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Drill String Fatigue Failure and Lockup Risks Assessment in Tortuous Trajectory Well in Algeria

Lallia Belkacem[a]*, Noureddine Abdelbaki[b], Mohamed Gaceb[a], Elahmoun Bouali[a], Mourad Bettayeb[a]

[a]University M'hamed Bougara, Boumerdes, Faculty of Hydrocarbons and Chemistry, Independence Avenue, Laboratory of Petroleum Equipments Reliability and Materials, 35000, Algeria
[b] University Akli Mohand Oulhadj , Bouira,10000, Algeria
lfep.umbb@gmail.com

Failure due to fatigue and lock up risks for drilling pipes in tortuous trajectory is a very costly problem in oil and gas industry, since the cyclic loading which occurs while rotating bent drill pipes in a dog leg are more dangerous than rotating buckled drill pipes. This study is aimed to assess these risks and determine whether by integrating 2024 aluminium alloy drill pipes in drilling string, it is possible to extend the drilling operation without having detrimental impact on the drilling string integrity. Accordingly, the obtained results showed that, even though steel drill pipes have better mechanical properties, compared to 2024 aluminium alloy drill pipes, the latter have a better fatigue resistance even in the simultaneous presence of high applied torque and axial load, and severe dog-legs, beside good resistance to wear and corrosion even at high temperature, thereby reducing environmental trash and full consumption in order to minimise pollution.

1. Introduction

In view of to date work , many researchers have assumed that the steel drill pipes constitute a significant part of the drill string while working in complexe loading conditions such as combined tension, compression, torsion and bending. Furthermore, these loads are constantly changing depending on the trajectory and dog leg severity according to Vlasiy et al. (2017), while Abdel Salam and Mahmood (2016) have reported that the drill pipe is one kind of important tools for drilling in oil field in which the later are subjected to various types of loads and are operated under different environmental conditions. Drill pipe failure Incidents due to fatigue, corrosion and stress corrosion are very common in the field.

Similarly, the heavy-weight drill pipe fatigue failures often occur in oil fields because drill pipes bear continuously changing tension, torsion and impact loads as well as internal pressures during drilling. Scientists have always, however, seen that by using aluminium alloy drill pipes instead of steel drill pipes these problems can be reduced. For instance Legarth and Lehner (2015) have stated that experience has shown that light weight drill pipes when used properly can lead to reduced drilling loads and lower torque and drag thus making more extended drilling depths possible. While aluminium drill pipes are not as strong as steel drill pipes and have a lower buckling limit, they have a significantly longer fatigue life because their lower Young's Modulus reduces nominal bending stress by a factor of three. This was also confirmed by Menand and Jeffry (2014).

Although this approach for using aluminium alloy drill pipes is interesting it does not, however, take into account wear and corrosion in addition to high temperatures. This gap between the foregoing works and the field realities need be filled.

In this context, this paper is an attempt to present a new approach to new material selection which is superficially treated 2024 aluminium alloy (Abdelbaki and Atmani, 2002) in order to give good wear and corrosion resistance at high temperature. The material proposed has been treated superficially with "plasma electrolytic oxidation PEO" which enhanced their mechanical properties on the one hand and decreasing torque and drag loads while keeping a good resistance to axial, torsional and lateral loads on the other.

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2. Methodology

Therefore, this article is based upon experiments on new drill string material (superficially treated 2024 aluminium) alloy which is integrated in drill string and analyses its behaviour during drilling 0.2159 m hole diameters section from 2,926 m to 5,400 m, and limit to what extent the aluminium drill pipe can drill without failures in this interval by using Soft Modelling Decision Space Well Engineering Software. Accordingly, light will be shed on engineering overview of 0.2159 m hole diameters section problems in well drilled in Algeria firstly and then a synopsis on failure by using steel drill string compared to 2024 aluminium alloy drill pipes and analysis its behaviour during drilling interval by using Stiff Modelling Decision Space Well Engineering Software. This will be completed by result and interpretation to give an optimum solution to the problem.

2.1 Engineering overview on the hole section (0.2159 diameter) drilling

The drilling program plan to set 7 in (0.1778 m) production liner in the base of Silurian Unit B2 at 5.420 m, where severe wellbore instability such us, differential sticking, hole wash out and caving were encountered previously on this interval and are still suspected to be one of the major challenges to be faced while drilling this section.
Furthermore, the Trias formations showed a tendency to cave for the whole phase. To help prevent this, it is recommended to drill the Trias formation with laminar flow accomplished by increasing yield point pressure to roughly 7,200-8,640 MPa and decreasing flow rate to approximate 84 m^3/h. This should provide adequate hole cleaning unless caving does initiate and becomes a problem. In this case flow rates will need to be increased to a more conventional to 108 m^3 /h. The section of the hole used approximately 3,557.45 m of 0.127 m nominal diameter for drill pipe grade G above BHA to surface. This should provide 375,692.76 N of over pull margin depending on the drag conditions of the hole. Temperature can exceed 7,773.15 K and pressure exceeds 51.71 MPa.

2.2 Load data analysis method

A normal analysis involves calculating the torque, drag and normal force besides axial and buckling forces besides to other parameters are performed for the following drilling string. All calculations are executed with the bit at one position in the wellbore, and with one set of operational parameters by using stiff string model, in order to plot the Stress graphs along the drilling string; Dog leg graph, side force graph and rotating on bottom graph besides to fatigue graph for G105 drill pipes and superficially treated 2024 aluminium alloy drill pipes.

2.3 Load results

2.3.1 Stresses in steel drill pipe

The most remarkable result to emerge from Table 1 obtained from DS well engineer Halliburton Software, which shows the dog leg severity as a function of measured depth (MD) is that the dog leg issue outweighs the other stresses failure during rotating on bottom operations.

Table 1: Dog leg severity m/30° for steel drill pipe

Depth (m)	Tortured TVD (m)	Dog leg Severity (°/30m)
3,051.00	3,049.67	8.004
3,058.82	3,057.26	8.283
3,060.00	3,058.40	8.901
3,067.96	3,066.02	9.933
3,077.11	3,074.62	10.945
3,087.00	3,083.69	11.715
3,095.40	3,091.20	11.153
3,096.00	3,091.74	10.278
3,105.00	3,099.65	9.241
3,113.68	3,107.21	3.511
3,114.00	3,107.49	3.253
3,122.83	3,115.00	4.052
3,123.00	3,115.14	9.917
3,131.97	3,122.47	10.886

Thus, it is clearly seen that, from 3,051.00 m to 3,131.97 m, the equivalent tortuous dog leg severity ranged from 8 to 11.71 °/30m is revealed. Subsequently, the bending effect significantly reduce the collapse resistance and the dog leg severity exceeds 10°/9.14 m as stated by Lubinski (1961) which leads to fatigue problem as mentioned in Table 2.

Table 2: Steel drill string load summary

Load on steel drill string	Stress failure limit			Buckling failure limit		
Operations	Fatigue	90% yield	100% yield	Sinusoidal	Helical	Lock-up
Tripping in	-	-	-	-	-	-
Tripping out	-	-	-	-	-	-
Rotation on bottom	Fatigue	-	-	-	-	-
Rotation off bottom	Fatigue	-	-	-	-	-

(-): There is no Load on steel drill pipe

Furthermore, severe dog-legs can also exert side force on the drill pipes and the tool joints as exposed in Table3, which displays the side force per unit length in the string during drilling operations and located points along the well that may be subjected to high forces. It is noted that if these latter are more than 8,896 N as reported earlier by Menand (2012) can cause key seat problem and common tool joints failure.

Table 3: Side force for steel drill pipe

True Vertical Depth (m)	Side force (N)
3,051.08	20,986.231
3,059.90	23,634.026
3,068.60	25,203.090
3,077.12	22,261.095
3,085.43	13,435.110
3,093.55	5,982.056
3,101.55	14,513.842
3,109.47	24,516.625
3,117.15	15,396.440
3,124.53	774.725
3,131.77	1,657.323
3,138.98	1,353.317
3,146.18	3,893.240
3,153.33	9,139.797
3,160.38	10,512.728
3,167.26	2,245.722
3,173.99	4,432.605

2.3.2 Stresses in aluminium drill pipe

The solution proposed in this paper consists in simply replacing joints of steel drill pipes by lighter aluminium drill pipes while keeping the same bottom hole assembly and the tool-joints which are manufactured from steel. An analysis of torque and drag by using Decision Space well engineering software has been run to limit the optimum number of ADP joints along the drill string so as to minimize friction. Table 4 presents details of each drilling string specification, followed by stress analysis during rotating on bottom in Table 5.

Table 4: Details in each specific drilling string

Section	Steel / Steel drill pipe	Aluminium /Steel drill pipe		
Hole diameter 0,127 m	Grade G105	Grade G105	Grade AL2024	Grade S135
Depth (m)	5,420	600	150	2,988.5
Yield strength (MPa)	723.94	723.94	359	723.94
Tensile strength (MPa)	792.89	792.89	467	792.89
Young module (MPa)	206,842.71	206,842.71	88,763	206,842.71
Fatigue Endurance limit (MPa)	137.89	137.89	160	137.89

Table 5: Rotating on bottom stress analysis for 2024 aluminum drill pipe.

Drill Pipe Depth (m)	Fatigue Failure	Stress Failure	Buckling Failure	Torque Failure	Bending Stress (MPa)	Bending Stress Magnification Factor	Von Mises Stress (MPa)	Von Mises Ratio	Fatigue Ratio
3,055.22	-	-	-	-	59.840	8.322	197.121	0.548	0.476
3,063.55	-	-	-	-	64.80	8.252	197.328	0.549	0.514
3,071.88	-	-	-	-	63.97	8.182	193.693	0.539	0.506
3,080.22	-	-	-	-	62.128	8.113	189.572	0.527	0.49
3,088.55	-	-	-	-	29.847	8.044	169.362	0.471	0.235
3,096.88	-	-	-	-	31.521	7.976	169.138	0.471	0.247
3,105.22	-	-	-	-	34.177	7.91	169.420	0.471	0.267
3,113.55	-	-	-	-	66.716	7.843	186.974	0.52	0.52
3,121.88	-	-	-	-	71.696	7.777	187.474	0.522	0.558
3,130.22	-	-	-	-	29.234	7.712	160.525	0.447	0.227

(-): There is no Load on steel drill pipe

3. Results interpretation

The most remarkable result to emerge from the data presented in Table 3 is that the side force in the dog leg region is greater than the value recommended by API about of 8,825.98 N, ranging from 9,139.797 N to 25,203.09 N limited from 3,051.08 m to 3,173.99 m. Accordingly, this study will be limited to discuss how this abnormal condition will make the side forces deviate from the normal trend as illustrated in Table 6 which gives a periodical shift in bending forces values during rotating on bottom due to increasing of the steel drill pipe side force in dog leg region. Thus, the first set of analyses highlighted the impact of dog leg interval in the drill pipe, because bending pipe around a dog leg increases tension on the pipe on the outside of the curve and decreases on the inside of the curve. Consequently, as long as the steel drill pipe is rotating in the dog leg region, the rotation causes back and forth bending which can quickly lead to fatigue failure if the bending stress is excessive (Paslay and Cannock, 1991).

Moreover, the theory of Lubinski (1950), states that a ductile material starts to fatigue at a location where the fatigue ratio exceeds roughly 1, Based on this; it is clearly seen from Table 6 that the fatigue ratio reached 2.75 value, for that reason the steel drill pipe at the dog leg region may fail under the combined effects of axial tensile, radial and torsional stress besides alternating repeated bending stress due to rotational flexion. Accordingly, the drill pipes cannot withstand a significant amount of compression before reaching a buckling failure. These results were confirmed by Sellami (2016). The correlation between Von Mises ratio (Eq.1) and bending stress factor and side force is interesting, since this value is greater than 1, so the steel drill pipe is approaching to plastic failure. This fact is confirmed by fatigue ratio (Eq.2) which is greater than 1 as revealed in Table 6.

$$\text{Von Mises ratio} = \text{Von Mises stress} / \text{Yield strength} \approx 1 \tag{1}$$

$$\text{Von Mises ratio} = \text{Bending/Buckling stress/Fatigue endurance limit} \approx 1 \text{ is equal to safety limit} \tag{2}$$

In contrast to steel drill pipe results above, the 2024 aluminium drill pipe has a significantly good fatigue resistance even in the simultaneous presence of high torque and axial load in addition to severe dog-legs. This was confirmed by the fatigue ratio value which is less than 1 roughly about 0.558 as illustrated in Table 5 compared to 2.75 for steel drill pipe as revealed in Table 6.

Table 6: Rotating on bottom loads for steel drill pipe

Measured Depth (m)	Component Type	Fatigue Failure	Buckling stress (MPa)	Bending stress (MPa)	Bending Stress factor	Von Mises (MPa)	Von Mises ratio	Fatigue ratio
3,052.44	Drill Pipe	F	-	255.359	2.938	478.854	0.661	2.365
3,061.57	Drill Pipe	F	-	252.029	2.927	472.425	0.653	2.331
3,070.69	Drill Pipe	F	-	263.197	2.916	477.621	0.66	2.431
3,079.81	Drill Pipe	F	-	253.822	2.905	465.196	0.643	2.341
3,088.93	Drill Pipe	F	-	216.738	2.895	429.970	0.594	1.996
3,098.05	Drill Pipe	-	-	94.984	2.884	334.296	0.462	0.873
3,107.17	Drill Pipe	F	-	228.987	2.874	435.827	0.602	2.103
3,116.30	Drill Pipe	F	-	300.400	2.864	494.818	0.683	2.755
3,125.42	Drill Pipe	F	-	278.093	2.855	470.975	0.651	2.547
3,134.54	Drill Pipe	-	-	79.191	2.845	309.670	0.428	0.724
3,143.66	Drill Pipe	-	-	46.059	2.835	287.625	0.397	0.421
3,152.78	Drill Pipe	-	-	35.699	2.826	280.606	0.388	0.326
3,161.91	Drill Pipe	-	-	81.439	2.817	308.961	0.427	0.742
3,171.03	Drill Pipe	F	-	143.024	2.807	352.628	0.487	1.302
3,180.15	Drill Pipe	F	-	158.678	2.798	362.807	0.501	1.443
3,189.27	Drill Pipe	F	-	122.127	2.789	332.181	0.459	1109
3,198.39	Drill Pipe	-	-	37.757	2.78	274.004	0.378	0.343

(-): There is no Load on steel drill pipe

Table 5 shows that the Von Mises ratio is lower than 1 in the aluminium drill pipes region. Consequently, the component is unlikely to fail. Moreover, owing to the large bending stiffness of steel drill pipe (Table 6), the rate of increasing bending stress in steel drill pipe related to DLS is larger than the corresponding value in aluminium drill pipe. The drill pipe fatigue failure is therefore improved by way of including the Aluminium drill pipe in dog leg region since axial-force transfer efficiency is enhanced.

4. Conclusions

To sum up, even though steel drill pipes have better mechanical properties in terms of density, Young's modulus, yield and tensile strength, than 2024 aluminium alloy drill pipes, the latter have a good fatigue resistance even in the simultaneous presence of high applied torque and axial load, and severe dog-legs, which makes the use of other options (Steel Drill Pipe and Titanium Drill Pipe) impractical from the fatigue failure standpoint.

Furthermore, the results show that the limiting factor for using aluminium drill pipe in such severe conditions is not the fatigue resistance of the pipe material, but the high contact forces between the wellbore and the drill pipe wall. Consequently, 2024 aluminium suffers much less fatigue damage than Steel drill pipe in dog-legs region, this property is due to low pipe stiffness.

However, the large contact forces at the pipe body can make relatively major scratches on the surface of the pipe tube Steel drill pipe, which can render their corrosion resistance features insignificant. But the following 2024 Aluminium drill pipe has a good resistance to wear and corrosion even at high temperature which leads to reduce environmental trash, for the reason that the following material has been treated superficially with "plasma electrolytic oxidation PEO" which enhanced their mechanical properties.

Finally, we can assume that there is significant fuel saving with the use of aluminium drill pipes compared to steel drill pipes, because the ratio of the engine power needed to supply the drilling fluid at the required pressure for ADP versus steel drill pipe is lower, leading to a reduction in fuel consumption and less environmental pollution.

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