rate vs. temperature and CO_2 pressure for carbide sprayed piston in couple with hard chromium cylinder in active anode Al-Zn presence

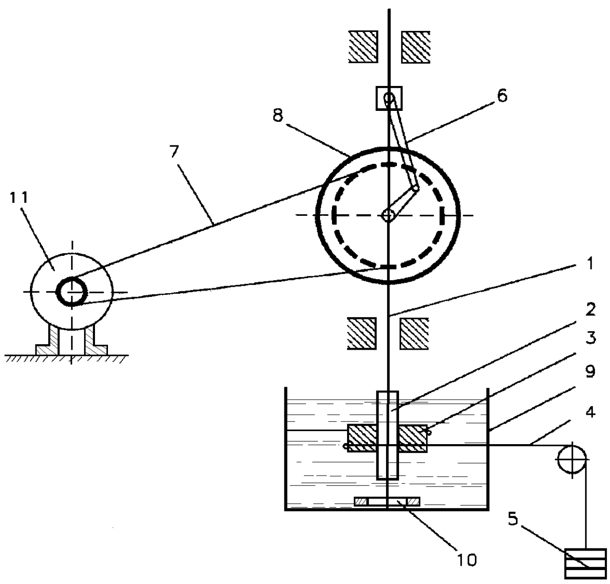

Figure 6. Cinematic diagram of the device

For wear tests it was used formation water with 3 % sand from rod pumps with a grain size smaller than 63 µm.

Testing conditions were [4]:

- cable load, 50 N;
- double stroke per min., 54;
- temperature, 20 °C;
- barbotage of CO_2.

Analyzing the experimental results from dynamic tests, a wear relation was formulated [4]:

$$u_{\mathrm{p,c}} = a_{\mathrm{p,c}} \cdot x + b_{\mathrm{p,c}} \tag{5}$$

where: $u_{\mathrm{p,c}}$ is piston respective cylinder wear [mg]; x is time [min.]; $a_{\mathrm{p,c}}$, $b_{\mathrm{p,c}}$ are coefficients depending of piston (p) and cylinder (c) materials couple and of testing conditions.

In Figure 7 [4] it is presented the wear curve for hard chromium plated cylinder in couple with metal sprayed piston [4]. For this material couple the relation (5) has $R^2 = 0.9390072263$.

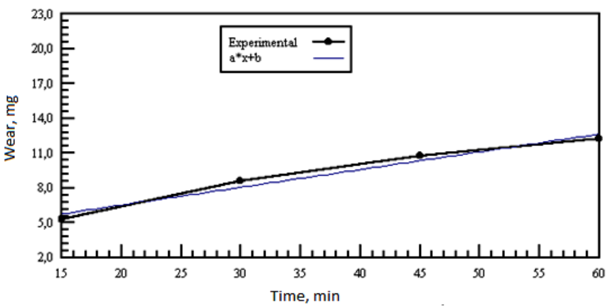

Figure 7. Wear for hard chromium plated cylinder in couple with metal sprayed piston

The obtained experimental results prove that the presence of active anode reduces wear depending on materials couples and working conditions [1,2,4-9].

2.3 Active anode for sucker rod pumps cathodic protection

Protection efficiency depends on active anode geometry. With bigger anode surface area the current efficiency is bigger, but anode consumption is very important. For the same anode weight the surface area has to be as small as possible to assure a great time life.

Minimum area for a maximum weight is spherical. For technological reasons it was adopted a cylindrical form.

In Figure 8 [2,4] it is presented the anode geometry. Active anode material is an alloy Al-Zn6.5. The cathodic protection method with active anode for sucker rod pumps and anode construction is patent RO118671-B.

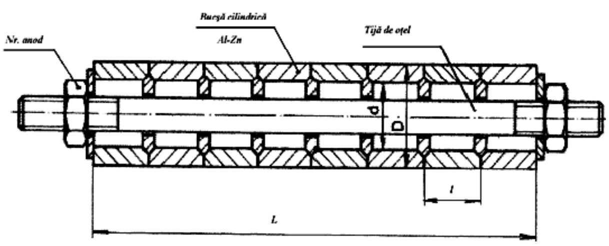

Figure 8. Active anode design

2.4 Evaluation of piston-cylinder durability

In order to evaluate piston-cylinder life time, we put the condition to obtain a minimum surface pumping efficiency, $\eta = 0.65$ [4]. Based on laboratory tests results and taking into account the transformations, to obtain similarity with a real pump working parameters a computer program was created for real pumps durability calculus. In Figure 9 is presented the program window simulation [4-6,9].

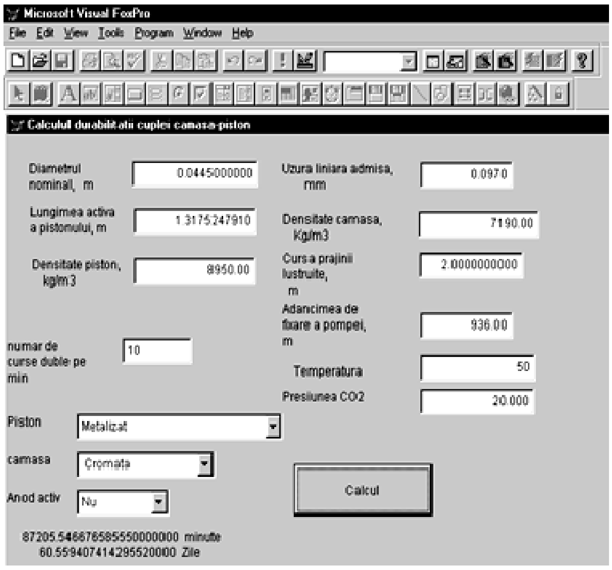

Figure 9. Program simulation for sucker rod pumps durability calculus

The program gives us the possibility to evaluate pumps' durability depending of pumps' type (nominal diameter, length, materials couples), active anode presence, CO_2 partial pressure, deep of the pump in well, temperature, double stroke per min. in pumping unit, etc.

3. CENTRIFUGAL PUMPS

In petroleum industry the pumps used are with the rotor and body made of carbon steel type OT450 (GS 45 DIN 1681), gray cast type EN-GJL-HB215, EN-GJL-HB155, AISI 304, AISI 316, etc. This paper presents the erosion-corrosion wear results from tests made in the presence of formation water with 3 % sand at different impingement angles, with and without active anode made on the materials from the rotor and body centrifugal pumps. Because of sand particles and corrosive character of crude oil, the wear mechanism is an erosive-corrosive one. The important quantities of formation water from crude oil make the aggressively crude oil to depend of formation water aggressively.

To reduce corrosive wear of centrifugal pumps, a cathodic protection with active anode was proposed.

Also, in austenitic stainless steels hardened by nitride thermochemical treatments the wear tests results are presented.

3.1 Corrosion rates

Samples were made of carbon steel type OT450 from a real pump rotor, of gray cast type EN-GJL-HB215 and

EN-GJL-HB155 from a real pump bodies. To evaluate the materials corrosion behavior in formation water, electrochemical tests were made using a potentiostat EG&G 350 Princeton and an ASTM cell with ECS reference electrode. In Table 1 [3] are shown the values of electrochemical parameters. In samples made of mentioned materials the corrosion rates were also established at different temperatures by immersion method. The values obtained were similar with the results obtained by electrochemical tests at 20 °C.

Table 1. The values of electrochemical parameters

Parameter	GJL-HB215	GJL-HB155	OT450	Zn anode
Corrosion current, i_{cor} [μA]	3.352	2.218	6.020	4.887
Corrosion potential, E_{cor} [V]	– 0.160	– 0.131	– 0.190	– 0.537
Corrosion rate, v_{cor} [mm/year]	0.045	0.030	0.080	0.074

3.2 Erosion wear tests

To establish the erosion influence the tests were conducted at 15°, 30° and 45° impingement angles at 1450 rpm (7.6 m/s) with and without active anode attached to samples. Wear for tested material samples was established, and roughness on impact samples face was also measured. The working medium was formation water with 3 % sand with the size smaller than 0.125 mm.

In Figure 10 [3] it is shown the wear results obtained for samples of material GJL-HB215 at 15° impingement angles and in Figure 11 [3] it is presented roughness modification curve for material GJL-HB215 at 15° impingement angles.

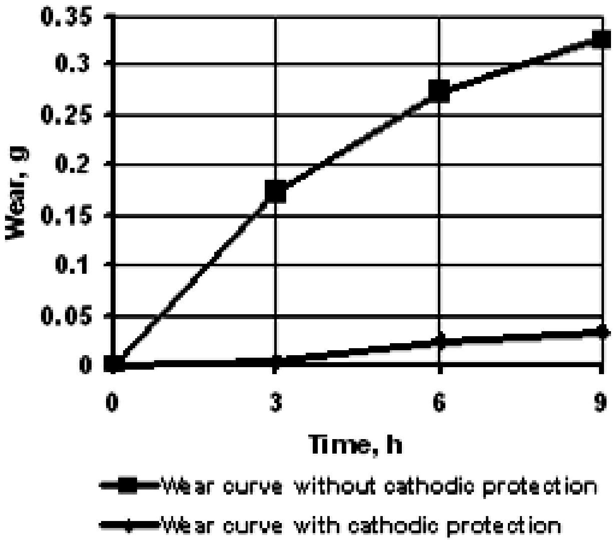

Figure 10. Wear curve for material GJL-HB215 at 15° impingement angles

From Figure 10 we could observe that cathodic protection reduces wear. Similar behavior was observed in all tested materials.

Cathodic protection with active anodes reduces erosion wear in all tested materials and impingements angles. Also, cathodic protection improves surface roughness. For roughness the critical impingements angles for sample materials GJL-HB155 and OT450 is 15° and for material GJL-HB215 without cathodic protection 15° and 30° and 15° with cathodic protection. These critical angles must be avoided.

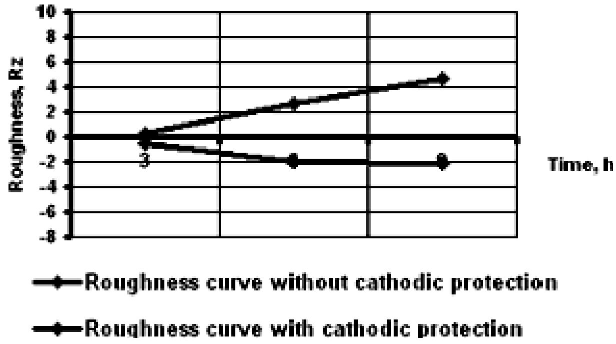

Figure 11. Roughness modification curve for surface of material GJL-HB215 at 15° impingement angles

Good results of cathodic protection with active Zn anode presented were also confirmed by tests made on centrifugal pump stand (Fig. 12) and in industrial conditions [3].

Figure 12. Centrifugal pumps testing stand

The obtained results regarding the cathodic protection efficiency give authors the possibility to formulate and obtain the patent RO122867-B.

3.3 Nitrating treatments influence on tribological behavior of austenitic stainless steels

Austenitic stainless steels have a good behavior in the presence of powerful oxidant or corrosive environments, but with the disadvantage of a weak attitude in friction conditions due to the combined effects of the temperature produced by friction and of the superficial plastic distortions, especially in the presence of work environments presenting poor lubricant qualities.

To improve tribological qualities, we can recall the application of thermal and thermo-chemical treatments, in the desire to obtain a tough, ductile and homogenous layer, which:

- reduces the action of conjugated asperities of the surface;
- increases shear resistance;
- increases resistance in superficial fatigue;
- increases corrosion resistance.

Two austenitic stainless steels, stainless steel AISI 304 (SR EN 10088-1: X5CrNi18-10) and stainless steel AISI 316 (SR EN 10088-1: X5CrNiMo17 12 2), have been elected having a spread use in the construction of equipment from petrochemical and refinery industry. Test samples obtained from these steels have been submitted to gases nitrating treatment in two stages, at the temperature of 505 °C, namely 545 °C for 14 hours, and in parallel to an ionic nitrating treatment at the temperature of 480 °C for 8 hours. Tribological parameters were established on universal tribometers like tribocorrosion wear machine, ball-on-disk CSM microtribometer, erosion wear testing machine.

Tests conditions on CSM microtribometer [10] were: disk samples made of 304 and 316 steels untreated, gas nitrided and plasma nitrided, Ø6 mm ball of 100Cr6, normal load N = 4 N, sliding speed v = 0.366 m/s, dry friction length L = 100 m, temperature T = 20 °C, relative humidity RH = 33 %.

In Figure 13 the friction coefficients are shown for AISI 316 material samples [10,11].

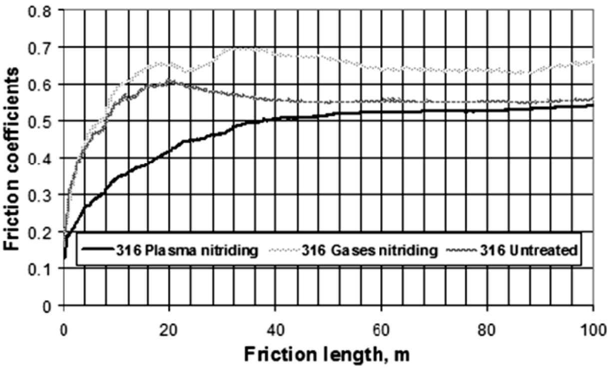

Figure 13. Friction coefficients vs. friction length

In the presence of formation water the mentioned materials were tested on the wear testing machine, at parameters: samples made of 304 and 316 steels untreated, gas nitrided and plasma nitride, normal load N = 25 N, sliding speed v = 0.42 m/s, cylinder diameter D = 40 mm, rotational speed n = 200 rpm, formation water as working medium, temperature T = 20 °C. In Figure 14 [10,11] the volumetric wear results are presented obtained for AISI 316 cylinder material sample.

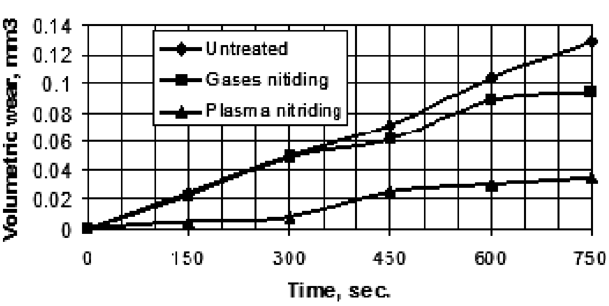

Figure 14. Wear curves for AISI 316 samples

In erosion wear tests the selected erosion wear test medium consisted of formation water from the water supply tank of an injection station, the latter having a high quantity of suspended sand particles and a high potential for corrosion. The main characteristics of the formation water used were: pH = 6.6, and the chemical composition with Na^{+} 79.58 g/l, Ca^{z+} 4.41 g/l, Mg^{z+} 0.90 g/l, HCO_3^{-} 0.92 g/l and Cl^{-} 133 g/l with a sand content of 10 g/l collected from water supply tank [12]. The sand particles collected for erosion testing are silicon (SiO_2) based, chemically inert, possessing high hardness (7 Mohs scale or 1500 Vickers scale). The specimens were mounted at an angle of 15° and then 30° angles corresponding to the input-output angles of the blades of the centrifugal pumps.

Figure 15 [12] shows the wear curves obtained for AISI 316 at an impingement angle of 15° and Figure 16 [12] at impingement angles of 30°.

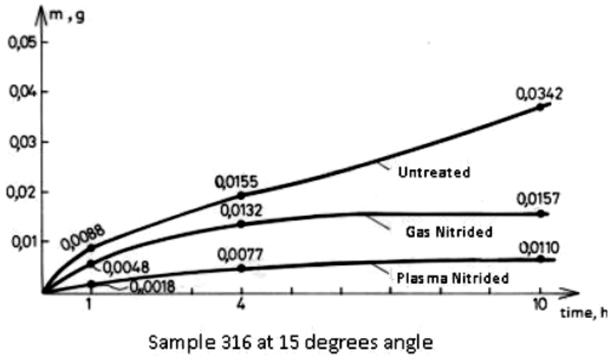

Figure 15. Erosion wear curves at impingement angle of 15°

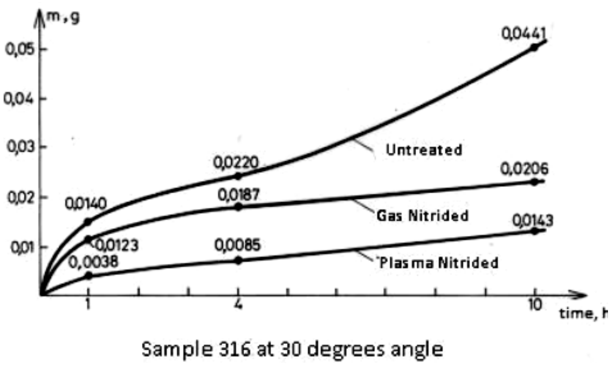

Figure 16. Erosion wear curves at impingement angle of 30°

Note that there is an important distinction between the erosion behaviors of the three states, and also depending of impingement angle. Increased surface hardness by nitrating treatments provides a significant reduction of wear by erosion. By increasing the impingement angle from 15° to 30°, erosion wear increases both in untreated condition and also when gas or plasma nitrating thermochemical treatment was applied.

4. CONCLUSIONS

In electrolytic aggressive liquid mediums, such as crude oil, industrial or urban residual waters, the corrosive part of wear could be reduced, with low costs, by applying cathodic protection with active anodes.

Zinc material has an anodic behavior in couple with tested materials for sucker rod and centrifugal pumps in formation water.

Chromium plated piston is better to work with nitrided cylinder instead of cylinder carbonitrided because electro-chemical potential is closer for nitrided cylinder. The same conclusion is for piston metal sprayed.

Cathodic protection with active anode reduces wear at all material couples.

Based on many experimental tests in the laboratory and in more than 100 different wells from Romanian oil fields, the program created could evaluate with an error smaller than 12 % the rod pumps lifetime, taking into account the piston cylinder materials couples, temperature, CO_2 pressure, deep of pump, double stroke per min. at pumping unit, surface stroke and rod pump type. We can also see that corrosion rate is bigger with a smaller pipe flow section. Also, a bigger roughness determines a bigger corrosion rate. The program created assures a fast instrument to evaluate corrosion rate.

Experimental tests establish that wear rises with temperature. With CO_2 pressure the influence on wear is different depending on the CO_2 pressure value and the materials couples. Because at CO_2 pressure tests only CO_2 gas was used the CO_2 pressure value is the same with partial pressure of CO_2. The maximum corrosion rate was obtained for 8 – 10 bar CO_2 pressure when the conductivity of tested formation water was maximal.

Cathodic protections with active anodes reduce erosion wear in all tested materials and impingements angles. Also, the cathodic protection improves surfaces roughness. For roughness the critical impingements angles for sample materials GJL-HB155 and OT450 is 15° and for the material GJL-HB215 without cathodic protection 15° and 30° and 15° with cathodic protection. These critical angles must be avoided.

The obtained results presented allow the authors to formulate a patent to protect sucker rod pumps and also a patent to protect centrifugal pumps with active anodes.

Increased surface hardness by nitrating treatments provides a significant reduction of wear by erosion.

By increasing the impingement angle from 15° to 30°, erosion wear increases both in untreated condition and also when gas or plasma nitrating thermochemical treatment was applied.

The wear in the same friction conditions decreased substantially in the case of plasma ionic nitriding. Also, the wear and friction coefficients were smaller for AISI 316 than for AISI 304 material samples. This behavior is due to the thickness of formed expanded austenite S phase with good behavior at friction. This also explains better tribological behavior of plasma nitrating than gases nitrating of austenitic stainless steels. Gases nitrating was performed at temperatures higher than plasma nitrating. Thus, due to higher temperature on the surface the phase γ' Fe_4N also appears and reduces the thickness of S phase.

The 480 °C plasma nitrating temperature was optimum for AISI 316 but for AISI 304 was too high, and the recommended value is 440 °C.

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ПРЕГЛЕД ПРИМЕНЕ АКТИВНЕ АНОДНЕ ЗАШТИТЕ НА ДЕЛОВЕ НАФТНЕ ЕПРЕМЕ У ЦИЉУ СМАЊЕЊА ХАБАЊА

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Рад представља синтезу истраживања, спроведених од стране аутора, могућности за смањење хабања делова нафтне опреме, као што су клипне и

центрифугалне пумпе. Клипне и центрифугалне пумпе раде у тешким условима, с обзиром да сирова нафта садржи одређену количину тзв. везане воде (високо минерализована вода која се налази у лежиштима нафте и гаса), гасове са великим процентом CO_2, зрнца песка, итд. Главни узроци отказа клипних пумпи су абразионо и корозионо хабање, а главни узроци отказа центрифугалних пумпи су ерозионо и корозионо хабање. Спроведена испитивања показују да катодна заштита са активном анодом може да буде примењена и да смањује хабање. Успостављена је и веза између величине хабања и температуре, притиска, парцијалног притиска CO_2, материјала делова, брзине клизања, угла удара флуида, итд. Такође су представљени прорачуни трајности делова нафтне опреме, као и патенти добијени као резултат истраживања.