IOP Conf. Series: Materials Science and Engineering **724** (2020) 012004 doi:10.1088/1757-899X/724/1/012004

Research on mechanical and geometrical characteristics of materials used for flexible tubing production

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Abstract. Coiled tubing used in operational exploitation of oil and gas wells are made of special steels which have to resists to some special requirements such as: tensile strength, internal pressure resistance, collapsing resistance, fatigue strength, corrosion resistance and action of weakening factors. It is interesting that various producers are using different compositions of their steels obtaining quite different mechanical characteristics of the flexible tubing delivered on the market. This paper is presenting the experimental programme for mechanical tests conducted on materials used for production of flexible tubing and the results obtained during these tests. In addition to the materials testing there were studied geometrical characteristics of the flexible tubing such as wall thickness, ovality, cilindricity and their impact on operational life of the flexible tubing.

1. Introduction

Coiled tubing equipment has become a necessity in the petroleum and oil industry, being required in many important applications such as horizontal or arborescent drilling, unclogging old wells or in recovery of broken tools.

Whatever the type of applications it is used for, the coiled tubing is significantly reducing the operational costs due to the reduction of assembly time as well as possibility of introduction of the coiled tube into the well bore without dismantling eruption head. Areas were the flexible tubing is stressed (bending, stretching, compression, traction, inside outside pressure) are presented in figure 1 as follows: introduction step (1-2-3), extraction step (4-5-6) [1].

Whenever the coiled tube is uncoiled from the drum, and it is passing through the guidance head, there are complex bending/unbending processes which could have a great impact on material structure. In addition, the exploitation of the coiled tube, according to the working cycles presented on figure 1, generates complex stress in the material and could lead to permanent deformations, fatigue and material deteriorations. Another source of stress is the vibration induced by the pump which generates the pressure of the working fluid, however, before proceeding to laboratory tests it should be measured the pattern of these vibrations in the field using specialized equipment [2 - 4].

In order to ensure the required state of health of the coiled tubing all the stress induced in the material should not be greater than the one which may generate permanent deformations (to maintain the material into its elastic limits). Any physical deformation of the coiled tubing could lead to irremediable damage both to the equipment from the bore well and to the injector.

In table 1 are presented in a centralised manner all the parameters which should be monitored, in order to establish the state of health of coiled tubing.

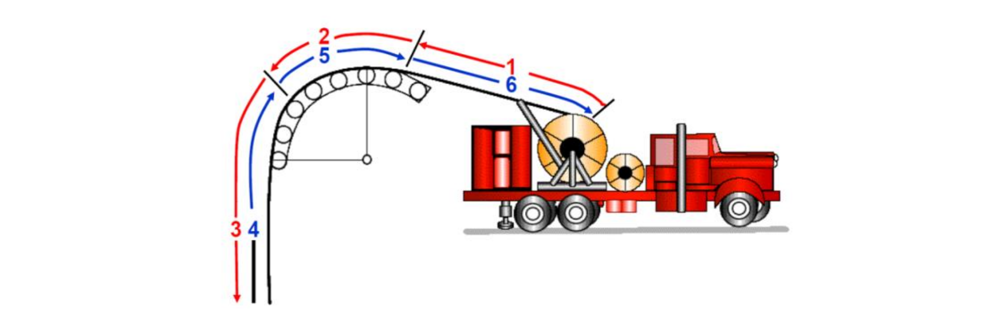

Figure 1. Coiled tube areas which are under a cyclic, repeated stress [1].
Well bore introduction cycle (1-2-3):
1. compression affected area, 2. bending and compression affected area; 3. area affected by traction;
Well bore extraction cycle (4-5-6):
4. traction affected area, 5. bending and compression affected area, 6. compression affected area.

Table 1. Parameters to be monitored in order to establish coiled tubing's state of health

Parameter/characteristics	Characteristic parameter
Functional technical characteristics of the equipment	• Traction force; • Speed of coiled tube introduction/extraction • Pressure on injector clamps; • Pressure of working fluid (pressure from inside of coiled tubing); • Pressure from outside (on the external walls of coiled tubing). • Vibration introduced by the working fluid pump (100-200Hz)
Mechanical characteristics of material from which coiled tubing is made off	• Traction breaking resistance (R_m) • Flow limit (Rp0,2) • Elongation after braking (percent) (A)
Geometric characteristics of coiled tubing	• External nominal diameter, D (mm) • Nominal thickness of coiled tubing wall, t (mm) • Ovality (O) • Coaxiality (C)
Coiled tubing resistance to corrosion	• Corrosion potential (Ecorr) • Corrosion current densities (Icorr) • Corrosion speed (Crr).

2. Exploitation generated stress in coiled tubing

Coiled tubing is affected by various and complex stress both during the operational phase (figure 2) and stationary phase (figure 3), all these accumulating and conducting to a reduction of its operational life.

The stress effects generated by exploitation could lead to:

- Ovalization of coiled tubing and this will decrease the surface of contact between the coiled tube and the clamps of the injection head. In this situation there could be situations when the

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injection head will not be capable to support the weight of the tubing, and this will get inside of the well bore driven by its weight, without any control.

- Reduction of coiled tube wall thickness and consequently decreasing the resistance to the external or internal pressure. The reduction of wall thickness is the result of coiled tube elongation (overloads in exploitation) and/or erosion due to the various corrosive agents encountered in the drilling process (acidization, salty water, hydrogen sulphide H_2S etc).

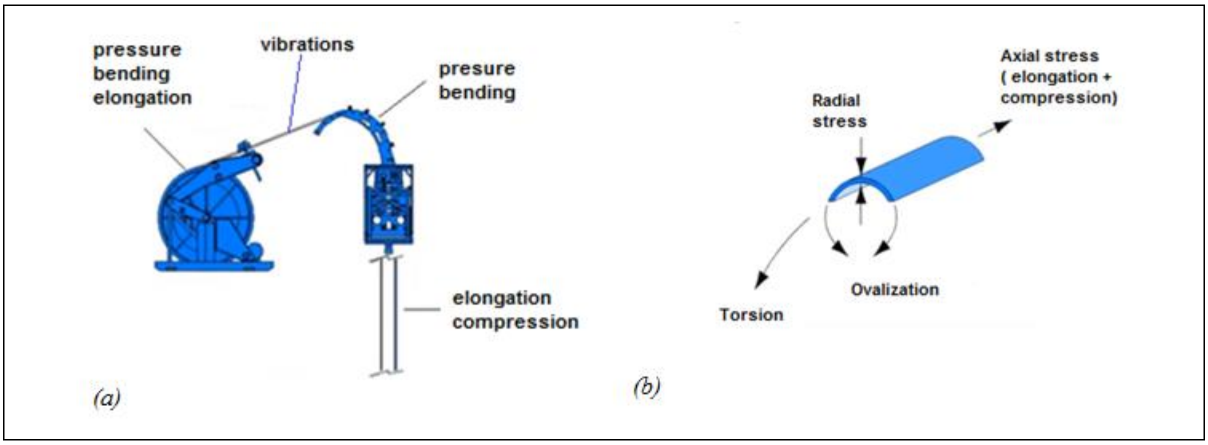

Figure 2. Stress affecting coiled tubing, coiled tubing introduction/extraction from/to well bore (a), stress represented in section of coiled tubing (b) [5]

Taking into account the issues presented a reliable system capable to provide reliable information concerning the state of health of the coiled tubing should monitor and record data regarding: nominal diameter wall thickness and ovalization of the coiled tubing.

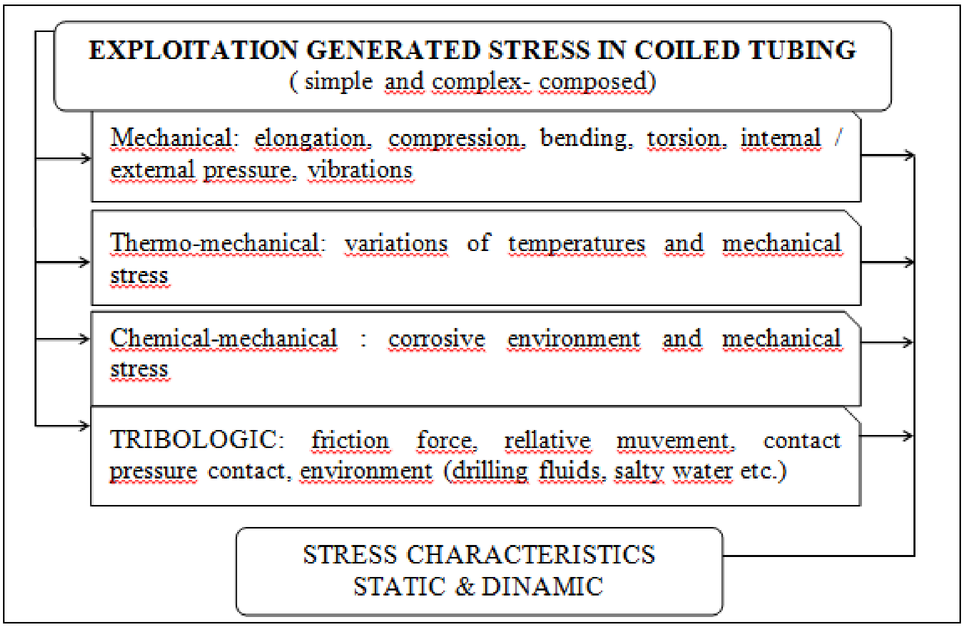

Figure 3. Exploitation generated stress in coiled tubing

3. Experimental research conducted

The experimental work conducted had the goal to establish the necessary state of health for the coiled tubing in order to ensure the required safety both for people and well during the operation of insertion/extraction. The coiled tubing is inserted/extracted in/from the well bore by using a device known as injector. The injector should provide the required force to introduce, extract and sustain the coiled tubing as presented in figure 4.

The injector assembly is designed to fulfil three main functions:

- provides the required force to introduce the coiled tubing inside the well bore acting against the internal pressure of the well and friction forces.
- control the speed of coiled tubing introduction when the weight of the tubing is pooling down the coil.
- sustain the weight of the column and speed up the extraction of the tubing during the extraction phase.

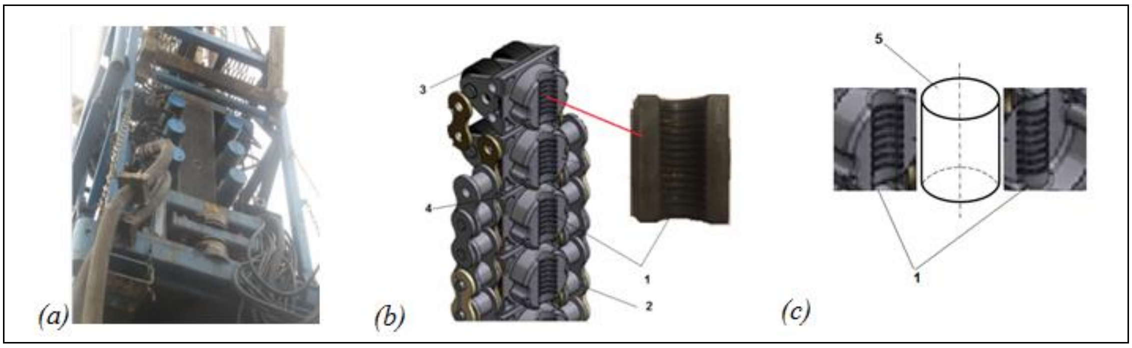

Figure 4. Coiled tubing injector assembly, injector assembly (a), fixing system with clamps (b) [6], clamps contact with the coiled tubing (c): 1. Clamps; 2. Chain; 3. Liaison roller; 4. Safety pin; 5. Coiled tubing.

Based on 4 pairs of clamps, hydraulically actuated, the injector generates the contact pressure (on the external side of coiled tubing), in order to pull and ensure guidance for it. The main working parameters for the injector assembly are: force pressing on clamp, geometrical dimensions of clamps, speed of chain, and the flow of working fluid, all of them being established in well working plan.

The state of health of equipment is established by the capability of injector to sustain the maximum weight of coiled tubing introduced into the bore well. This capability is based on the system of forces developed at the contact between the external surface of coiled tubing and internal surface of injector's clamps as presented in figure 5.

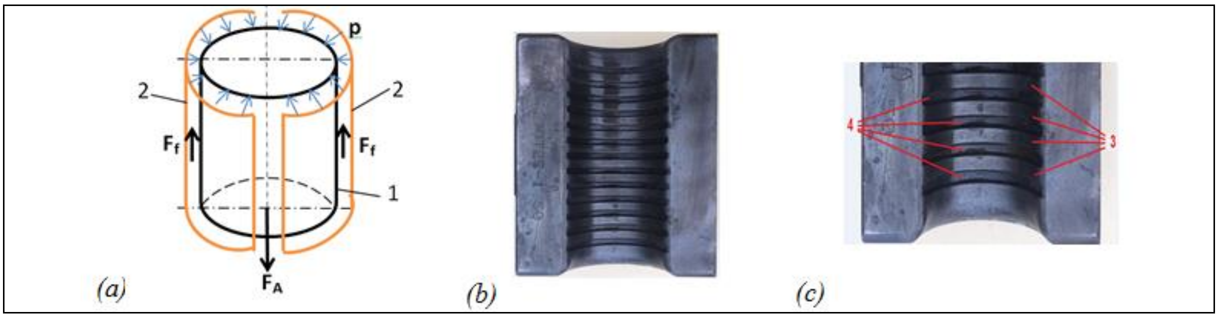

Figure 5. Injector assembly, Forces distribution schematics (a),clamp internal profile (b), geometry of clamp surface of contact with coiled tubing (c): F_f - slip friction forces, F_{A}- force generated by the weight of the column, p - pressure, 1. Coiled tubing, 2. Clamps, 3. Clamps usable surface of contact with coiled tubing, 4. Channel.

Injector functioning is based on slip friction forces (F_f) which occurs between the clamp and the external surface of the coiled tubing, as a result of perpendicular forces on the surface of contact is resulting the pressure p as presented in figure 5. During the extraction on the coiled tubing is auctioning a force (F_A) generated by the weight of the column:

$$F_A = m \times \mathrm{g} \tag{1}$$

were: m, the mass of the column of flexible tubing inside of the bore well and g, the gravitational acceleration (g = 9.81 ms^{-2}).

A proper functioning of the equipment requires to be fulfilled the condition:

$$F_A < F_f \tag{2}$$

According to [7] slip friction force is calculated with the relationship:

$$F_f = \mu \times A_r \times \tau_f \tag{3}$$

where: μ is the coefficient of slip friction at the contact of clamp with the coiled tubing; A_r is the area of contact between clamp and coiled tubing; τ_f – shear resistance of coiled tube material.

The value of slip friction force depends on slip friction coefficient μ, which could be affected by several factors such as clamp geometry, greasing material, clamp or coiled tube oxidation, the type of material used for clamps etc. The recommended values for slip friction coefficient μ are μ = (0.07 …0.16) [1].

According to [7] shear resistance τ_f of the coiled tubing material is calculated by using formula:

$$\tau_f = (0.2 \ldots\ldots 0.3) \times R_{p0.2} \tag{4}$$

where: $R_{p0.2}$, the flow limit of the material..

Based on the previous presented issues it was decided to focus the research on the establishment on impact of stress affecting the geometrical characteristics of coiled tubing. According to the manufacturing specifications the coiled tube is made off A 606 steel, and based on the ASTM A standard the mechanical characteristics of this material are presented in table 2. The experiments were conducted on coiled tubing samples as presented in figure 6.

Table 2. Physical characteristics of A606 steel [8]

Material	Mechanical characteristics (min)		
	Traction resistance R_m, MPa (ksi)	Elasticity limit $R_{p\,0.2}$, MPa (ksi)	Elongation, %
A606	450 (65)	310 (45)	22

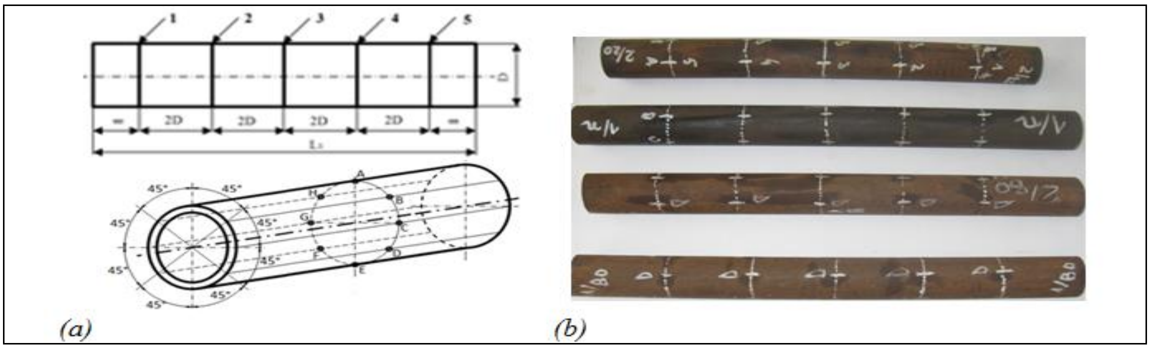

Figure 6. Geometrical characteristics of samples, sample design (a), Four different samples (b): D – External diameter, L_1 – minimum length of tested sample, *1, 2, 3, 4, 5* – Five different zones for each being measured external diameter and wall thickness.

The equipment used for tests is INSTRON 600 LX. The tests results are presented in table 3. The values obtained during the conducted tests (table 3) are certifying that the material is fulfilling the provision of ASTM A 606 Standard as presented in table 2. According to the types of samples measured (figure 6) and exploitation conditions (table 3) there were conducted measurements of geometrical characteristics of sample P3 from coiled tubing as presented in table 4.

Table 3. Experimental results

Sample code[a]	Measured characteristics[b]
P1 – sample taken from coiled tubes with 0 hours of functioning	Elasticity limits $R_{p\,0.2}$ = 509 (MPa) Traction resistance R_m= 645 (MPa) Elongation = 22.78 (%)
P2 – sample taken from coiled tubing used for 30 operational cycles	Elasticity limits $R_{p\,0.2}$ = 502 (MPa) Traction resistance R_m= 636 (MPa) Elongation = 22 (%)
P3 – sample taken from coiled tubing used for 80 operational cycles	Elasticity limits $R_{p\,0.2}$ = 435 (MPa) Traction resistance R_m= 587 (MPa) Elongation = 22 (%)

[a] Geometrical characteristics of samples are: external nominal diameter, *D* = 38.1 (mm), nominal wall thickness, *t* =2.76 (mm), sample length L = 400 (mm).
[b] Presented values are calculated as the average of tree measurements conducted in similar conditions.

Variations of coiled tubing external diameter correlated to each measured areas ("1", "2", "3", "4", "5") and each marked position (A-E, B-F, C-G, D-H) is presented in figure 7.

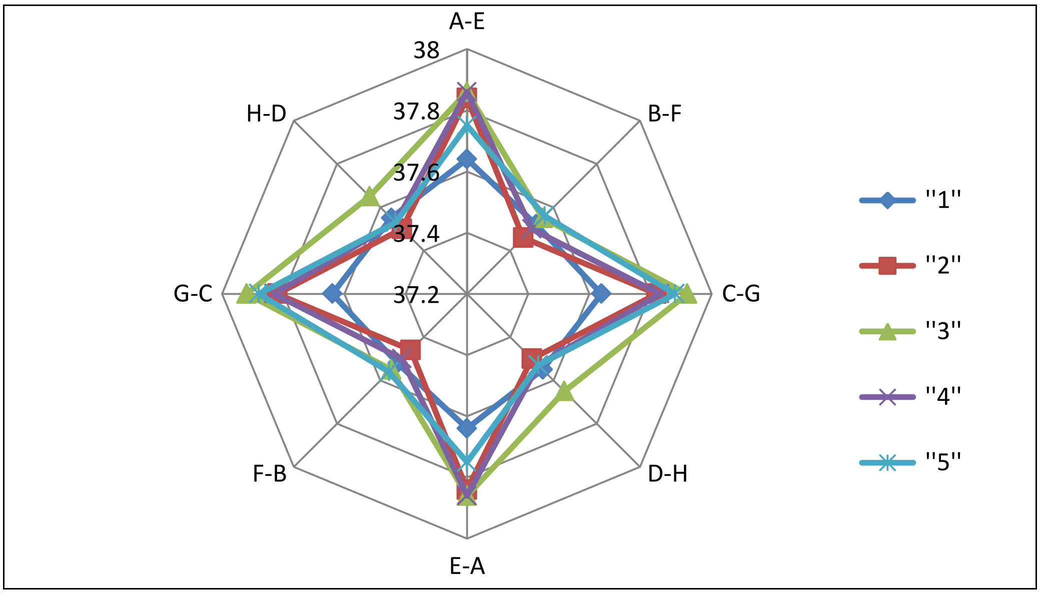

Figure 7. Variations of coiled tubing external diameter, D for sample P3.

Table 4. Measurements of geometrical characteristics conducted on Sample P3.

Sample P3 / (D = 1 1/2 in, 38.1 mm), 80 cycles of operation						
Measured values of wall thickness, t (mm)						
Position	"1"	"2"	"3"	"4"	"5"	Average
"A"	2.820	2.850	2.840	2.980	2.800	2.858
"C"	2.700	2.900	2.950	2.840	2.750	2.828
"E"	2.920	2.980	2.970	2.980	2.970	2.964
"G"	2.820	2.890	2.940	2.850	2.900	2.880
Average	2.815	2.905	2.925	2.9125	2.855	2.882
Eccentricity (%)	$E = [(t_{max} - t_{min}) / t_{med}] \times 100$					9.859
Ovality (%)	$O = [(D_{max} - D_{min}) / D_{med}] \times 100$					1.220
External diameter measured values, D (mm)						
Position	"1"	"2"	"3"	"4"	"5"	
A-E	37.640	37.840	37.860	37.860	37.750	
B-F	37.520	37.460	37.550	37.500	37.560	
C-G	37.640	37.820	37.920	37.830	37.880	
D-H	37.550	37.500	37.650	37.530	37.530	
Average	37.588	37.660	37.745	37.680	37.680	
Wall thickness, t (mm)			External diameter, D (mm)			
t_{max}	2.980		D_{max}	37.920		
t_{min}	2.700		D_{min}	37.460		
Average, t_{med} (mm)	2.840		Average, D_{med} (mm)	37.690		

Geometrical characteristics are used in the process of state of health estimation of coiled tubing due to their impact on real surface of contact with the injector clamps A_r calculated with ecuation (3), as well as wall thickness (t) and ovality (O).

4. Case study

The continuous monitoring of mechanical and geometrical characteristics of coiled tubing it is a key element in establishing the state of health of this equipment and the data collected during all these measurements could be used with a high degree of confidence in the prediction of operational life of the coiled tubing.

This case study has the goal of establishing the requirements for establishing the operational status of coiled tubing (2). The input data of experiments are presented in table 5.

In order to verify the state of health of the equipment (injector capability to sustain the coiled tubing weight) as presented by (2), in table 6 there are presented calculation elements and in table 7 surface of contact area. The loading mass is considered as for a coil of tubing with total length of 3300 m, external diameter 38.1 mm (1.5 inch), wall thickness 2.84 mm and specific weight, 2.41 kg/m.

Table 5. Input data

No. crt.	Characteristic	Calculation formula	Measured value	Observations
1	Average, external nominal diameter of coiled tubing	D_{med}	D_{med} = 37.69 mm	According table 3
2	Average value of coiled tube wall thickness	t_{med}	t_{med} = 2.84mm	According table 3
3	Area of contact between clamps and coiled tubing	A_r	$A_r = 56176 \times 10^{-6}$ m^2	There are used 9 pairs of clamps see figure 5, *c*
4	Slip friction force coefficient at the contact clamp-coiled tubing	μ = (0.07 ..0.16)	μ = 0.1	Contact surfaces are greased according to exploiting instructions.
5	The flow limit of material	$R_{p0.2}$	$R_{p0.2}$= 435 MPa	There it was considered minimum value experimental measured (Table 2)
6	Shear resistance of material	$\tau_f = (0.2 \ldots 0.3) \times R_{p0.2}$	$\tau_f = 0.2 \times R_{p0.2} = 0.2 \times 435 = 87$ MPa	

Table 6. Calculation elements

No. crt.	Wall thickness, g (mm)	Internal diameter of clamp, D (mm)	Load mass, m (kg)	Axial force $F_A = m \times g$ (N)	Slip friction force $F_f = \mu \times A_r \times \tau_f$ (N)
1.	2.59	32.91	14234	139635.54	
2.	2.76	32.56	15133	148454.73	
3.	2.84	32.10	16276	159667.56	
4.	3.17	31.75	17157	168310.17	
5.	3.40	31.29	18269	179218.89	488731.2
6.	3.68	30.73	19613	192403.53	
7.	3.96	30.17	20929	205313.49	
8.	4.45	29.21	23144	227042.64	
9.	4.77	28.55	24619	241512.39	

Table 7. Surface of contact area

Wall thickness, *g* (mm)	2.59	2.76	2.84	3.17
Load mass, *m* (kg)	14234	15133	16276	17157
Axial force, F_A	139635.54	148454.73	159667.56	168310.17
Surface of contact, $Ar \times 10^{-6}$ (m^2)	0.1×Ar	0.2×*Ar*	0.3×*Ar*	0.4×*Ar*
Slip friction force, F_f (N)	48873	97746	146619	195492

5. Conclusion and future work

According to the results presented in table 6 for t = 2.84 mm and a column of coiled tubing with the weight of 16276kg is resulting a force F_A = 159667.56 N < F_f = 488731.2 N. This results in a loading of about 33% and a reserve of 64%. The reserve was specially designed for special situation when the coiled tubing is stacked in the bore well or it is used for recovering stacked tools inside of the bore well and there it is a need for a higher axial force F_A.

One very important factor in the equipment well-functioning as presented in formula (2) is the surface of contact between the clamp and the coiled tubing (*Ar*). Great impacts of this surface have the clamp geometry as well as the ovality of the coiled tubing. Thus it is very important to monitor both deformation of clamp and the ovality of the coiled tubing. Considering this, a brief calculation will lead to an acceptable maximum deformation which still provides 40% contact between the coiled tubing and clamps (0.4×*Ar*).

Another important factor which main lead to malfunctioning of the device could be some local transversal deformations/constrictions, generating also reductions of the surface of contact between the clamp and the coiled tubing (*Ar*)

The results obtained in this article as well as the one presented in [9] are to be used in an intelligent system for coiled tube state of health monitoring.

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