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RESEARCH AND STUDIES ON FLEXIBLE TUBING WEARING

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Abstract: *Flexible tubing (coiled tubing) demonstrated its capabilities and has been becoming nowadays a necessity in the oil and gas industry. Within the applications of flexible tubing have to be mentioned inclined drilling or horizontal drilling, cleaning clogged wells, interventions on wells both on production wells and during the drilling activities. The flexible tubing used in exploitation and/or operating the wells should meet the following requirements: tensile strength resistance collapse resistance, fatigue strength, corrosion resistance and resistance to fragilizant factors. In particular, the damages that may occur with respect to the functionality loss of flexible tubing are manifested by breakage or loss of tightness, excessive plastic deformation, bumping, and breakage. During the use of the flexible tubing in the well, it undergoes a series of stresses that lead to wear and degradation, changes in dimensional, geometric and mechanical characteristics. The paper presents the theoretical and experimental studies performed in order to establish the admissibility conditions regarding the mechanical and dimensional characteristics (shape deviations) of the material, the influence of working environments on the state of operation of the flexible tubing.*

Keywords: *flexible tubing, mechanical characteristics, geometric characteristics, corrosion, wear.*

1. ASPECTE GENERALE

For drilling equipment the tubing column is one of the key elements. The crisis of fossil fuels in parallel with the high demand of oil has been leading to deeper bore hole drilled in the search for this key resource as well as in the development of new drilling technologies as guided horizontal drilling, arborescent drilling. These challenging tasks are demonstrating that classic, segmented columns cannot be used since the threaded joint is not resisting to the high requirements of these applications. At the same time economical pressure to conduct in the shortest possible time the needed intervention at the wells such as cleaning, removing colmatation, rectification of the bore whole or extraction of damaged tools cannot be fulfilled with segmented columns [1].

The development of new materials and new welding technologies generated the opportunities for the development of flexible, flexible tubing (coiled tubing). In all the applications where it is used drilling, well interventions, the flexible tubing is reducing the time and consequently the operational costs of activities conducted.

In all the conducted activities on the flexible tubing is applied a lot of stress and in addition is prone to erosion and corrosion. All these are leading to wearing and sometimes modifications of its physical and geometrical properties. Thus it is obviously necessary that all the wearing factors to be considered, monitored and taken into calculation in order to establish properly the degree of flexible tubing wearing in order to analyse the risk of using it in further operations.

The main factors which affect flexible tubing wearing depend on well specific requirements (whole diameter, depth, deviation) as well as different operations required in the drilling process (acidulations boring, milling, transportation of special instrumentations packages, tools recovery, washing, circulation of different fluids etc.).

In this context this article presents the research conducted for establishing the mechanical characteristics of the flexible tubing used in the intervention equipment.

2. TYPES OF STRESS APPLIED TO FLEXIBLE TUBING

On the flexible tube there is applied at the same time and at the same operation a complex stress (Fig. 1), which generates an accelerate wearing and consequently decrease its operational life.

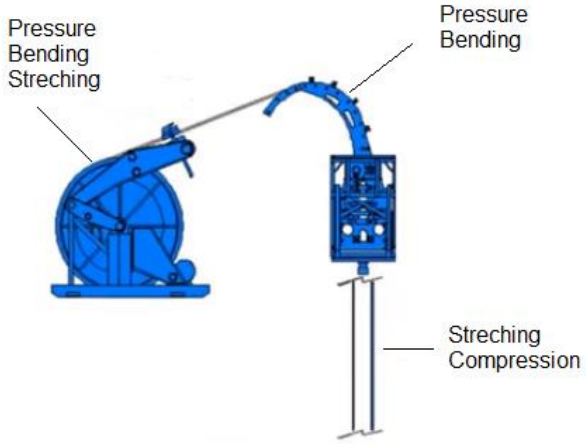

Figure 1. Types of stress applied to flexible tubing [1]

Every time when the flexible tube is coiled / uncoiled and is pushed/pulled through the injector it is affected by bending, compression, stretching as presented in Fig. 1. In addition, on the flexible tubing are acting pressure forces both from inside and outside.

Areas were the flexible tubing is stressed (bending, stretching, compression, traction, inside outside pressure) are presented in Fig. 2 as follows: introduction step (1, 2, 3), extraction step (4, 5, 6).

An operational cycle for the coiled tubing consists of all the phases required for fulfilling the operation staring with the uncoiling from the drum, insertion on the well bore, drilling, rectifying, washing, removing damaged parts etc., extraction from the bore well and coiling it on the drum as presented in Fig. 2. By following these operations there, it could be identified six bending steps as could be seen also in Fig. 2.

There should be mentioned that the stress applied to the flexible tubing should not be greater than the limits established by the producer for material. However, if these limits are overcome cold lead to a premature fatigue of the flexible tubing or even worst in its physical deformation making it unusable.

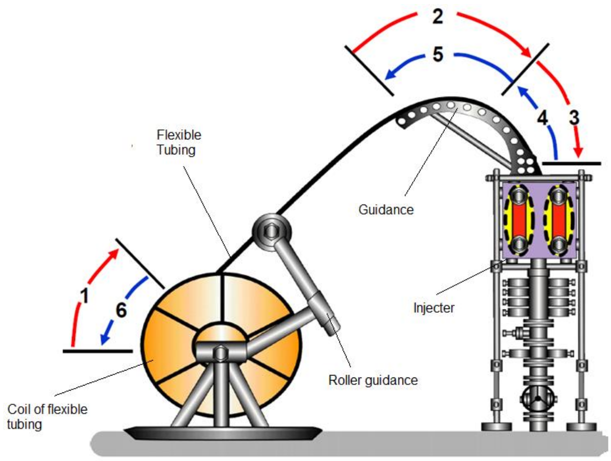

Figura 2. Flexible tube areas which are under cyclical bending stress [2]: Flexible tube introduction in well bore (1-2-3); Extraction of flexible tube from well bore (4-5-6).

In addition to the stress factor described previously there are other factors which contribute to the flexible tubing wearing: corrosion generated by the liquid medium from the well bore (salty water, different non neutral PH liquids, etc.) and erosion due to the touching the walls of bore well and due to mineral particles existing in the liquid working medium.

Taking into account all the stress, corrosion and erosion factors and assessing their impact on the flexible tubing there it could be established the wearing degree as well as the risk coefficient for using the coiled tubing in further applications. Consequently, research and studies regarding coiled tubing wearing are very important in establishing its operational life and thus avoiding accidents with human and financial losses.

3. ESTABLISHMENT OF EXPERIMANTAL DETERMINATION PROGRAME

The experimental determination programme has the goal to establish mechanical and geometrical (shape deformations) of coiled tubing. In addition in order to establish the impact of corrosion on flexible tubing there was conducted experimental research using different liquids used in the drilling or intervention processes.

Input data used for conducting the planned tests as well as the output data (measurement results, calculation based on output measurements) are presented in Fig. 3.

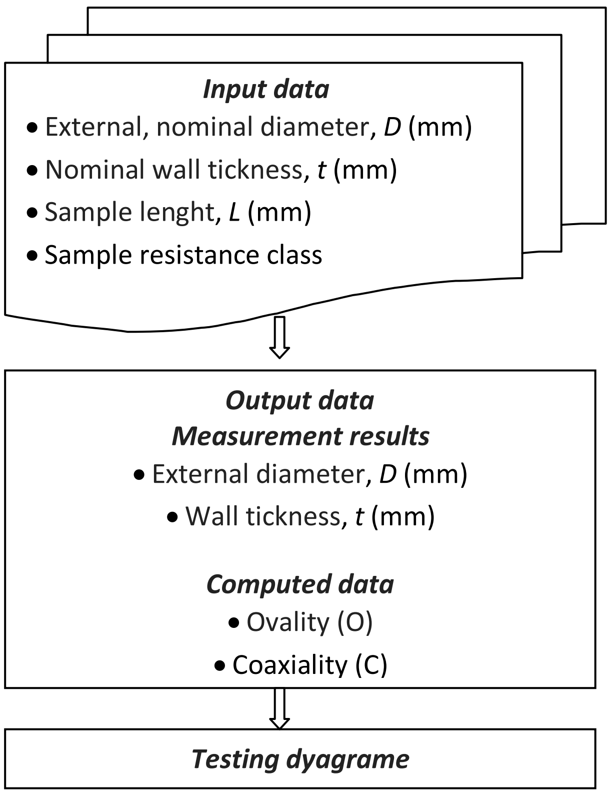

Figure 3. Establishment of testing conditions for flexible tubing.

The programme of experimental research encompasses the tests as are presented in Table 1.

The classification of samples used in the programme of experimental testing is presented in Table 2.

Table 1. Programme of experimental research

Type of test/ determination	Characteristic specifications
Determination of geometrical characteristics of studied flexible tubing	• External nominal diameter, *D* (mm) • Nominal thickness of wall, *t* (mm) • Sample length, *L* (mm) • Ovality (O) • Coaxiality (C)
stretching testing of flexible tubing	• Tensile strength (R_m) • Yield strength (R_c) • Elongation after breaking (A)
Corrosion tests for flexible tubing	• Polarization resistance (R_p) • Corrosion potential (E_{corr}) • Corrosion current density (I_{corr}) • Corrosion rates (C_{rr}).

Table 2. Classification of samples used in the programme of experimental testing

Sample	Marking on the testing sample	Number of functional hours
P1	P1/1	New flexible tubing (0 operational functioning hours)
	P1/2	
	P1/3	
P2	P2/1	Tubing with 30 full operation conducted
	P2/2	
	P2/3	

In Table 3 are presented the geometrical characteristics of tested samples.

Table 3. Geometrical characteristics of tested samples

Tested sample (D = 1½ in) (*D* = 38,10 mm)	
External nominal diameter, *D* (mm)	38,1
Nominal wall thickness, *t* (mm)	2.76
Length of sample, (mm)	400

The tested flexible tubing was made off A 606 steel, this material presents a high resistance to atmospheric corrosion [3]. According to ASTM standard, chemical composition and main mechanical characteristics are as presented in Tables 4 and 5.

Table 4. Steel A606, chemical composition [3]

Steel standard	Chemical composition (%), max.		
	C	Mn	S
A606	0.26	1.30	0.06

Table 5. Material A606 – mechanical characteristics [3]

Steel standard	mechanical characteristics, min.		
	Tensile strength, MPa (ksi)	Yield strength, MPa (ksi)	Elongation %
A606	450 (65)	310 (45)	22

3.1 Establishment of geometric characteristics of flexible tubing

In order to establish the testing parameters for the experiments to be conducted first step is to identify testing sample as presented in Fig. 4. The measurements are conducted in six measurement planes (1, 2, 3, 4, 5, 6), equally distributed on the tube generator at 2D distance one for other. In each measurement plane will be conducted 8 measurements on the circumference (A, B, C, D, E, F, G, H) – angular these points being placed at 45^0.

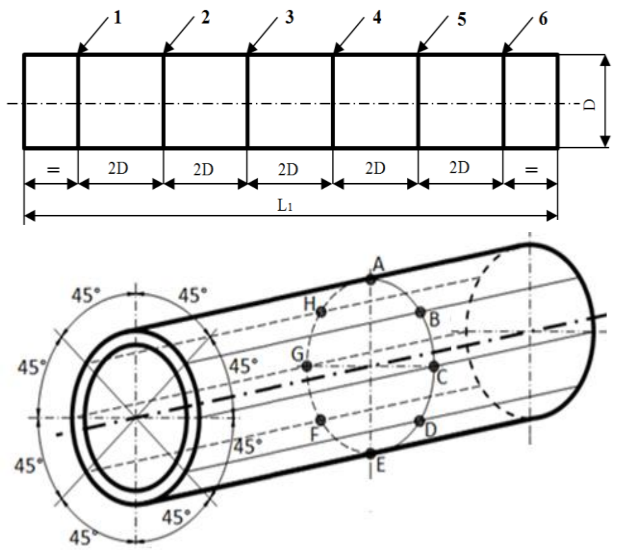

Figure 4. Establishment of geometrical characteristics of test samples:

D –external diameter; L_1 – minimum length of tested sample; *1, 2, 3, 4, 5,6* – five areas in plane for each being measured external diameter, and wall thickness.

The dimensions of external diameters and wall thickness according to the catalogue data are presented in Table 6 [4].

Table 6. External diameters and wall thickness [4]

External diameter (D)		Wall thickness (t) (mm)
(inch)	(mm)	
1,000	25,40	2,41 - 3,17
1,250	31,75	2,41 - 3,96
1,500	38,10	2,59 – 4,77

Hereunder is presented the methodology of measurements conducted on samples from P1 and P2 classes.

First set of measurements are conducted in order to verify external diameter of tubing (*D*) in each measurement plane (1, 2, 3, 4, 5, 6) and on each position established on the circumference (A-E, B-F, C-G, D-H). The same measurements are conducted for wall thickness (*t*) in each measurement plane (1, 2, 3, 4, 5, 6) and on each position established on the circumference (A-E, B-F, C-G, D-H). The obtained results for sample P1/1 are presented in Tables 7 and 8.

Table 7. Measured values of external diameter

Measured values of external diameter, *D* (mm) – sample P1/1						
Position	"1"	"2"	**"3"**	**"4"**	"5"	"6"
A-E	37.51	37.56	37.56	**37.58**	37.61	37.66
B-F	37.85	37.76	37.96	**37.78**	37.92	37.84
C-G	37.75	37.74	37.99	**37.85**	37.7	37.71
D-H	37.51	37.52	37.74	**37.33**	37.67	37.87
Average	37.655	37.645	37.813	**37.635**	37.725	37.77

Table 8. Measured "t "values and calculated values of "E "and" O" for sample for P1/1

Measured "t" values and calculated values of "E" and "O" for sample for P1/1						
Position	"1"	"2"	**"3"**	**"4"**	"5"	"6"
"A"	2.72	2.70	**2.67**	**2.67**	2.74	2.66
"C"	2.63	2.68	**2.67**	**2.60**	2.62	2.66
"E"	2.60	2.68	**2.62**	**2.62**	2.66	2.69
"G"	2.67	2.69	**2.60**	**2.68**	2.60	2.67
Average	2.65	2.68	**2.64**	**2.64**	2.65	2.67
Excentricity (%)	$E = [(t_{Max} - t_{Min}) / t_{med}] \times 100$					5.243
Ovality (%)	$O = [(D_{Max} - D_{Min}) / D_{med}] \times 100$					1.752

Measurements of the flexible tubing was conducted by using the ultrasonic portable measurement device, OLYMPUS 38DL Plus, which is capable of measuring thickness from 0,1 up to 635,0 mm. Based on the obtained results were calculated eccentricity (*E*) and ovality (*O*) according to the relationship presented in Table 8.

Based on measured parameters for sample P1 and P2 there were established the variations of diameters for each measurement plane (1, 2, 3, 4, 5, 6) and on each point of circumference (A-E, B-F, C-G, D-H). The obtained graph for P1/1 is presented in Fig. 5.

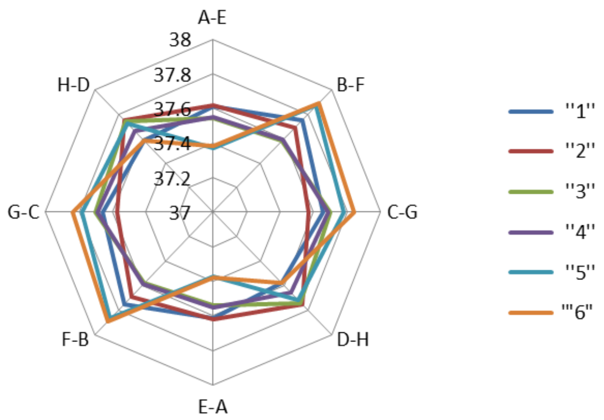

Figure 5. The variations of external diameters (D) for sample for P1/2

The geometric characteristics of flexible tubing have an important impact on its behaviour during the exploitations since a smaller external diameter or a smaller thickness of the wall are possible areas of flexible tube breaking.

3.2 Stretch testing of the flexible tubing

In real life the flexible tubing is under various types of stress which are almost impossible to be reproduced in laboratory. Usually the tests conducted in laboratory are verifying one by one different types of stretch, thus the monoaxial stretch is one of the most important tests [3].

The stretching test is conducted applying an axial growing force to a sample of material usually until the sample is breaking. To the entire period of testing data related to sample elongation correlated with the applied force are recorded. For the conducted tests was used the Walter Bay LF300 universal testing device. This equipment is designed to be used for both static and dynamic tests having the capacity of applying a force 300 in static regime and ± 250 kN with a frequency of up to la 20 Hz regime and is presented in Fig. 6.

Figure 6. Walter Bay universal testing equipment.

The tests were conducted on the two samples P1 (new flexible tubing) and P2 (30 cycles conducted) and the samples are presented in Fig. 7.

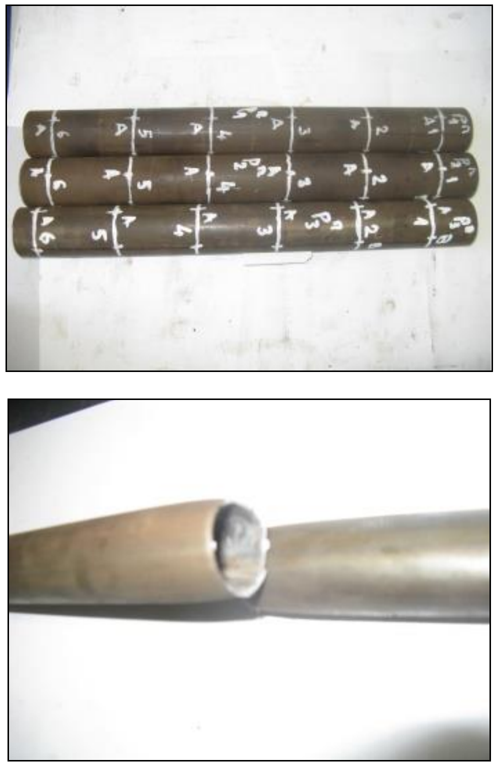

Figure 7. Tested samples

The results obtained after testing the samples are presented in Table 9.

Table 9. Strength measured values for the samples of flexible tubing.

Sample	Measured values
Sample P1 –Flexible tubing 0 hours of operations	
P1/1	D_{med} = 37.66 mm; t_{med} = 2.67 mm; S_0 = 104.28 mm^2
	R_m = 637MPa; R_c = 608 MPa; A = 21.9 %
P1/2	D_{med} = 37.63 mm; t_{med} = 2.725 mm; S_0 = 106.301 mm^2
	R_m = 633 MPa; R_c = 582 MPa; A = 21.4 %
P1/3	D_{med} = 37.68 mm; t_{med} = 2. 71mm; S_0 = 104.397 mm^2
	R_m = 633 MPa; R_c = 582 MPa; A = 22.8 %
Sample P2 – Flexible tubing with 30 cycles of operations	
P2/1	D_{med} = 37.88 mm; t_{med} = 2.765 mm; S_0 = 107.22 mm^2
	R_m = 620 MPa; R_c = 598 MPa; A = 17.61 %
P2/2	D_{med} = 37.835 mm; t_{med} = 2.82 mm; S_0 = 107.22 mm^2
	R_m = 611 MPa; Rc = 588 MPa; A = 20.48 %
P2/3	D_{med} = 37.77 mm; t_{med} = 2.775 mm; S_0 = 106.63 mm^2
	R_m = 620 MPa; R_c = 588 MPa; A = 20.9 %

In the Table 9 were used the following notations: D_{med} – average of measured diameters; t_{med} – average of wall thickness; S_0 – surface of breaking surface; R_m – tensile strength; R_c – yield strength ; A – elongation at breaking.

According to the obtained results it could be established that plasticity index (A – elongation) in lower at P2 samples that at P1 samples, while breaking resistance and limit of flow does not have significant variations.

These results shows that the material of which the flexible tubing is made of is going through a process of cold hardening due to the complex stress generated by operational use (stretching, compression, stretching combined with internal pressure, bending combined with internal pressure and external pressure due to roller guidance's from the injection head).

In regard with the geometry (*D*, *t*) of the samples used another important observation is that the tested samples broken in the areas of variations of diameter and thickness where these two parameters had the minimum value.

3.2 Corrosion testing of flexible tubing material

The corrosion resistance was tested on six samples taken from flexible tubing (three form the new and 3 from the one with 30 operational cycles).

The samples were taken both from area were the flexible tube was welded and area without any weld as presented in Figure 8. The cutting of samples was conducted in less intensive regimes in order to avoid introduction of additional stress in the structure of material.

a b

Figure 8. Samples to be tested:
a – from welded area; b – area without weld.

The sample surface which should be in contact with the liquid was rectified and polished with abrasive material with a granulation of 600 Mesh. The liquid used for testing was the liquid taken from a functional well and has the chemical composition presented in Table 10.

Table 10. Well liquid chemical composition

Components	Measured value	U.M.
pH	7.2 at 15.9 ^{0}C	unit. pH
Calcium	2450	mg/L
Magnesium	1020	mg/L
Sodium	30100	mg/L
Sulphate (SO4)	64.8	mg/L
Chlorate (Cl^{-})	56800	mg/L
Bicarbonates (HCO3)	296	mg/L

The pH was measured with PHM201 MeterLab (Radiometer) with a combined electrode Ag/AgCl. For testing was used the Volta Lab PGZ 100 potențiostate and an electrochemical cell according ASTM G5. The electrochemical cell consists of a glass vessel, a Haber-Luggin capillary installed on a special fixture, two graphite electrodes in series as counter, a reference electrode made of saturated Calomel and the third one which was the sample. The setting is presented in Fig. 9.

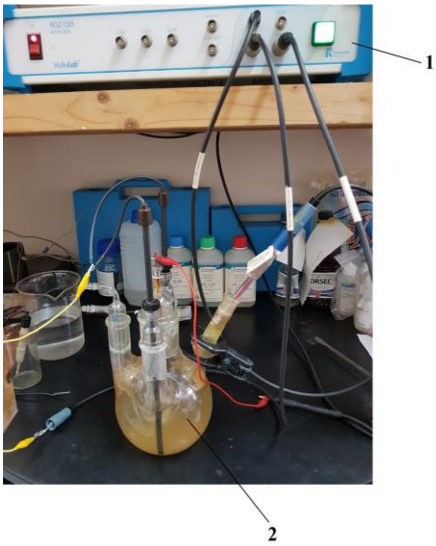

Figure 9. The experimental testing used for testing the corrosion:

1 –Volta Lab PGZ 100 potentiostate;
2 – Electrochemical cell.

The holder of the sample was made of Teflon with an opening with the surface of 1 cm^{2} through this opening the sample getting in contact with the well liquid. In front of the opening was fixed the capillary tube.

There were acquired the polarization curves and Evens diagrams containing Tafel lines. From these outputs there were established polarization resistance (R_p), corrosion potential (E_{corr}), corrosion current densities (i_{corr}), and corrosion rates (C_{rr}). The results are presented in Figs. 10-13 and Table 11. For the polarization curves the limits of balancing were between -1 and 1V with a speed of 1mV/sec.

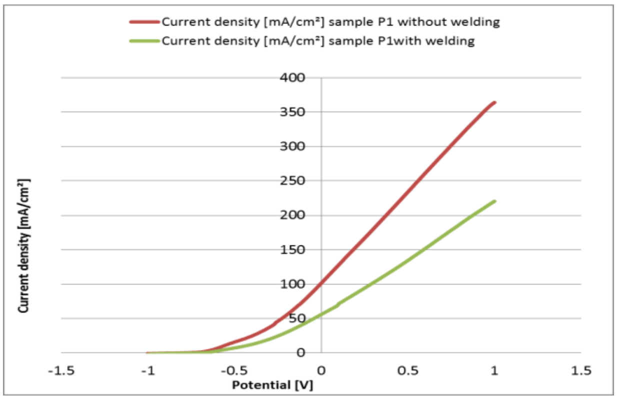

Figure 10. Variation of current density in regard with potential for the not used flexible tube sample

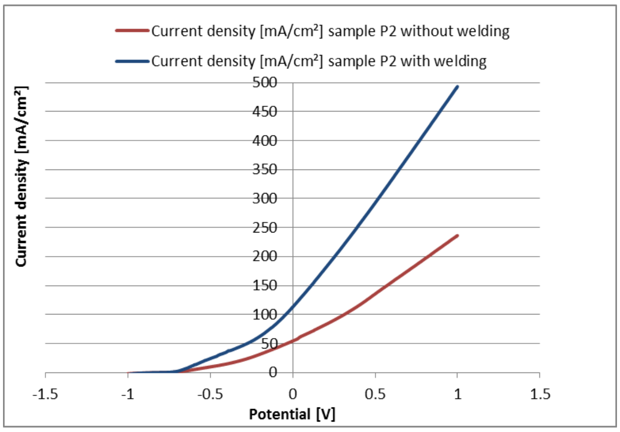

Figure 11. Variation of current density in regard with potential for the sample taken from flexible tube with 30 cycles of use.

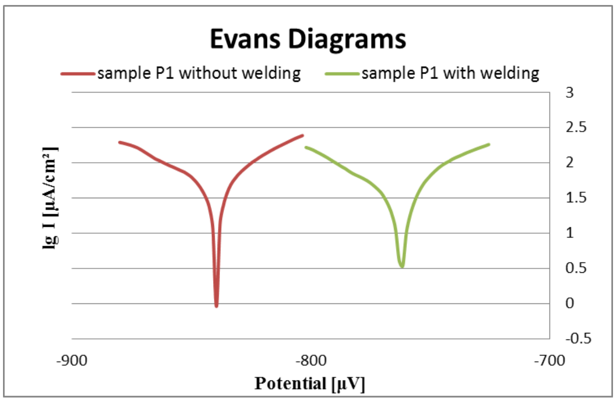

Figura 12. Evans diagram for the not used flexible tube sample

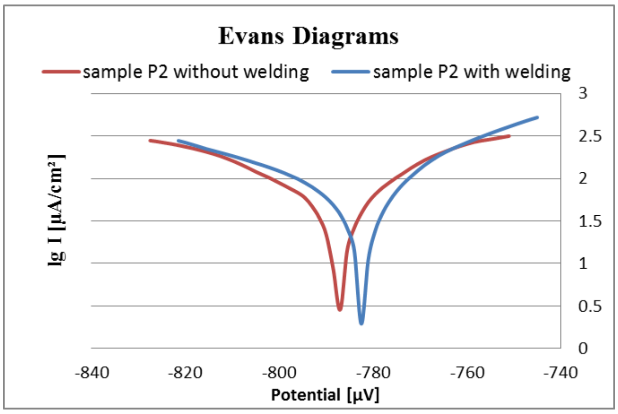

Figure 13. Evans diagram potential for the sample taken from flexible tube with 30 cycles of use

Table 11. Results of experimental testing

Sample Type	R_p ($\Omega.cm^2$)	E_{corr} (mV)	i_{corr} ($\mu A/cm^2$)	C_{rr} (μm/year)
P1/2	191.900	-839.0	39.724	461.600
P1/3	239.130	-761.8	27.772	322.700
P2/2	134.840	-787.0	40.368	469.100
P2/3	121,630	-782,4	64,643	751,200

The conducted tests show that the samples present a good resistance to corrosion in the medium specific to the wells; however, the values of i_{corr} should be at lower level and R_p should be at high values in order to obtain these results.

Taking into consideration the criterion described previously we could observe that samples taken from the new flexible tubing P1/3, are more resistant to corrosion than the sample P1/2. This behaviour could be explained due to the fact that the chosen welding material is more resistant to the corrosion, or the welded areas were treated after welding. The same behaviour could be observed studying corrosion rates for the two samples.

The sample taken from the flexible tubing with 30 cycles of operational use we could observe a different behaviour; the sample with welding on it P2/3, had a higher rate of corrosion that one with no welding on it P2/2. This could be explained by the fact that during the 30 operational cycles conducted, the surface treatment was eroded / corroded and the welded area is less resistant than the other one.

A coil of flexible tubing is used an average of 80 cycles/year, and a working cycle with an average of 12 hours duration. When is not used in operations, the flexible tubing is also affected by atmospheric corrosion. A reliable monitoring system of flexible tubing wearing must take into consideration the effect of atmospheric corrosion on the flexible tubing state of health.

In order to establish the corrosion velocity in atmospheric conditions there were taken three samples from the flexible tubing P1. The weight of each of the three samples was recorded and samples were introduced in well liquid. Samples were taken out of the liquid and let in a controlled temperature room at 15 ^{0}C for 7 days. After that the weight of the samples was recorded and the corrosion rate was determined according to NACE SP0775-2018-SG standard [8]. Using this method the corrosion rate calculated was C_{rr} air = 0.154 mm/an.

Taking into consideration the statistical data regarding operational use and time of sitting on standby and being affected by atmospheric corrosion there it was obtained a corrosion rate of C_{rr} tubing = 0,214 mm/year (C_{rr} P2/3 = 751.200 mm/year (Table 11) and C_{rr} air = 0.154 mm/year).

It could be observed that traces of well liquid which remain on the flexible tubing could severely affect speed of corrosion consequently it is highly recommended to clean the liquid from the tubing both from inside and outside.

4. CONCLUSIONS

Flexible tubing used in well related operations is prone to complex stress which could lead to its premature wearing, consequently to reduce the operational life. Some of the first indications of flexible tubing wearing are the modification of tubing geometry. These local modifications also depend on the quality of injection system, and different length of the wells operated. When used for deep wells (over 3000 m) due to friction with well bore walls and elongation generated by its own weight the diameter and wall thickness of flexible tubing are smaller and the danger of breaking it is higher.

Simultaneous stretching and pressure stress accelerates the wearing of flexible tubing and consequently reduce its operational life. In addition when it is used for horizontal applications the friction with well bore walls increases consequently the force for pushing/puling the tools are greater and the elongation increases.

In order to develop a reliable system for assessing the wearing of flexible tubing one first step to be considered is the monitoring the modifications occurred in geometry of tubing: external nominal diameter (*D),* wall thickness *(T),* ovality *(O)*. When considered the corrosion then the thickness of the tubing wall is also decreasing significantly.

As monitoring methods to be used there could be mentioned the followings:

a) Periodic visual verifications looking for geometrical modifications.
b) Periodic measurement of flexible tubing wall thickness (the measurement should be conducted on different segments in order to avoid mistakes).
c) Periodic measurement of flexible tubing coil weight and length (this situation gives a better information on corrosion and elongation).

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