



Influence of Chemical Corrosive Environment with H₂S on Drill Strings, Experimental Researches

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Abstract: The present researches established the failure causes of the drill string, used in corrosive environments with H₂S, in an oil field, by initiating fatigue cracks from the corrosion points on the inner surface of the drill pipes, which favoured the diffusion of hydrogen, the brittleness of the material and the brittle fracture.

Keywords: drill pipe, failure, fatigue, corrosion, hydrogen sulfide

1. Introduction

In the petroleum industry, the drill string is the drilling assembly that is used to rotate the bit, to conduct the drilling fluid to the bit, to realize the weight on bit and control the drill bit, [1, 2]. Wear, corrosion and fatigue are recognized as a major cause of drill string failures. According to the statistics presented in the specialized literature, the drill string failures occurs, after every seven drilling operations and costs more than 100.000 \$ per failure event, [3]. Moreover, if the failures consist in complete drill pipe separation (called twistoff), especially when it is not possible to recover the remaining part of the drill string from the borehole, the costs can upward to one million dollars, due to the unplanned interventions (drilling a new hole parallel to the section occupied by the broken drill string, and replacing the broken parts), and due to the waste of time, about several months, to solve the problems [3, 4]. The failure of the drill string is an unpleasant incident in the drilling industry, because the companies will record huge financial losses. When the drill string failure occurs, the cause that produce it is not known, and in order to prevent such accident from happening again, a complete failure analysis of the fractured drill pipe is required, [5].

The present paper brings forward the failure analysis of a drill string which has been fractured for five times, during the drilling process in a corrosive environment, with high hydrogen sulfide concentration (H₂S).

2. Materials and methods

In order to establish the causes that led to the drill string failure, the investigations were performed on two fractured drill pipes (3 ½ in, grade G105), components of the investigated drill string, provided by the drilling operator, with different lengths, respectively 100 mm (symbolized drill pipe A - Figure 1) and about 1000 mm (symbolized drill pipe B - Figure 1), [6].

The drilling operator provided information on operating conditions during the drilling, that were investigated in detail, underlined, among others that the drill string worked in a corrosive environmental, having a high content of hydrogen sulfide, with unknown concentration. Probable causes of the drill pipes fracture were analyzed systematically by performing investigations and measurements, such us: macroscopic analysis, metallographic analyses by optical microscopy, hardness measurements, chemical analysis determinations, mechanical characteristics testing, liquid penetrant nondestructive testing and dimensional measurements, [6].

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Figure 1. Fractured drill pipes

The analysis were performed on samples and specimens taken from the drill pipes (cut from all the circumference of the drill pipes), as shown in Figure 2.

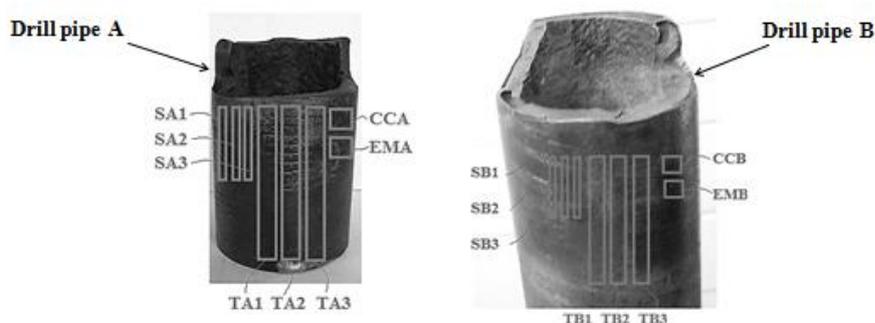


Figure 2. Samples and specimens marked for testing:

EM - samples for metallographic examination; CC - samples for chemical analysis;
T - specimens for tensile testing; S - specimens for Charpy impact testing.

3. Results and discussions

3.1. Macroscopic analysis of the fractured drill pipes

In order to establish the type of fracture, the aspect and the surface of the fractured area were investigated by visual inspection, with the naked eye, and also by using the stereoscopic microscope. The information obtained from the macroscopic study is presented below.

The fractured occurred in the body of the drill pipes, in the cylindrical area. On the outer surface of both drill pipes were visible fingerprints from the gripping and rotating devices used for make-up/break out connection. The fingerprints can be cracks source for fatigue failure.

For both drill pipes, on the fractured surfaces, two distinct zones were highlighted: a relatively flat area, extended on approx. 3/4 of the cross-sectional area of the drill pipe, having a perpendicular orientation on the axis of the drill pipe, which represents the main fracture surface, and a fracture zone unevenly compared to the fracture plane, with the height of approx. 20 mm (for drill pipe A), respectively approx. 30 mm (for drill pipe B), which represents the final fracture zone (Figure 1, Figure 2).

The fracture surface of the drill pipes present a typical morphological aspects of a fatigue fracture surface, caused by the nucleation/initiation and propagation of cracks under cyclic loading. The fatigue cracks were initiated and developed from the corrosion points on the inner surface of the drill pipe, strongly corroded, as shown in Figure 3. The corrosion points, with depths up to 1 mm, represent stress

concentrators that initiate the fatigue cracks. The fatigue cracks, starting from the corroded inner surface, were propagated through the thickness of the drill pipe towards the external surface.

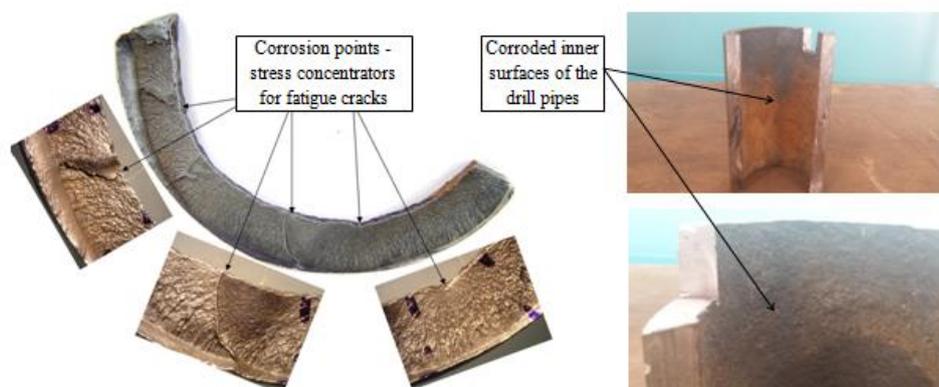


Figure 3. Fatigue cracks initiation from the corrosion points

No significant corrosion phenomena are observed on the outer surface of the drill pipes, most likely due to their removal by the friction with the traversed rocks in the drilling process. The information mentioned in the specialized literature show that approx. 75% of the drill pipe failure is caused by fatigue, [6].

The effect of the corrosive environment is manifested by a drastic reduction of the fatigue resistance, defining the notion of corrosion fatigue, with a synergistic action of corrosion and fatigue, much more serious than each of the two degradation mechanisms considered separately.

Having the information that in the oil field in which the fractured drill pipes were used, the presence of hydrogen sulfide was reported, the possibility as the fracture to occur as a result of the brittleness of the material, due to the diffusion of hydrogen, was analyzed. This hypothesis is supported by the following aspects:

- the fracture of the drill pipes has a typical aspect of brittle fracture;
- the production of a large number of fracture (five), suggesting the existence of a common cause, namely the effect of hydrogen sulfide;
- relatively long duration (8 hours) of exposure of drill pipes to hydrogen sulfide, under conditions of high pressures and high tensile stresses;
- the location of the fracture in the upper part of the drill string, where the conditions to cracking and fracture under the action of hydrogen sulfide are realized simultaneously;
- the chemical test performed with sodium arsenite, recommended for the identification of possible sulphur compounds, on the fractured surfaces of the drill pipes confirmed that the drill pipes were exposed to working environments with H₂S.

Acid environments with hydrogen sulfide can lead to the phenomenon of cracking and fracture under tension of the drill pipes, internationally named as Sulfide Stress Cracking (SSC). Four conditions are required for the fracture to occur:

- a state of tensile tension;
- an environment containing water (even traces) and hydrogen sulfide, at least 1 ppm;
- a material susceptible to cracking and fracture under the action of hydrogen sulfide, having yield strength over 630 MPa (90000 psi) or hardness greater than 22 HRC.

The drill pipes grade G105, subjected to this study, have a high susceptibility to brittleness in hydrogen sulfide environments, because they have a high hardness of more than 30 HRC, higher than the recommended NACE standards of max. 22 HRC, [6, 7].

Cracking and fracture under the action of hydrogen sulfide (SSC) occurs due to hydrogen diffusing into the crystalline structure of the metal, producing material brittleness (reducing ductility) and cracking phenomena, [8, 9].

The cracking produced by the SSC phenomenon leads to the reduction of the cross section, which has the effect of fracture under the action of a mechanical stress.

The conditions that favor the SSC phenomena in the drill pipes, in addition to those mentioned above are the following, [6, 8, 9]:

- high tensile stresses, mainly determined by the own weight of the drilling string;
- relatively high concentrations of H_2S ;
- low pH of the drilling fluid or of the fluids extracted from the well (for pH values up to 7, the fracture can occur in less than one hour);
- high pressure (determines the partial pressure of H_2S);
- high chlorine content;
- lower temperatures, around the ambient temperature; at temperatures above $66^{\circ}C$ the susceptibility to SSC decreases;
- high hardness of the material (the higher grade, above X95, is susceptible to brittleness and fracture due to H_2S).

In the presence of these factors simultaneously, the fracture under the action of hydrogen sulfide can occur in a few hours.

For comparison, Figure 4 shows the aspects of the fractured surfaces of two drill pipes due to the presence of hydrogen sulfide (SSC), presented in the specialized literature, [10]. In the first image presented in Figure 4, was observed an identical aspect of the fractured surface with the fractured surfaces of the analyzed drill pipes in this paper.

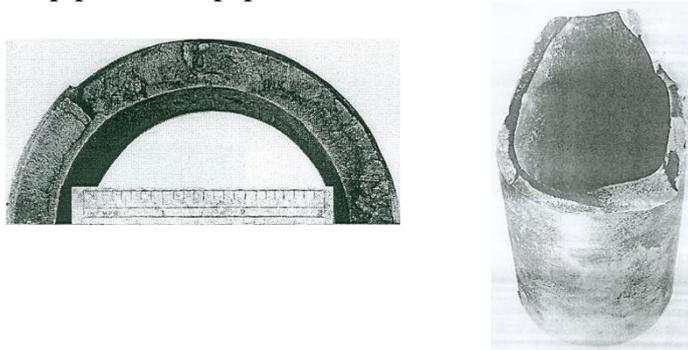


Figure 4. Fractured drill pipe due to the presence of hydrogen sulfide (H_2S), [8]

It can be appreciated, after the macroscopic analysis, that the fracture of the drill pipes occurred by initiating fatigue cracks from the corrosion points on the inner surface of the drill pipes. These corrosion points represent stress concentrators that favored the diffusion of hydrogen at the peak of the concentrator, the brittleness of the material and the brittle fracture. The effect of hydrogen sulfide was manifested in two aspects:

- a direct effect consisting of the brittleness of the material and the propagation of the cracks with the production of a brittle fracture;
- an indirect effect, consisting in favoring the severe corrosion phenomena on the inner surface of the drill pipes, generating the fatigue cracks.

3.2. Dimensional analysis of the fractured drill pipes

The dimensional analysis of the fractured drill pipes consisted of measuring the outer diameter and their wall thickness. The outer diameters (OD measured) of drill pipe A and B were measured in different planes, situated at a distance of 20 mm from each other, noted I... V for drill pipe A and I...VII for drill pipe B (Figure 5). In each plane, two diameters were determined, perpendicular to each other. Also, the wall thickness of the analyzed drill pipes A and B was measured, at the measuring points marked 1, 2, 3.....onto the surfaces.

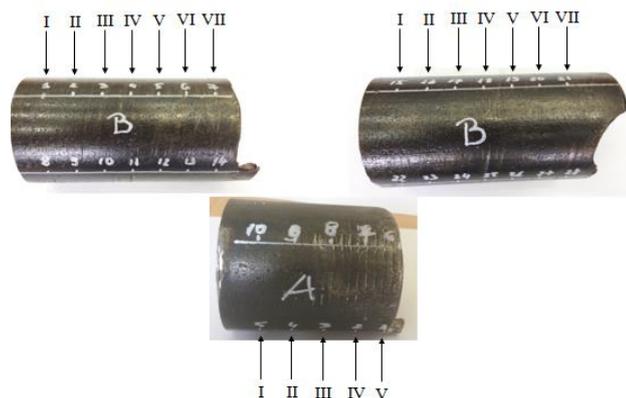


Figure 5. Planes and points marked for outer diameter and wall thickness measurements

Table 1 shows the dimensional characteristics measured for drill pipes A and for drill pipes B.

Table 1. Outer diameter and wall thickness for drill pipes

Parameter	Standardized values			Measured values	
	nominal	max	min	drill pipe A	drill pipe B
OD, mm	88.9	89.69	88.11	87.19...86.94	87.64...87.35
t, mm	11.4	-	9.975	10.92...9.53	10.76...9.73

The outer diameters measured are smaller than the minimum standardized diameter for drill pipes (tolerance to the standardized outer diameter is ± 0.79 mm). The wall thickness measured is within the tolerance provided by the standard (12.5% of the standardized wall thickness).

There were no significant differences between the values of wall thicknesses, which show a uniform corrosion inside the drill pipes.

Measurement of outer diameter of the analyzed drill pipes have shown the fact that in the fractured area the diameter is constant, indicating a fracture without plastic deformation of the drill pipe, having another cause than the tensile overstress of the drill pipes. For comparison, in Figure 6 is presented, from specialized literature, the aspect of the fracture for two drill pipes subjected to tensile stress by exceeded the yield strength of the material (overload), where the plastic deformation of the fractured area is highlighted, having a specific fracture aspect cone-cup.

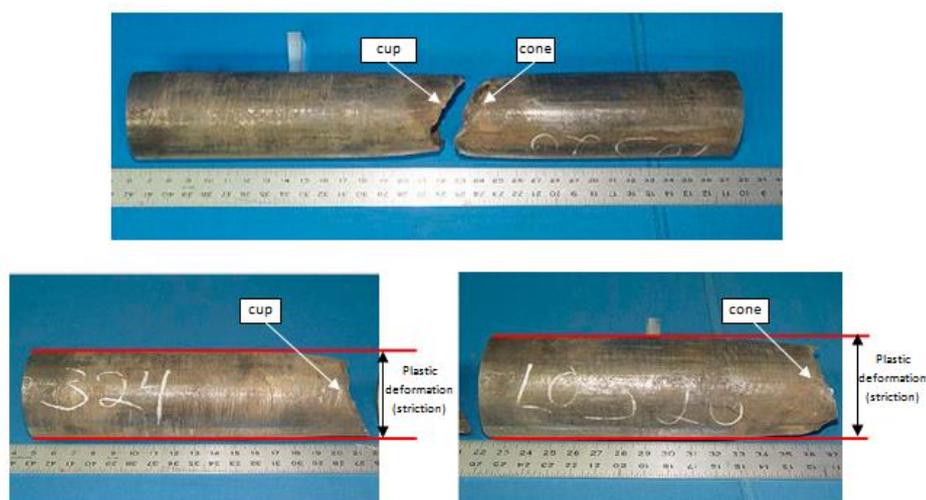


Figure 6. Typical aspect for fracture of the drill pipes subjected to tensile stress



3.3. Determination of the chemical composition for fractured drill pipes' material

The objective of determining the quantitative chemical composition was to establish the steel grade used in the manufacture of the studied drill pipes, in order to verify if they are according to the steel grade mentioned by the technical bulletin provided by drilling operators, and by the standardized recommendations. The results of average values for the quantitative chemical analysis performed by optical emission spectrometry are presented in Table 2.

Table 2. Chemical composition of the fractured drill pipes' material

Material	C, %	Si, %	Mn, %	P, %	S, %	Cr, %	Mo, %	Ni, %	Al, %
Drill pipe A	0.2543	0.277	1.545	0.00679	0.00369	0.7225	0.2075	0.0215	0.0306
Drill pipes B	0.2453	0.275	1.485	0.00629	0.00249	0.7077	0.1948	0.0213	0.0378
Standardized				max.	max.				
Grade G	-	-	-	0.020	0.015	-	-	-	-

The results for the chemical composition of the materials confirm the steel grade used for drill pipes subjected to this study, respectively grade G. The steel belongs to the category of steel used for quenching and tempering, with a percentage of $1.48 \div 1.54\%$ Mn, $0.70 \div 0.72\%$ Cr, $0.19 \div 0.20\%$ Mo, being used usually for the manufacture of the drill pipes.

3.4. Determination of the mechanical characteristics for fractured drill pipes' material

The mechanical characteristics fractured drill pipes' material were determined by performing tensile tests, Charpy impact tests, hardness tests, with the average values obtained presented in Table 3.

Table 3. Mechanical characteristics for fractured drill pipes' material

Material	Yield strength $R_{0.6}$, N/mm ²	Tensile strength R_m , N/mm ²	Elongation A_f , %	Absorbed energy KV, J	Hardness HBW _{2,5/187,5}
Drill pipe A	623	1089	9.6	79.8	315.3
Drill pipe B	699	999.6	9.8	83.4	311.6
Standardized	min. 724		min. 13.6	min. 38 (individual value)	-
Grade G	max. 931	min. 793		min. 43 (average values)	

The mechanical characteristics obtained from the tensile test indicate that the drill pipes analyzed correspond to the steel grade G105 only in the aspect of tensile strength, R_m , but not correspond under the aspect of yield strength, $R_{0.6}$ and elongation, A_f , their values being lower than the standardized values. This is the reason why the determination of the absorbed energy during the Charpy impact test, KV, corresponds to the standardized values, not highlighting the effect of the brittleness due to the hydrogen sulfide presence. The obtained hardness values of the drill pipes analyzed meets the requirements of international standards for quenching and tempered steels, commonly used for the drill pipes manufacture.

3.5. Metallographic analysis of the fractured drill pipes

The examination of the metallographic structure was carried out on samples taken from the fractured drill pipes.

The metallographic analysis performed by optical microscope revealed that the structures consist of tempered sorbite (Figure 7), corresponding to the application of a quenching and tempering heat treatment.

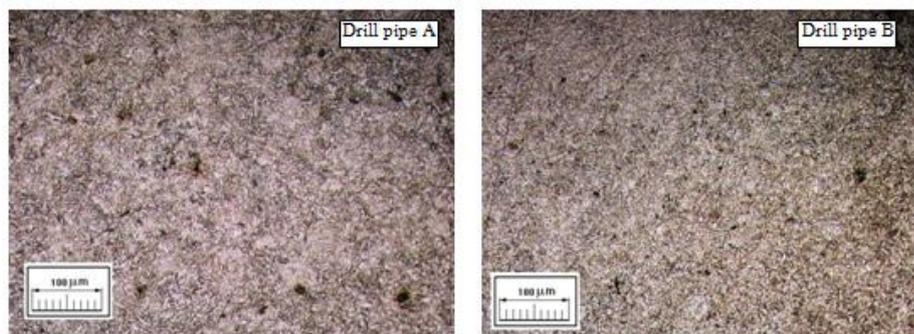


Figure 7. Metallographic structures of the fractured drill pipes' material

The metallographic analysis performed by the scanning electron microscope (SEM) revealed a brittle fracture with possible areas of hydrogen accumulation (Figure 8).



Figure 8. The electron microscope appearance of the fractured surface of drill pipe A (the craters observed on the fractured surface correspond to possible hydrogen accumulations)

3.6. Liquid penetrant non-destructive testing of the fractured drill pipes

The liquid penetrant non-destructive testing performed onto the fractured drill pipes (Figure 9) aimed to determine their surface's defects. On the surface of the drill pipe A, there were visible deep scratches due to the clamping in the gripping device but, no cracks were observed. In contrast, on the surface of drill pipe B there was observed a crack propagated from the fractured surface, fingerprints due to clamping in the gripping device, deep scratches of abrasive wear, without no other cracks detected.

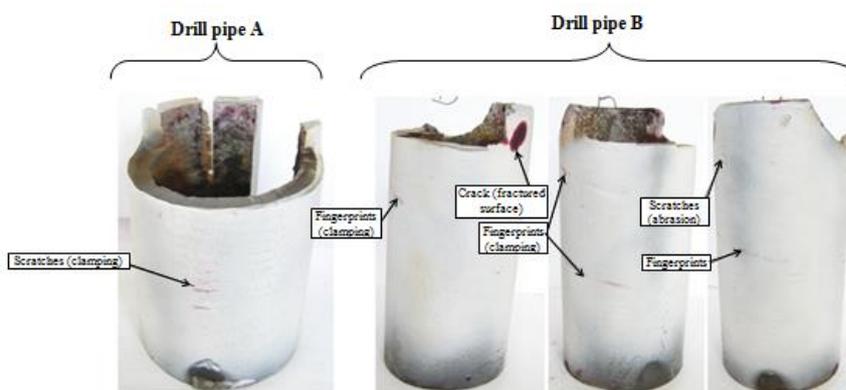


Figure 9. Liquid penetrant non-destructive testing



4. Conclusions

The drill string failure which has fractured for five times, during the drilling process in a corrosive environment (with high hydrogen sulfide content, H₂S) were analyzed on two fractured drill pipes (3 ½ in, grade G105), components of the studied drill string. Documentations provided by the drilling operator doesn't contain information regarding the history of the working conditions of the studied drill pipes, maintenance activities for their technical evaluation and the hydrogen sulfide concentration from the working environment. As a result, the expertise of the failure was based on the results obtained from the examinations and tests performed, supplemented with information from the specialized literature.

The chemical composition analysis highlights and confirms the fact that the steel grade G was used for the fractured drill pipes' materials. The steel belongs to the category of steel used for quenching and tempering, with a percentage of 1.48 ÷ 1.54% Mn, 0.70 ÷ 0.72% Cr, 0.19 ÷ 0.20% Mo, being used usually for the manufacture of the drill pipes.

The mechanical characteristics of both fractured drill pipes are almost similar.

The drill pipes analyzed correspond to the steel grade G105 only in the aspect of the tensile strength, R_m, but not correspond under the aspect of yield strength, R_{0.6}, and elongation, A_f, their values being lower than the standardized values. These inconsistencies are probably due to the effect of the drill pipes material's brittleness. In general, the effect of brittleness due to hydrogen sulfide is evidenced by mechanical tests performed with a low test speed, such as tensile test, but is not evidenced by dynamic tests, respectively by Charpy impact test. This is the reason why the determination of the energy absorbed during the Charpy impact test, KV, corresponds to the standardized values, not emphasizing the effect of the brittleness due to hydrogen sulphide.

The dimensional measurements performed on fractured drill pipes indicate that the outer diameters measured are smaller than the minimum standardized diameter for drill pipes (tolerance to the standardized outer diameter is ± 0.79 mm). The wall thickness measured is within the tolerance provided by the standard (12.5% of the standardized wall thickness).

The drill pipes did not have an inner coating and, as a result, they show severe corrosion, with pitting points up to 1 mm deep. The pitting points represent stress concentrators, initiators of cracks for fatigue fracture or brittleness fracture in the presence of hydrogen sulfide.

On the outer surface of the fractured drill pipes there are observed deep fingerprints due to the gripping device, which can represent, also, stress concentrators, initiators of cracks for fatigue fracture in the presence of hydrogen sulfide.

In conclusion, the analysis carried out showed that the drill pipes were made of suitable steels, from the chemical composition aspect, and the heat treatments were properly applied. It can be appreciated that both the steel and the heat treatment applied to the drill pipes can ensure the mechanical characteristics of the G105 grade steel, under the conditions in which brittleness factors do not operate in the drilling process.

The failure of the drill string occurred by initiating fatigue cracks from the corrosion points on the inner surface of the drill pipes. These represent stress concentrators that favored the diffusion of hydrogen at the peak of the concentrator, the brittleness of the material and the brittle fracture. The effect of hydrogen sulfide was manifested under two aspects: a direct effect consisting of the brittleness of the material and the propagation of the cracks with the production of a brittle fracture and, an indirect effect, consisting of favoring the severe corrosion phenomena on the inner surface of the drill pipes, generating stress concentrators for fatigue fracture.

Acknowledgments:

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