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EXPERIMENTAL RESEARCH ON THE CORROSION RESISTANCE CHARACTERISTICS OF A606 MATERIAL USED IN THE MANUFACTURE OF COILED TUBING

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Abstract: *Within the equipment of drilling rigs, coiled tubing (CT) is the main element that performs the manoeuvring of drilling tools to perform various operations in challenging conditions. The CT is subjected to complex stresses, which can manifest statically and dynamically, under the action of functional loads (forces, torques, pressure, temperature, etc.). To these tasks can be added the action of corrosive and embrittlement factors specific to the working environment. In this article are presented, the program of experimental tests aimed at establishing the chemical composition of the material, macro and micro structural analysis, tensile strength, flattening and the corrosion behaviour in different working environments (bore water, acidization solution, air etc.).The results of the conducted tests are a clear indicator that only through continuous monitoring the operational life of the coiled tubing could be established.*
Key words: *coiled tubing, corrosion, steel A606, operational life*

1. INTRODUCTION

The coiled tubing (CT) installation is used for the execution of guided drilling as well as for different maintenance operations such as acidization, extraction of tools etc.

Flexible tubing operates under cyclic bending loads which combined with the action of aggressive working environments, contribute to the appearance and development of corrosion phenomena.

Corrosive degradation of CT can result from contact with the atmospheric environment, transported fluids and production fluids. Corrosion, especially localized corrosion, must be prevented as it can affect the service life of the tubing by premature fatigue crack initiation and growth during cyclic bending. In addition, corrosion can reduce the usable strength of the tubing and the integrity of wellhead operations.

At the same time, localized corrosion is characterized by the highest speeds, especially under the action of cyclic bending loads [1, 2, 3, 4].

The combined effect of fatigue and corrosion of the flexible tubing material is one of the main causes of reduced life of flexible tubing rolls.

The decrease in the durability of the flexible tubing occurs as a result of mechanical defects on the surface (scratches, pinches, flattening, local crushes, dents) which are accentuated by cyclic bending stresses and corrosion phenomena due to the action of the operating environment.

In general, flexible tubing used in drilling rigs must be made of materials with a low specific density to facilitate proper transportation and handling of the equipment. It must also withstand the performance of a considerable number of functional cycles (several hundred wells), without speeding up the drilling process and reducing the cost per job performed.

In this context, material selection analysis is performed on a variety of material categories using the performance index method. The performance indices are evaluated according to the specific density, bending/straightening capacity, loading capacity with operational loads, specific stiffness, breaking strength and corrosion resistance [5, 6, 7].

Coiled tubing operations currently rely on the use of flexible steel tubing. The conventional flexible tubing material available on the market is High Strength Low Alloy Steel (HSLAS), which present a reduced fatigue at bending/straightening operations.

The experimental determinations carried out within the work aim to establish the corrosion resistance characteristics of the A606 material (according to ASTM B704) used in the manufacture of coiled tubing.

The corrosion properties of the researched material are evaluated based on the indicators determined by experimental research: corrosion potential (Ecorr), corrosion current densities (Icorr) and corrosion speed (Crr).

Depending on the conditions and operating costs of the wells, flexible tubing is made of different materials, such as [5, 6, 7, 8]: steels (with different strength characteristics), titanium alloys, nickel alloys, composite materials etc.

Various classes of steels have been tested to study the composition and structure in order to determine the strength and corrosion characteristics of the materials [1, 2, 9].

The technical conditions, strength classes and physical-mechanical characteristics of the steels used in the manufacture of flexible tubing are regulated by API RP 5C7 specifications, equivalent to the SREN 10208-2:2009 standard, [11]. In the framework of the elaborated work, the experimental researches were carried out on the A 606 steel, resistant to atmospheric corrosion, which is elaborated in two types:

- type 2 with alloying elements with 0.2% to increase corrosion resistance;
- type 4 with additional alloying elements to improve corrosion resistance more than Cu alloying of carbon steels.

According to [10], thorough studies and research were done on CT-80 steel, from which flexible tubing pipes are manufactured. CT 80 is high strength steel containing alloying elements to ensure resistance to atmospheric corrosion. The chemical composition meets the requirements of the API 5ST CT80 standard: 0.150 % C; ≤ 0.430% Si; 0.820% Mn; 0.570% Cr; ≤ 0.019% P; ≤ 0.001 % S; ≤ 0.220% Cu; ≤ 0.08% Ni; 0.19% Mo; 0.017% Nb; 0.010...0.020%Ti; 0.015...0.040% V; 0.070...0.120 % Al, rest - % Fe. The material structure consists of polygonal ferrite and granular bainite.

2. MATERIALS AND METHODOLOGY

2.1 Material A606 according to the standard

To carry out the tests, flexible tubing made of A606 steel is considered, according to ASTM B704, and from the point of view of geometric characteristics, the reference dimensions are: outer diameter D_e = 31.75 mm (1 ¼ inch), wall thickness t = 2.54 mm (0.1 inch).

According to the ASTM A606 standard, the chemical is presented in table 1 [12].

Table 1

Chemical composition of A606 steel [12].

Material	Chemical composition		
	C %	Mn %	S %
A606	0.26	1.30	0.06

Mechanical characteristics of A606 steel are presented in table 2 [11].

Table 2

Mechanical characteristics of A606 [11].

Mechanical characteristics	As rolled	Annealed or normalized
Tensile strength, MPa	480	450
Yield strength, MPa	310	340
Elongation, %	22	22

2.2 Methodology

The program of experimental determinations aims at the following types of tests: determination of the chemical composition; macrostructural and microstructural analysis; mechanical and technological tests (tensile test, hardness test, flattening test); tests on the corrosion behaviour of the A606 material.

2.2.1 Chemical composition analysis

To determine the chemical composition of the flexible tubing material, ring-type specimens were used (fig. 1). Two types of specimens were studied: P1 – specimen made of new (unused) flexible tubing; P2 – test piece made of flexible tubing with 20 operating cycles.

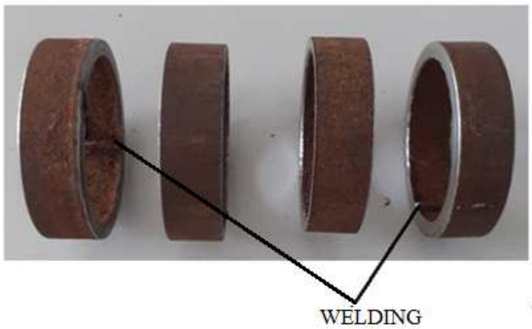


Fig. 1. Samples used for the chemical composition analysis [15].

The composition was determined with PMI – Genius 5000 with radioactive cell (X-ray based). According to [11], the material from which the tubing is made is a steel resistant to atmospheric corrosion and only the maximum percentages of C, Mn and S are specified, no other elements being specified.

2.2.2 Macro and micro structural analysis

The macro structural examination of the specimens was carried out by electron microscopy, STEREO microscope for defectoscopy SZM Series, modernized metallographic research microscope MC5-A (IOR).

The microstructure of the samples was examined with a metallographic microscope, after preparing the samples (attack with specific reagent 2% nital, 98% C2H5OH) at x100 magnification.

2.2.3 Hardness determination of the coiled tubing material

The hardness test was performed according to the Vickers method, according to [13] on samples taken from new flexible tubing (sample P1) and used tubing with 20 operating cycles (sample P2). The device used for testing is the EmcotestDuraScan 20 microduritometer, with test loads ranging from 0.01 to 10 daN. For the samples subjected to the tests, the loading of 5 daN was chosen. The prints were placed in base material.

2.2.4 Flattening test

The flattening test was performed in accordance with the provisions of SR EN ISO 8492:2014, [14].

The specimen intended for testing is of the type of pipe section (fig. 2), which is cut from the flexible tubing. The length L of the tested specimen is 1.5 times the outer diameter of the flexible tubing (L = 1.5 × D = 1.5 × 31.75 = 47 mm; it is adopted: L = 50 mm)).

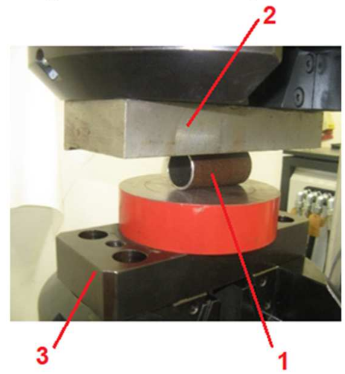


Fig. 2. Flattening test [15]:
1 – specimen; 2 – fixture; 3 – testing table.

2.2.5 Tensile test

To determine the mechanical characteristics, the Walter Bai LF300 universal machine (fig. 3) was used for static and dynamic tests with the following technical characteristics: force in static mode: ± 300 kN; force in dynamic mode: ± 250 kN; duty cycle frequency: up to and including 20 Hz.

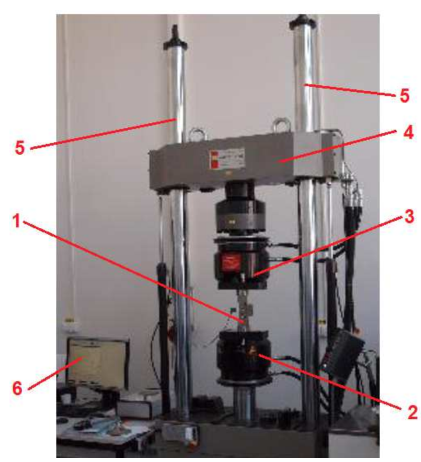
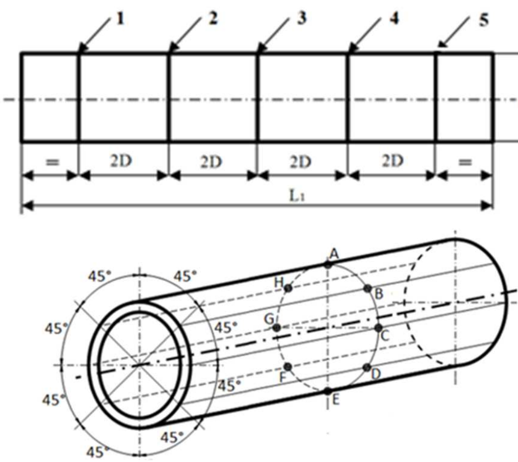


Fig. 3. Tensile test [15]:
1 – sample; 2 – lower clamping device;
3 – upper clamping device; 4 – crossbar;
5 – guide axis; 6 – data acquisition system.

The tests were performed for two classes of specimens: P1 – specimen made of new (unused) flexible tubing; P2 – test piece made of flexible tubing with 20 operating cycles. The test specimen is of the pipe type (fig. 4.a). In order to establish the portions where the rupture will occur, the specimens were marked on longitudinal and transverse measurement areas, where the diameter and wall thickness are measured (fig. 4.b). In this way correlations between the geometric characteristics of the flexible tube and the areas where the rupture occurs could be established.



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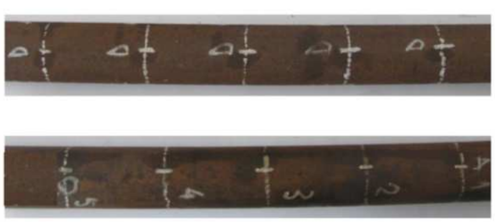


b

Fig. 4. Specimen used for tensile tests:
coiled tubing ϕ 31.75 mm [15]:
a – establishing measurement plans of geometric characteristics; b – marking of the test pieces.

The geometric characteristics of the flexible tubing are important through two aspects: the integrity of the flexible tubing, which must withstand the stresses and operating conditions without being damaged, and the impact that the variation of the diameter of the flexible tubing has on the handling equipment, especially the injector head. Measurements were made in five measurement planes (1, 2, 3, 4, 5), equally spaced on the flexible tubing generator (at distance 2D, where D is the outer diameter of the flexible tubing, D = 31.75 mm). Circumferential measurements were taken in each measurement plane. Measurements were conducted (fig. 4.a) on the outside diameter of the flexible tubing (D) in each measuring plane (1, 2, 3, 4, 5) and on each marked circumferential position (A-E, B-F, C-G, D-H) and also, the thickness of the wall (*t*) in each measuring plane (1, 2, 3, 4, 5) and on each marked circumferential position (A, C, E, G).

2.2.6 Experimental research on corrosion resistance of flexible tubing material

Corrosion resistance was evaluated on plate-type specimens (fig. 5), having the characteristics shown in table 5. The specimens were taken both from the weld bead area and from the one without the weld bead. The sampling of the samples from the flexible tubing as well as the processing were carried out with less intensive regimes in order not to change the structure of the material and/or introduce residual stresses.

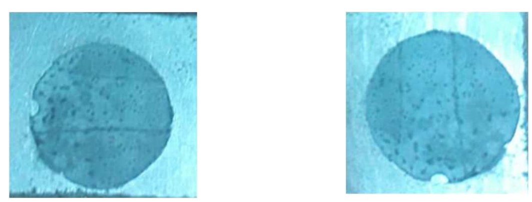


Fig. 5. Samples for corrosion resistance testing, coiled tubing ϕ 31.75 mm [15].

The surface of the samples exposed to the work environment was rectified and then sanded on 600 Mesh sandpaper.

For the tests, borehole water with the composition shown in table 3 was used as the working medium. The determination of the pH of the deposit water was carried out according to the Norsok M-506 method, using the PHM201 MeterLab (Radiometer) type device with a combined pH Ag/AgCl electrode. A VoltaLab PGZ 100 potentiostat and an electrochemical cell were used for tests (observing ASTM G5) (fig. 6).

The electrochemical cell consists of a glass vessel, a Haber-Luggin capillary tube, a capillary tube holder and three electrodes: 2 series graphite counter electrodes, a saturated calomel reference electrode and the working electrode (test sample).

Table 3

The composition of the working medium [15].

Measured characteristic	**Value**	**U.M.**	**Method of determination**
pH	7.16 at 15.9 ^{0}C	unit. pH	Norsok M-506
Calcium	2450	mg/L	SR ISO 11885 – 2009; SR ISO 15587-2-2003
Magneziu	1020	mg/L	SR ISO 11885 – 2009; SR ISO 15587-2-2003
Sodium	30100	mg/L	SR ISO 11885 – 2009; SR ISO 15587-2-2003
Sulfate (SO_4)	64.8	mg/L	SM 4500 – SO_4 E
Chlordesi (Cl^-)	56800	mg/L	SR ISO 9297-2001
Bicarbonaes (HCO_3)	296	mg/L	SR ISO 9963/1- 2002

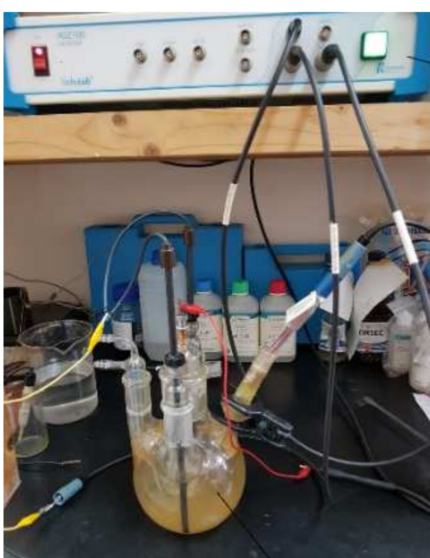


Fig. 6. Equipment used for corrosion resistance testing [15]:
1 – potențiostatVoltaLab PGZ 100;
2 – electrochemical cell.

For each determination, the samples were inserted one by one into a Teflon support with a 1 cm^2 hole through which the sample was in direct contact with the working medium (formation water).

The capillary tube was placed in front of the hole. Polarization curves and Evans plots with Tafel lines were acquired and: corrosion potential (E_{corr}), corrosion current densities (I_{corr}) and corrosion rate (C_{rr}) were determined.

3. RESULTS OBTAINED

3.1 Chemical analysis

The results of the testing performed as presented in 2.1 are presented in the table 4. Analysing the compositions in table 4 and comparing with the values in the A606 standard (table 1,2), it is found that the material of both sample P1 and sample P2 is low-alloy steel, which, in addition to C, Mn and other alloying elements. The values obtained for C and Mn fall within the values provided in standard A606. The material of samples P1 and P2 has in its composition N and higher percentages of Mn, Cr, Ni, Mo, which give it good resistance to corrosion.

Table 4

Coiled tubing samples chemical composition [15].

Chemical composition (%), max.	**Sample notation**	
	P1 – unused material	**P2 – material with 20 working cycles**
C	0.14	0.13
Mn	0.72	0.8
Cr	0.66	0.67
Ni	0.19	0.28
Cu	0.27	0.23
Mo	0.14	0.12
V	-	0.03
Ti	0.15	-
Nb	0.13	0,13
Co	-	-
Al	-	-
Si	0.34	0.317
P	0.01	0.013
S	0.001	0.002
N	0.008	0.006

3.2 Macro and micro structural analysis

From the analysis of the macrostructure, it was found that the material has no external defects (craters, cracks, etc.), concavities or elevations.

The tubing is welded to the generators, so it was noticed, on the inside of the tubing, in the area where the seam is raised, that the material shows deposits of impurities, making the area more difficult to clean.

From the analysis of the microstructures (fig. 7 and 8) it was found that the structure of the material of the samples is biphasic, ferrito-pearlitic (white ferrite, black pearlite), very fine, evenly distributed, with portions slightly oriented in lamination rows, having the grain size punctate (9 … 9.5) according to EN ISO 643 and ASTM E112.

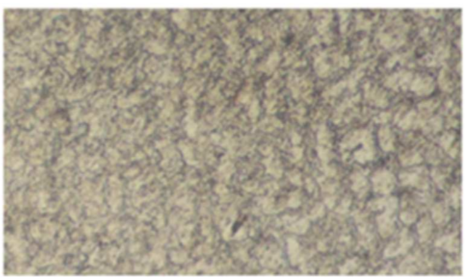


Fig. 7. Microstructure P1 x100, tubing ϕ 31.75 [15].

Fig. 8. Microstructure P2 x100, tubing ϕ 31.75 [15].

Darker pearlite grains have a higher Carbon concentration, and lighter (light-Gray) grains have a lower Carbon concentration. In the samples examined with a welded joint, it was observed that there is no additional material, the joint being executed.

3.3 Hardness

The obtained results are presented in table 5.

The analysis of the obtained values confirms the appropriate resistance and tenacity characteristics of the flexible tubing material.

Table 5

Hardness values HV experimental established on coiled tubing ϕ 31.75 [15].

Sample type	Hardness HV			Averrage HV	Averrage HRC
P1 unused material	220	225	221	215	20
	221	223	226		
P2 material with 20 working cycles	240	242	240	227	20 *) Hardness $HRC_{max.}$ 22, API RP5C7
	248	238	232		

3.4 Flattening

For the experimental tests, the samples were completely flattened, the inner surfaces contacted each other. The areas at the bent ends (areas 3 and 9) were visually examined and no cracks or cracks in the material were observed (fig. 9).

Fig. 9. Flattened samples [15].

3.5 Tensile tests

The measured specimens were subjected to the tensile test. It was found that the breakage occurred in most cases in zones 2 and 3, respectively 1 and 2, marked on the examined samples (fig. 10 a, b, c).

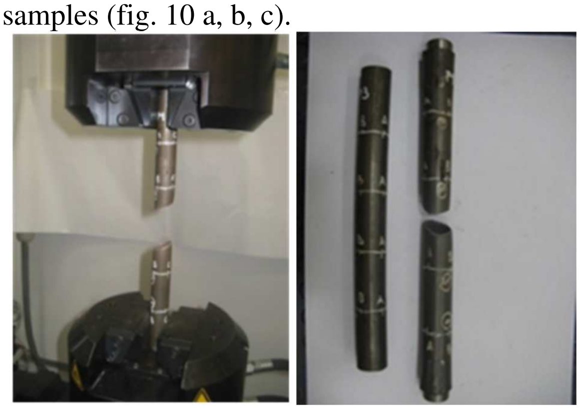


Fig. 10. a) Specimen P1/1 broken in area 2-3 [15].

Fig. 10. b) Specimen P1/2 broken in area 2-3 [15].

Fig. 10. c) Specimen P1/3broken in area 1-2 [15].

In table 6, the results obtained in the tensile tests are presented. As the number of duty cycles of the flexible tubing increases, the ductility of the material decreases.

Table 6

Mechanical characteristics [15].

Sample	Unused material			Material with 20 working cycles		
	P1/1	**P1/2**	**P1/3**	**P2/1**	**P2/2**	**P2/3**
R_m, (MPa)	645	702	15	664	685	676
$R_{p0,2}$, (MPa)	561	610	618	573	578	571
E , (MPa)	158465	146589	127863	149254	145026	148625
A_r,(%)	20.12	24.54	15.88	19.09	19.91	24.75
$R_m/R_{p0,2}$	1.15	1.15	1.15	1.15	1.18	1.18

In practice, elongation at break above 10% indicates a ductile material, and if it is below 3%, the material is brittle.

According to the data presented in table 4, it follows that the values of the ratio ($R_m/R_{p0.2}$) vary within the limits $1.15 \le R_m/R_{p0.2} \le 1.17$, and A_r = min. 15.88%, which leads to classifying the investigated material of flexible tubing in the category of ductile materials.

The verification of the characteristics obtained through our own tests with those specified in the material standards (A606, API RP5C7), as well as how the obtained indicators evolve according to the number of operating cycles, proves that the material of the flexible tubing corresponds to the work standards.

3.6 Corrosion testing

The results of testing are presented in figures 11,12,13,14 and in table 7.

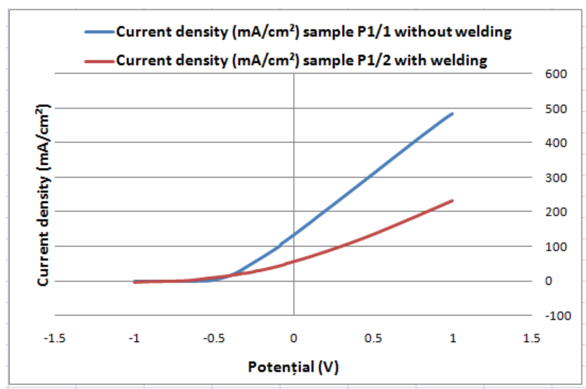


Fig. 11. Variation of current density with potential for unused flexible tubing specimens, flexible tubing with diameter D = 31.75 mm [15].

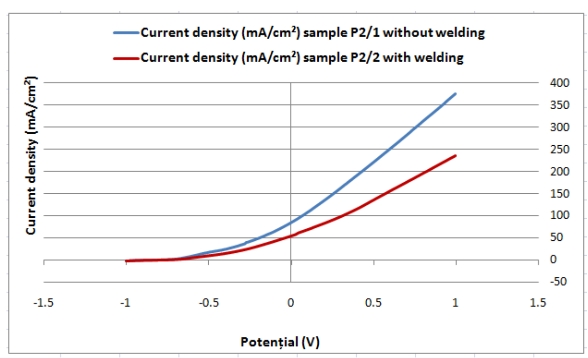


Fig. 12. Variation of current density with potential for flexible tubing specimens with 20 duty cycles, flexible tubing with diameter D = 31.75 mm [15].

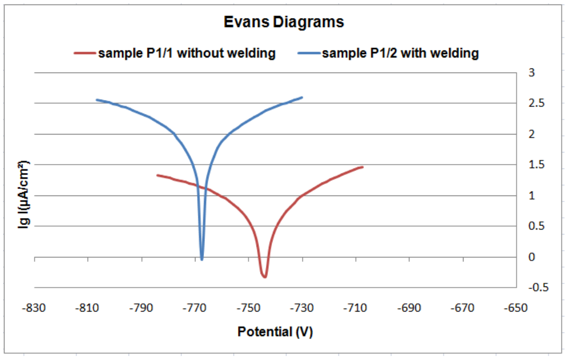


Fig. 13. Evans diagrams for unused specimens fromcoiled tubing with diameter D = 31.75 mm [15].

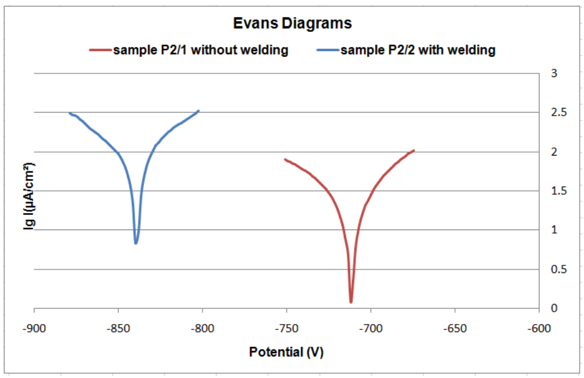


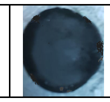
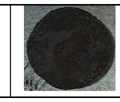
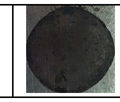
Fig. 14. Evans diagrams for coiled tubing specimens with 20 duty cycles, diameter D = 31.75 mm [15].

In the bias curves the potential sweep range was between (-1 …. 1) V, with a scan rate of 0.1667 mV/sec. Resistance values Rp were calculated from Tafel curves as the slope of the plot of potential versus current density at intensity, i = 0.

Table 7

The results of corrosion testing [15].

Sample type	**P1 unused material**		**P2 material with 20 working cycles**	
	P1/1 without a weld seam	P1/2 with a weld seam	P2/1 without a weld seam	P2/2 with a weld seam
R_p (Ω cm^2)	1540	103.94	337.41	120.34
E_{corr} (mV)	-744.1	-767.6	-712.8	-839.0
i_{corr} (μA/cm^2)	4.8078	65.8626	37.825	63.7214
C_{rr} (mm/an)	0.0558	0.7654	0.4326	0.7405

Corrode d samples				

The speed of corrosion C_{rr}, in mm/year, was calculated using the relationship:

$$C_{rr} = i_{corr} \cdot K \cdot \frac{EW}{A} \cdot \rho \qquad (1)$$

where: i_{corr} is the intensity of corrosion in A/cm^2); K – constant defining the units for corrosion rate (0.003272 for corrosion rate given in mm/year), EW – equivalent weight, in grams/equivalent; ρ – density in g/cm^3; A – sample surface in cm^2.

Analyzing the corrosion rates in Table 7, it is observed that the specimens with a weld seam, samples P1/2, P2/2, have higher corrosion rates than those without a weld seam, samples P1/1, P2/1.

A roll of flexible tubing is used per year (70 ... 80) cycles of 12 hours each in the working environment. While the tubing is not in service, it is subject to atmospheric corrosion.

Samples were taken from the tubing material, which, after weighing with an analytical balance, were immersed, and left in the deposit water for 12 hours, then they were taken out and left in the room, at a temperature of 15 ^{o}C, for 72 hours. After this period, the samples were weighed and the corrosion rate was determined. Using this method, it was obtained:

- m_i - m_f = 3.5823 g – 3.5777 g = 0.0046 g (where: m_i is the initial mass; m_f – final mass of sample).
- corrosion rate in air: $C_{rr\ air}$ = 0.1284 mm/year.

Considering the duration of the operation of the tubing in the reservoir water and the time it is subjected to atmospheric corrosion, using in the calculation the average value of the corrosion rates in the reservoir water (table 7), $C_{rrmedia}$ = 0.4985 mm/year and $C_{rr\ air}$ = 0.1284 mm/year, a tubing corrosion rate was obtained: $C_{rr\ tubing}$ = 0.1689 mm/year.

Using in the calculation the highest value obtained for the corrosion rate in the deposit water, C_{rr} P1/2 = 0.7654 mm/year (table 7) and $C_{rr\ air}$ = 0.1284 mm/year, the following were obtained:

- in working environment: (840 hours × 0.7654 mm/year): 8760 hours/year = 0.0733 mm/year
- in air: (8760 - 840) hours/year × 0.1284 mm/year: 8760 hours/year = 0.1160 mm/year

The corrosion rate of the tubing material: $C_{rr\ tubing}$ = 0.1893 mm/year.

4. CONCLUSIONS

The main conclusion of the tests is that only through a continuous monitoring of the main mechanical parameters of the coiled tubing it is possible to assess its remaining operational life.

The correlation between all the factors which affects the coiled tubing operational life is difficult to establish, however, it could be done if the information regarding material properties is well known.

Tests were carried out to determine the mechanical and technological characteristics of the flexible tubing material, which aimed to determine the hardness, tensile tests, and the flattening test. The purpose of these determinations consisted in verifying the characteristics obtained through proper tests with those specified in the material standards (A606, API RP5C7), as well as how the obtained indicators evolve according to the number of operating cycles of the flexible tubing.

The analysis of the obtained values confirms good resistance and tenacity characteristics of the flexible tubing material.

The determination of the corrosion rate is important in the calculation of the life of the tubing, considering that it can thus determine the reduction of the wall thickness over time, and together with the determination of the maximum number of stress cycles, the life of the tubing will be evaluated.

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Cercetări experimentale privind caracteristicile de rezistență la coroziune ale materialului A606 utilizat la confecționarea tubingului flexibil

Rezumat: *În cadrul echipamentelor componente ale instalațiilor de foraj, tubingul flexibil (CT) reprezintă elementul principal care realizează manevrarea sculelor de foraj pentru a efectua diverse lucrări.*

În condiții de exploatare, CT este supus la solicitări complexe, care se pot manifesta static şi dinamic, sub acțiunea sarcinilor funcționale (forțe, momente de torsiune, presiune, temperatură etc.). La aceste sarcini se pot adăuga acțiunea factorilor corozivi şi de fragilizare specifici mediului de lucru.

În acest context, programul încercărilor experimentale a vizat stabilirea compoziției chimice a materialului, analiza macro şi microstructurală, comportarea la coroziune în diferite medii de lucru (apă de sondă, soluție de acidizare, aer etc). Rezultatele testelor efectuate arată că numai printr-o monitorizare continuă se poate stabili durata de viață a tubingului flexibil.

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