Engineering Failure Analysis 65 (2016) 74–85

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Failure analysis of drillstring in petroleum industry: A review

M.T. Albdiry, M.F. Almensory

Department of Materials Engineering, College of Engineering, University of Al-Qadissiya, Al-Diwaniya, Iraq

ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form 13 March 2016
Accepted 14 March 2016
Available online 16 March 2016

Keywords:
Drillstring
Drill collar
Drilling bit
Hammer bit
Drilling performance
Petroleum industry

ABSTRACT

Understanding the failure analysis of drillstring and its components i.e., drill collar and drilling bit is one of the essential issues in the oil and gas industry for the high cost of oil well drilling. Different ways such as air drilling, percussion drilling and downhole hydraulic ultra-high pressure (UHP) jet assisted drilling have been often used to improve the rate of penetration (ROP), minimize the cost of drilling per foot and diminish well deviation. Nevertheless, these drilling ways aggravate the working conditions of the downhole drilling tools materials and hence their properties cannot meet the demands of these conditions and consequently causing a risk drillstring failure. The unfavorable geological conditions and the repeated impact for breaking the rock may also cause severe bit bouncing and violent vibration. Tooth loss, tooth fracture, tooth wear and microcracks in addition to drill pipe fatigue from bending stress caused by buckling load are realistic examples of failure modes which occurred in the drilling tools. This study comprehensively describes the reasons causing these failure modes in order to manage risks and achieve high performance of wells and borehole sections. The role of working parameters i.e., bottom hole temperature and solid content on the drilling tools' life time, and the role of predrill predictions of pore pressure or wellbore stability on the drilling process are presented.

Contents

1. Introduction . . . 75
   1.1. Drilling process in the oilfield . . . 75
   1.2. Drilling operation efficiency . . . 75
   1.3. Scope of the research . . . 75
2. Failure analysis of drilling tools (drillstring) . . . 76
   2.1. Failure analysis of the drill pipe (or the drill collar) . . . 76
      2.1.1. Fatigue . . . 76
      2.1.2. Vibration . . . 77
      2.1.3. Buckling . . . 78
      2.1.4. Wash out and twist-off . . . 79
      2.1.5. Other failure modes occurred in the drill pipes . . . 79
   2.2. Failure analysis of the drilling bits (hammer bits) . . . 79
      2.2.1. Tooth loss . . . 80
      2.2.2. Tooth fracture . . . 80
      2.2.3. Tooth wear . . . 80
      2.2.4. Bit balling . . . 82

E-mail address: mushtaqalbdiry@gmail.com (M.T. Albdiry).

http://dx.doi.org/10.1016/j.engfailanal.2016.03.014
1350-6307/

3. Other failure modes occurred through the drilling process . . . 82
4. Conclusion . . . 83
References . . . 84

1. Introduction

1.1. Drilling process in the oilfield

In the petroleum industry, the paramount way to get oil and gas is well drilling which is used to create holes in the earth subsurface using a special machine called drilling rig. The term "rig" generally refers to the complex of equipment that is used to penetrate the surface of the Earth's crust. The lower part of drilling rig is hollow column or string called drillstring which is typically made up of three sections: Bottom hole assembly (BHA), transition pipe and drill pipe [1]. The first section, BHA including drill collar that is a rock breaking tool and drill bit where the BHA is heavy with a thick walled hollow tube used for drilling fluid being pumped down through it and circulated back up the annulus (the void between the casing and the drillstring). The second section is a heavyweight drill pipe (HWDP) used to provide a flexible transition between drill collars and drill pipe which in turn, works to reduce the number of fatigue failures occurred directly above the BHA and add additional weight to the drill bit. The third section is a drill pipe, makes up the majority of the drillstring back up to the surface. Each drill pipe comprises a long tubular diameter portions with an outside diameter called the tool joints which has a male "pin" threaded connection at one end and a female "box" connection at the other end for making segment to the next segment. Although, all drill pipe has the same diameter, its upper section is handled by using a higher strength material to carry a higher axial loading and supporting the entire drillstring in these portions. For further information, Fang and Duan [2] comprehensively described the development of oil and gas fields by improving drilling speed and quality. They also described the drilling platform categories in the relation to their operation characteristics, while the current and historical costs of the oil and gas wells drilling processes are described in Lukawski et al. [3].

1.2. Drilling operation efficiency

In order to improve the rate of penetration (ROP) at less overall cost and good borehole conditions and enhancing drilling efficiency at high performance in wells and borehole sections; different ways were used such as the optimal design of downhole and well trajectory, using drilling fluid aligned with drillstring and reducing the well placement uncertainty in both depth and azimuth [4]. Percussion drilling was also widely used in oil and gas industry for its contribution in a significant increase in the ROP with less well deviation and less formation damage compared to ordinary mud drilling [5]. The air drilling technology has also proven to significantly increase the ROP [6].

Furthermore, hydraulic ultra-high pressure (UHP) jet assisted downhole drilling is installed right above the drill bit in order to improve the ROP and utilize the intensifier by the way of producing UHP jet flow via pressurizing the drilling fluid, cutting and breaking the rock. This technique is further incorporated with cutting-cleaning mechanisms [7].

On the other side, each of the drilling ways discussed above, has its own drawback that could possibly add a significant threat to the drillstring safety due to the severe working conditions. For instance, in percussion drilling, bit rotation is used to make the bit tooth impacts new positions on the rock each time so that severe drilling tool failures such as tooth loss, tooth fracture and tooth wear occurred where they restricted the further development of the drilling process [5]. Also, despite the truth of using percussion drilling or air drilling with drillstring is resulted in a high quality well drilling at less cost per foot in the lowest time possible, it may also result in emerging of several factors limiting the drilling performance such as drilling vibration [8]. Along with this, using drilling fluids like water-based fluid muds in drilling boreholes to cool and lubricate the drill bit, clean the hole bottom and carry cuttings to the surface. However, this fluid may contain various dissolved synthetic chemical compounds (e.g., alkalies, salts and surfactants), various insoluble substances (e.g., barite and clay) and organic polymers in colloidal state and emulsified oil, which can be aggressive and give rise to corrosion threat for the drillstring tool materials [9]. Thus, a sophisticated study determining the modes and mechanisms of drilling tool failures occurred in drilling operations is required. Hence, this review article mainly aims at conducting failure modes occurring at drilling tools through the cutting processes of the oilfields.

1.3. Scope of the research

This research attempts to comprehensively review most failure modes occurred in the drilling tools (drillstring and drill bit) during the drilling process of the oilfield. To discuss the main concepts of the drilling process and important aspects of drillstring components as well as the drilling aid methods that used to improve the drilling efficiency. It also highlights the main reasons behind these failure modes in order to manage risks and achieve high performance of wells and borehole sections. The research also presents the role of working parameters i.e., bottom hole temperature and solid content on the drilling tools' life time and the role of pre-drill predictions of pore pressure or wellbore stability on the drilling process.

2. Failure analysis of drilling tools (drillstring)

The drillstring at its lower and upper sections continuously undergo tension, compression, bending, and twisting stresses through the drilling process of oilfield downhole particularly at complex geological conditions and continental deposition environment coexists in some regions of the drilled formations. This is, in turn resulting in a drilling tools failure, reduction of the ROP, extra time spent on replacing the failed tool and consequently poor borehole conditions and delaying the development of the oil and gas industry. Thus, many experimental studies have analyzed in details the factors affecting premature failure of drillstring and determining the best working conditions of the downhole in order to reduce the accidents associated with the drillstring failure. In the following sections, the failure analysis for a variety of drillstring sections with respect to the failure type and its possible causes is discussed.

2.1. Failure analysis of the drill pipe (or the drill collar)

A downhole failure of the drill pipe means a complete separation of the drill pipe or a separation in a part of the bottom hole assembly (BHA). Failure of the drill pipe is often occurred in drilling of ultra-deep well at complex geological conditions. A number of common drillstring failures, especially failure modes of the drill pipe collected from previous literature are presented.

2.1.1. Fatigue

The majority of drill pipe's failures is attributed to fatigue. Fatigue failure considers that the drilling hook at surface or drilling bit undergoes fluctuated weight ranging from 0 to 3000 kN, and rotational speeds ranging from 50 to 200 rpm. The rate of penetration of the drilling tools can vary from 1 to 50 $m \cdot h^{-1}$, and torque applied to the drillstring at surface is ranging from 0.5 to 70 $KN \cdot m$ due to the borehole friction [1]. As shown in Fig. 1, a high level of stress concentration in the thread roots connections [10] and a high stress concentration at the upset transition area of the drill pipe [11] are responsible on causing fatigue failure in the drilling tools.

Knight and Brennan [10] examined the relationship between the bore eccentricity in the drill collar and fatigue life improvement. They conducted that any stress concentration combined with a modest amount of the drill collar bore eccentricity can result in a notable reduction in the fatigue life of the drill pipe under bending loads. While, Lin et al. [11] simulated the mechanical properties of the drill pipe upset transition area using ANSYS software in order to provide a reasonable reference for the optimization of the drill pipe upset transition's size and its practical application. Yonggang et al. [12] also simulated the stress state of the drill pipe transition zone position. They proved that the transition zone is the weakest position of the whole drill pipe, and the length of transition zone and transition zone chamfer radius R had a significant influence on the stress concentration.

There are two types of fatigue loadings on the drillstring: dog-legs that is reversed bending through borehole features, and a raft of sources collected under dynamic vibration [1]. Dog-legs are regions of the wellbore which have unavoidable deviations that

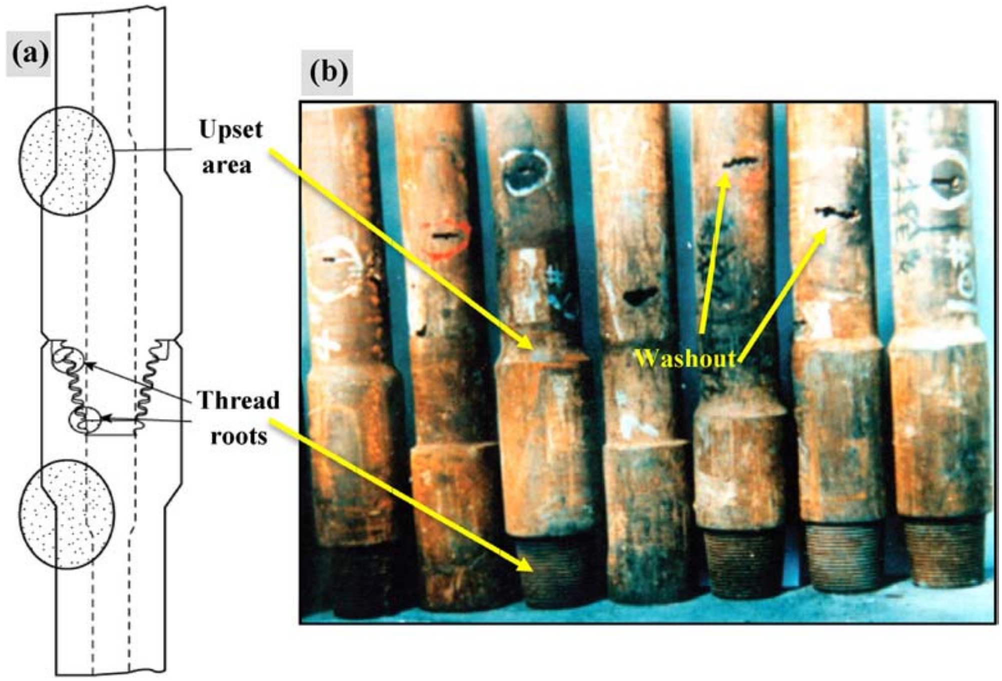

Fig. 1. (a) Critical regions of the drill pipe and connection causing fatigue failure [1], and (b) washout failure of the drill pipe transition zone [12].

can happen with drilling of horizontal wells where the drill pipe rotates in a curved segment as shown in Fig. 2. The curved segments cause fully reversed alternating tension-compression stresses (cycles).

Zhu et al. [13] tested beveled shoulder threads (BST) in the horizontal directional drilling (HDD) technology. The BST revealed their suitability for drill pipe threads design since they showed a high bending strength, a large flexural rigidity and withstanding large bending loads.

The effect of stress concentration on the pin and box threaded joint's failure of the upset drill pipes was investigated by Luo and Wu [14] under the combined tensile and bending loads. The tool failure is caused by the maximum stress concentration and fatigue crack nucleated at the first root of the tooth from the pin tool joint shoulder of the drill pipe, and then propagated through the wall of the tool joint. The deterioration of the fatigue resistance of the tool joint is related to dogleg region where severe cyclic bending load exists due to the local deviation of the drill pipe from the vertical line.

Wang et al. [6] collected various cases of the drillstring failures in northeast Sichuan, China. It was observed that poor quality of the drillstring or presence of manufacturing defects on the drillstring, and the unscientific design or design faults of the drillstring are detrimental to maintain the drillstring strength. These defects perhaps lead to uneven propagation and distribution of the stresses which in turn, resulting in a premature failure of the drillstring. It was also observed that fatigue failure of the drillstring that seen in Fig. 3, caused by the extra-large tensile or compressive stress acting on the drillstring, resulted from drillstring sticking and the improper anti-sticking methods like over pushing and over pulling of the drillstring.

2.1.2. Vibration

The applied heavy and complex dynamic loadings on the drillstring that caused by the rotation of the rotary top drive in the surface can produce different states of stresses with a turbulent movement in the downhole and consequently causing excessive vibrations and potentially premature failure [15]. Vibration is a to and fro movement or it is the manifestation of the oscillatory behavior in the drillstring. The application of drilling aid methods such as air drilling may also exacerbate the drillstring vibration due to the damping effect of the drilling fluid [6].

There are three forms of drillstring vibrations: axial, torsional and lateral vibrations. Axial vibration is occurred when the drillstring moves along its axis of rotation; torsional vibration is occurred when an irregular rotation of the drillstring rotated from the surface at a constant speed, and lateral vibration is occurred when the drillstring moves laterally to its axis of rotation.

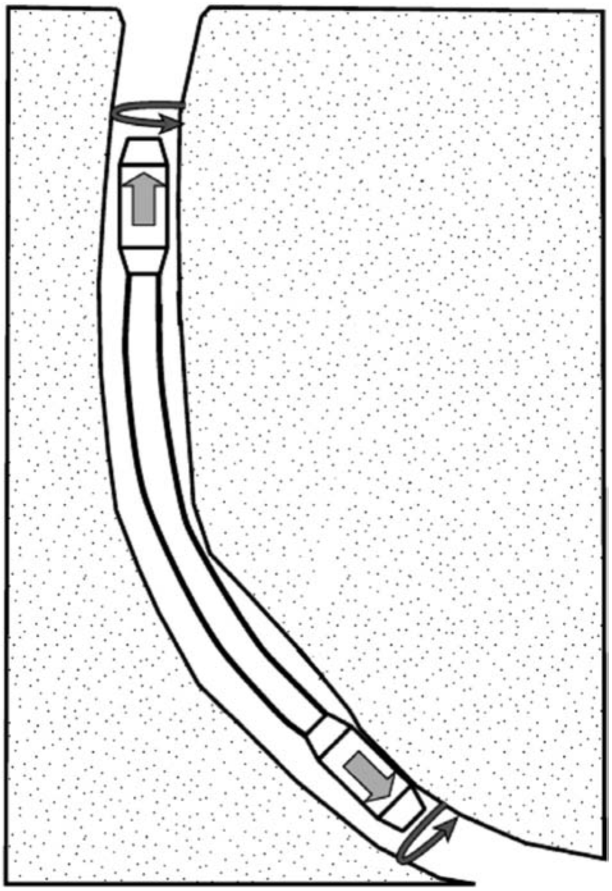

Fig. 2. Loading on a drillstring through a dog-leg [1].

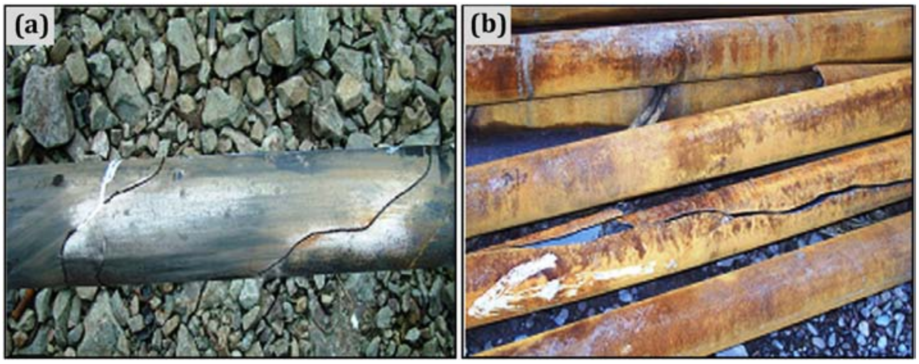

Fig. 3. (a) fatigue fracture caused by gas drilling, and (b) fracture of the drillstring due to hydrogen embrittlement [6].

In general, the drillstring more frequently vibrates as combinations of all these three basic forms that can result in unwanted vibration modes of the drillstring and inefficient drilling. Hence, it is essentially operating the drillstring above or below the critical speed as well as carrying out pre-drilling analysis and real time analysis of the drillstring dynamics to reduce the vibrations and the probability of a premature failure of the downhole [16,17].

Ghasemloonia et al. [18] predicted the effect of vibration modes that changed with the variation of the drilling parameters such as rotary speed and weigh-on-bit on the bottom-hole assembly (BHA) configuration. In the study, the effects of mud damping, driving torque, and spatially varying axial load were qualitatively investigated. The nonlinearities resulted from the geometry, axial stiffening, strain energy and Hertzian contact forces on the drillstring were also investigated. They revealed that the coupled nonlinear axial-transverse vibrations and lateral instabilities resulted in damaging the drilling tool and damaging the entire drillstring. While, Kapitaniak et al. [19] conducted the effect of complex drillstring vibrations and the role of stick–slip oscillations, whirling, drill-bit bounce and helical buckling of the drillstring on the drilling rig conditions.

To further understanding the role of the advancement of “Measurement While Drilling” (MWD) tools and their real-time implementation on the drillstring vibrations modeling and the state-of-the-art of axial, torsional and bending vibrations (uncoupled and coupled) models and how they can be mitigated, there are several recently published articles by Butt's team [18,20] comprehensively summarized the drillstring vibration modeling can be helpful. Additionally, Chi et al. [22] identified the key factors affecting the combined role of axial and torsional drillstring vibrations during drilling the gas-bearing igneous formations in the Songliao basin, China in order to develop a control-mechanism of the severe damage of the drillstring and reduce its premature failure. Results of computerized model that was built to simulate loads from the axial and the torsional vibrations revealed that the vibration had a great impact on the drilling performance in that area and significantly shortened the drill string's life.

Moreover, a number of researchers [23–28] identified the effects of varying drillstring velocities of translation and rotation to maximize the efficiency of drilling process on nonlinear stochastic dynamics i.e., bit-bounce, stick–slip, and transverse impacts. For instance, Kreuzer and Steidl [23] studied the effect of changing the direction of dynamics traveling waves; in the direction of the top drive and in the direction of the drill bit on the torsional vibrations (or stick–slip vibrations) in the drillstring. It was revealed that the stick–slip vibrations are detrimental to the drilling process where they slow down the rate of penetration and then possibly lead to the drilling failure. The effects of lateral vibrations on bottom hole assembly (BHA) during back reaming operations (or during the operation of pulling out the drillstring) were evaluated by Agostini and Nicoletti [24]. It was shown that the occurrence of abnormal lateral vibrations during back reaming can effectively cause BHA electronic equipment failure, falling rocks into the well, and drillstring blockage. The analytical results of block-on-belt model presented by Tang and Zhu [26] also indicating that the stick–slip vibration on a drillstring length of 3000 m is detrimental to the drilling equipment and the drilling efficiency.

The drillstring vibrations in relation to the effective length of the string when it rests on the borehole wall and the exact form of the beam curvature were analyzed by Hakimi and Moradi [29] using the differential quadrature method (DQM). The numerical results showed that the axial and torsional natural frequencies are affected by the length of string and the beam curvature and consequently detrimental to the efficiency and accuracy of the drilling process.

2.1.3. Buckling

In the oil and gas drilling industry, analysis of the drill pipe buckling load has been a challenge since the buckling load can increase the bending stress and over time lead to fatigue failure of the drill pipe [30]. Most of the analytical, numerical and experimental studies conducting the buckling failure in different wellbore geometries such as vertical, inclined, and curved are reviewed in the Ref [30]. The effects of torque, friction, flow rate, and tool joints on the sinusoidal and helical critical buckling loads are presented in the Ref [31]. They concluded that a comprehensive model is required to manipulate different aspects of the buckling in the drillstring that may especially encounter with increasing depth and deviation of the wells. In inclined wellbores, the drillstring first changes into a sinusoidal buckling shape and then changes to a helical buckling. The drillstring is usually considered as a long beam with a length to thickness ratio is high.

Sun. et al. [32] analyzed the nonlinear static post-buckling deformation, critical dynamic buckling load, and two different kinds of snaking motions i.e. the pipe moves up and down around its static buckling configuration or the pipe moves from one side of the wellbore to the other side of a rotating drillstring constrained in a horizontal well. The theoretical calculations of the buckling loads and the right selection of the bottom hole-assembly components were found to be useful for the practical design applications of the rotational drill pipe at high speeds and at small or large oscillation amplitudes.

2.1.4. Wash out and twist-off

Wash out and twist-off are common failure modes encountered at the drill pipes. These failures consider to mostly be due to the mechanical fatigue damage or corrosion [33]. Corrosion in the drill pipe is sort of the deterioration happened due the reaction between the pipe and the environment. The corrosion mechanisms in the drill pipes are either electrochemical corrosion or corrosion by mechanical action or by a combined effect of the mechanical and the corrosive agents. However, describing of the principal concepts of corrosion and its types or its mechanisms encountered in the drill pipe is not considered in this review article.

The wash out as a non-critical failure can be defined as a leak, crack or a small opening in the drill pipe [34], see Fig 4 a, caused by a large pressure of the drilling mud. Large pressure that drives flow of the mud from the pipe bore to the annulus would widen and propagate the created opening through the pipe body which, in turn resulting in a post-separation catastrophic failure to the fracture surface of the drill pipe. This phenomenon is called "twist-off" (Fig. 4 b).

The wash out is relatively a more common failure while the twist-off failure is a less frequent, that is severe and very expensive failure. Based on the collected database from previous studies conducted the failure analysis of the drillstring [1,6,33], it was revealed that around a 95% of the drill pipes failed by washout near the bottom hole assembly and the rest failed by the twist off. A 65% of these failures are belonging to the slips area, and a 22% of them occurred in the drill collars. Moreover, another operational factor is capable to generate a stress concentration and lead to a complete fracture, that is die-marks which produced from slip and tongs [33]. This, in turn, can produce permanent marks on the external pipe body as shown in Fig. 5. For further understanding the washout failures in the drill pipes, numerous images were reproduced and presented in Fig. 6.

2.1.5. Other failure modes occurred in the drill pipes

With the drilling process of an oil well, many failures modes are encountered in the drill pipes rather than those discussed above, such as pipe sticking, pipe-parting, collapse and burst failure [35]. These failures frequently occur due to the similar uncertainty in stresses imposed on the downhole even with very careful planned wells. The ductile fracture, brittle fracture, and fatigue are also considered within these damage mechanisms (see Fig. 7).

External damage arising from poor pipe handling practices can occasionally lead to failure at random locations along the length of the drill pipe. For such occasions, the stabilizers are normally used to reduce the drillstring vibration and enhance the drilling performance. The stabilizers are also used to improve the wellbore stability and optimize the well placement for faster production in the borehole enlargement operations [36]. Without stabilizers, the drill pipe is stuck where it cannot be freed and pulled out of the borehole unless the pipe is damaged or it is exceeding the maximum allowed hook load of the drilling rig [35,37]. There are two common kinds of the pipe sticking failures: Mechanical pipe sticking that happens due to the inadequate removal of the drilled cuttings from the annulus; and the differential-pressure pipe sticking that happens when a portion of the drillstring becomes embedded in the mud cake (or fine solids).

The pipe-parting failure is happened when the induced tensile stress exceeds the pipe-material ultimate tensile stress. In other words, such kind of failure happens when the pipe is sticking and hence a higher pull force is required to pull it out so that an over force will be added to the weight of the suspended pipe in the hole above the stuck point. The extra force will tend in turn, in parting the drill pipe [35].

2.2. Failure analysis of the drilling bits (hammer bits)

Drilling bit is a cutting tool or boring tool that is made up on the end of the drillstring, which drills through the rock by scraping, chipping, gouging or grinding the rock at the bottom of the hole. The repeated impact forces required for breaking the rock at complex downhole conditions besides the inadequate mechanical properties of the bit material, result in a severe bit bouncing or

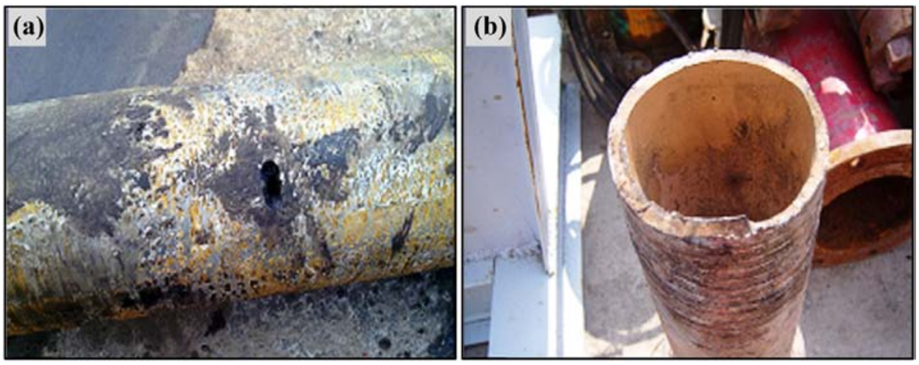

Fig. 4. (a) The washout failure of drillstring, and (b) Twist-off fracture surface [6].

Fig. 5. Effect of die-marks on the failure of drill pipe [33].

failure of the drilling bits [38]. There is a number of failure modes occurred in the hammer bit such as tooth loss, tooth fracture and tooth wear as well as micro- and macro-cracks [19]. A brief description of each one of these bit failures is given below.

2.2.1. Tooth loss

The drilling bit body is susceptible to a plastic deformation when it is compressed by harder teeth under the effect of a severe repeated impact and rotation. This is resulted in a reduced shrink range (or joint surfaces) between the tooth holes and the teeth [33]. And as a result of the frictional force of the tooth holes, the holes become weak and then wear down. The lost teeth are mainly peripheral teeth on the inclined plane of the bit end face (see Fig. 8 a).

2.2.2. Tooth fracture

The tooth fracture is probably occurred due to the impact spalling where the failed teeth contain many different sizes of spalling pits and grooves linked together by spalling bits (see Fig. 8b). The crack extensions around the spalling pits formed due to growing of the grooves deeper and wider can also result in tooth fracture and local spalling. Additionally, under the repeated impacts, the tooth generates fatigue cracks and this would tend to a tooth fracture [41].

2.2.3. Tooth wear

The tooth wear (or a high-stress crushed abrasive wear) shown in Fig. 8c, is occurred when a compressive stress on the joint surfaces between the tooth and the abrasive particle exceeds the breaking strength of the abrasive particle. Consequently, a stress concentration will be generated on these joint surfaces which tends to continually crush the abrasive particles. The stress concentration will work to increase the fatigue damage on the tooth surfaces. The scouring effect, or the compressed air mixed with large

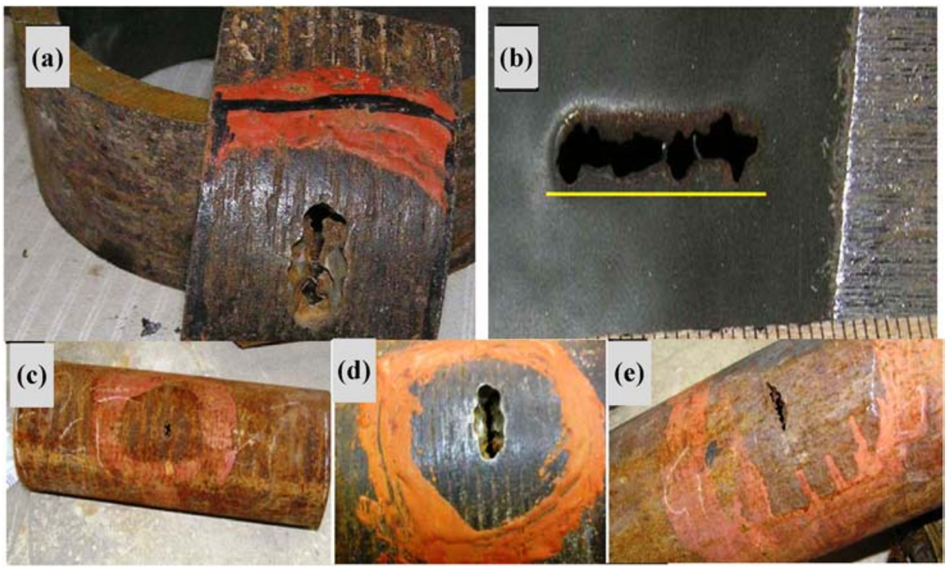

Fig. 6. Washout failures occurred on the external surfaces of the drill pipes [33].

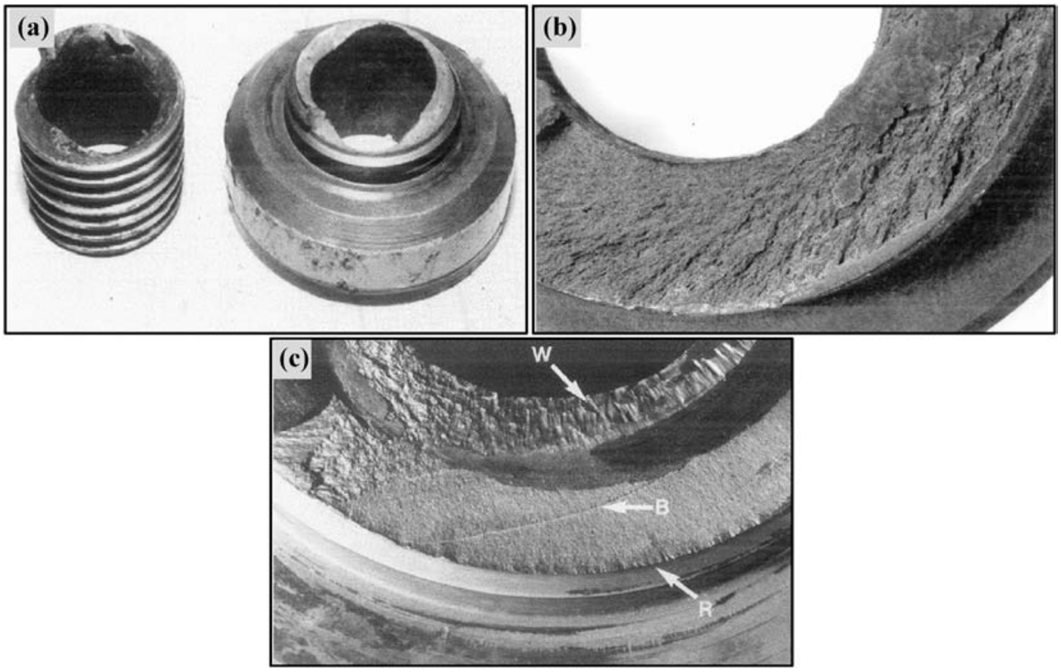

Fig. 7. Common modes of fracture, (a) ductile, (b) brittle, and (c) fatigue. The letter R in image (c) refers for radial steps along initiation region at thread root, B for beach marks from fatigue and W for wash-out [1].

amount of the hard cuttings flows over the tooth surfaces increases the abrasive wear on the tooth surfaces. Also, when a tooth surface encounters sharp edges or protrusions, the tooth scrapes happen easily.

Basically, there are three types of drilling bits: drag bits, roller cone bits, and diamond bits (see Fig. 9) [42]. Although, drilling fluid is more often used to remove the hard drilled cuttings and circulate through passageways in the bit and consequently lengthening the bit's life; there are many parameters that could determine the function of the drilling bits and their life. These are as drillstring rotations per minute (RPM), weight on bit (WOB), and the properties of mud as well as hydraulic efficiency and how severe does the dogleg if any. However, understanding these operating parameters and their effects on the drilling bit is not the main topic of this study.

The vibration is unavoidable factor affecting the performance of the bits due to the drilling process of cutting rock either by chipping (using drag bits) or crushing (using roller cone bits) action. Thus, many experimental and numerical studies were done on various drill bits materials in order to conduct the appropriate design of the drilling bits these can be successfully used to drill very soft or ultra-hard formations and withstanding high temperatures and extended run time. For instance, Fan et al. [5] analyzed the reasons behind the failures of the WC–Co cemented carbide hammer bit under the percussion drilling using the rock-breaking mechanism. They revealed that the mechanical properties of the used bit material cannot undergo the coupling action of the impact spalling, impact fatigue and abrasive wear. Hence, an alternative new Al_2O_3/WC–Co nanocomposite material was used instead; that is observed much better micro-hardness, bending strength and impact toughness.

Ehmann and Che [43] experimentally analyzed the drilling performance of Polycrystalline Diamond Compact (PDC) bits under different face turning cutting conditions of rock in order to determine the force responses and the shear cutting mechanism as

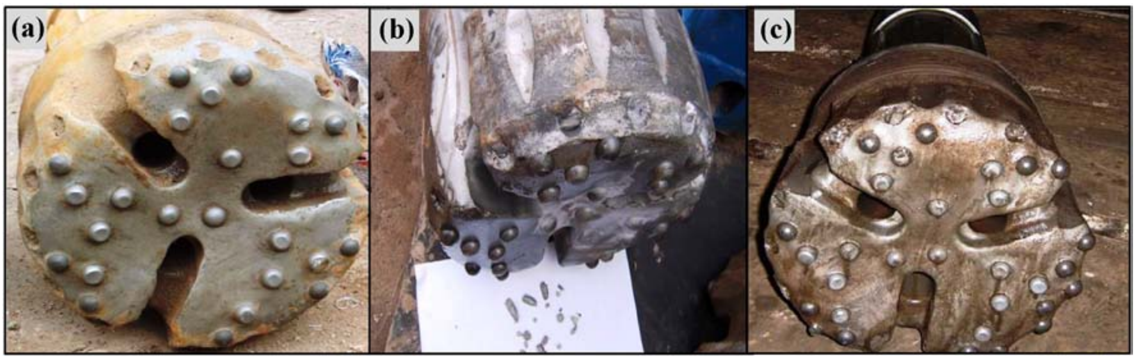

Fig. 8. Failure modes of the hammer bits: (a) tooth loss, (b) tooth fracture, and (c) tooth wear [5].

Fig. 9. Types of drilling bits [42].

well as achieve faster drilling speeds in the real-time. It was found that the PDC bits can only cut relatively soft rock formations such as shales, soft and unconsolidated sand stones, and carbonates. They cannot effectively drill hard formations such as granite, chert, pyrite, quartzite, and conglomerate. It was also found that the force response can be classified into four categories: frictional effect, plowing effect, lateral interaction effect, and shearing effect.

In addition, numerous research topics were achieved to improve the performance of the hammer drilling bits. Some of these studies involving strengthening of a bit material and profile optimization. Others involved wear prevention, force response predictions, and in-field process monitoring and dynamic process control. For example, Karakus and Perez [44] improved the performance of diamond hammer drilling bits by estimating the depth of cut, weight on bit and torque on bit (TOB). They simply determined the relationship between the acoustic emission (AE) signals and the drill bit wear using the time spectrum of the acoustic emission. Katiyar et al. [45] recently analyzed the failure mechanisms of the WC/Co tungsten carbide drill bits/blades in rock drilling. The results showed that the WC/Co drill bit exhibited a unique strength at elevated temperature and high mechanical and chemical resistance, but it gradually degraded till it broke at the end of its life.

2.2.4. Bit balling

Bit balling is a failure occurred due to sticking of drill cuttings on the bit surface in water-reactive clay/shale formations. There are two mechanisms of bit balling sticking: mechanical and electrochemical. Numerous factors affecting the bit balling sticking such as clay calcite content, highly reactive clays with large cation exchange capacities promoted by a high hydrostatic pressure of borehole ranging from 5000 to 7000 psi. High weight on bit, poor projection of bit cutting structure due to inappropriate bit choice or bit wear, poor bit hydraulics or low flow rate are also affecting the bit balling. Hence, anti-balling coating is the best solution to combat the bit balling. A metallic layer with highly specialized properties covers the bit surface leads to smoothen the surface and eliminate the bit balling since the rough surface of the bit will increase the surface area and increase the adhesive forces [46].

Luo et al. [47] designed a newly structured drill bit for a reverse circulation downhole air hammer as an attempt to reduce the bit balling. For this purpose, three optimized drill bits having two mid-pressure restoring grooves with a diameter of 8 mm; two symmetrically placed flushing nozzles with a diameter of 3 mm and six uniformly distributed suction nozzles with a diameter of 6 mm for each layer were built.

Failure analysis of chrome coated drilling bit under a variety of drilling fluid characteristics upon circulation and influxes was studied by Ranjbar and Sababi [48]. They also studied the effects of working parameters i.e., bottom hole temperature and solid content on the bits' life time. It was observed that various types of damages such as scratches, coated layer detachment, deep and shallow cuttings as well as spalling pits, micro and macro-cracks occurred on the chrome coated surface as shown in Fig. 10.

3. Other failure modes occurred through the drilling process

Wellbore instability considers one of the drilling operation problems where it is affected by properties of the drilling mud and its interaction with the formation, by the mechanical properties of the formation and by the magnitude and distribution of the forces around the wellbore [49,50]. Sloughing or swelling shales and abnormal pressured shale formations are also affected the wellbore instabilities [51].

The main mechanisms of the shale instabilities i.e., the pore pressure transmission and chemical osmosis were investigated by Akhtarmanesh et al. [51] in order to evaluate their significance in the wellbore stability with respect to the physical and chemical properties of the shale and thermodynamics condition. It was revealed that the shale formations can cause many problems such as partial or huge slump which in turn, resulting in pipe sticking or poor hole conditioning, bit balling and bit floundering as well as low quality logging and drilling fluid contamination due to its mixing with dispersed active clay particles.

Jincai Zhang [52] calculated the borehole failures, wellbore sliding/shear failures in relation to the mud weight along borehole trajectories with various drilling orientations versus bedding planes (see Fig. 11). The rock anisotropy and their impacts on the horizontal stresses were considered and the slip failure gradient in the weak planes derived to improve the borehole stability. Two main types of borehole instabilities, are tight hole and stuck pipe incidents, which are potentially dangerous and caused

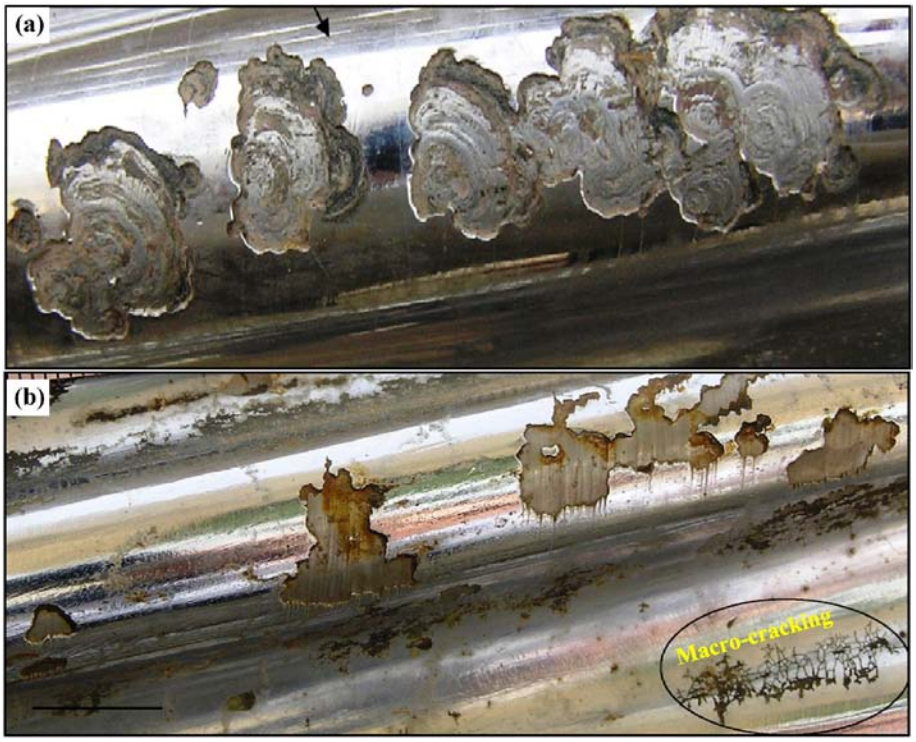

Fig. 10. Showing spalling failure and cutting of chrome coated rotors surface (a), and detachment surface failure of chrome layer and macro-cracking (b) [48].

by the hole collapse (rock mechanical failure), inappropriate hole cleaning, differential sticking, and deviation from ideal trajectory.

4. Conclusion

Failure analysis of the drill pipes and drill bits were presented in this review article in order to understand the downhole drilling conditions and determine the factors causing these failures. A brief description on the most prevalent failures of the drilling tools such as fatigue, vibration, buckling, washout and twist off as well as tooth wear and tooth fracture was provided. Other failure modes of the drilling process i.e., pipe sticking, hole deviation, borehole instability, mud contamination were also briefly discussed.

Understanding the drilling problems and their causes, and planning solutions are necessary to avoid very costly drilling problems and successfully achieving the target zone. The article concluded that among many metallurgical and mechanical failures, fatigue cracks are responsible of the majority of drillstring failures. These cracks initiated mainly due to different forms of vibrations, slip cuts and similar irregularities. Table 1 briefly describes most of the dominant forms of the drillstring failures occurred during the drilling process of wellbore and reasons (or working conditions) causing these failures as concluded from previous published studies.

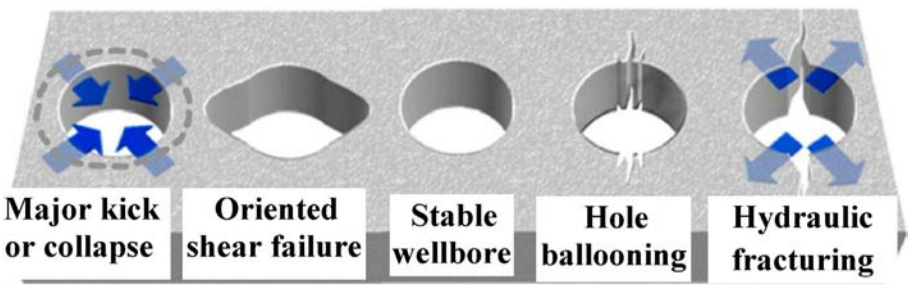

Fig. 11. Schematic showing borehole failures in relation to the mud pressure [52].

Table 1
Some types of failure modes occurred in the drillstring (drill tools).

Failure modes	Reasons causing these failures	Remarks
Fatigue failure	- Fluctuated weight. - Repeated rotational speeds (loads or torque). - High penetration rate of the drillstring.	Fatigue failure occurs due to a high stress concentration in the thread roots connections and a high stress concentration at the upset transition area of the drill pipe.
Axial vibrations Torsional vibrations Lateral vibrations	The drillstring moves along its axis of rotation. An irregular rotation of the drillstring rotated from the surface at a constant speed. The drillstring moves laterally to its axis of rotation.	It is essentially operating the drillstring above or below the critical speed and performing pre-drilling analysis and real time analysis of the drillstring dynamics to reduce the vibrations and the probability of a premature failure of the downhole.
Buckling in the drill pipe	Bending stress.	Over time the bending stress causing the buckling load tends to the occurrence of fatigue failure of the drill pipe.
Wash out and Twist-off failure in the drill pipe.	- Mechanical fatigue damage or corrosion. - A large pressure of the drilling mud.	The wash out is a leak, crack or a small opening in the drill pipe. Twist off is a post-separation catastrophic failure to the fracture surface of the drill pipe.
Pipe sticking; Pipe-parting; Collapse and Burst failure	- The induced tensile stress exceeds the pipe-material ultimate tensile stress. - Poor pipe handling practices.	The stabilizers are normally used to reduce the drillstring vibration and improve the wellbore stability and optimize the well placement for faster production in the borehole enlargement operations.
Tooth loss	Severe repeated impact and rotation.	–
Tooth fracture	- The impact spalling where the failed teeth contain many different sizes of spalling pits, and grooves linked together by spalling bits. - The crack extensions around the spalling pits formed due to growing of the grooves deeper and wider can also result in tooth fracture and local spalling.	The tooth generates fatigue cracks and this would tend to a tooth fracture.
Tooth wear	- When a compressive stress on the joint surfaces between the tooth and the abrasive particle exceeds the breaking strength of the abrasive particle. - When a tooth surface encounters sharp edges or protrusions, the tooth scrapes happen easily.	A stress concentration will be generated on these joint surfaces which tend to continually crush the abrasive particles. The stress concentration will work to increase the fatigue damage on the tooth surfaces. The scouring effect, or the compressed air mixed with large amount of the hard cuttings flows over the tooth surfaces increases the abrasive wear on the tooth surfaces.
Bit balling	- Sticking of drill cuttings on the bit surface in water-reactive clay/shale formations. - Inappropriate bit choice or bit wear. - Poor bit hydraulics or low flow rate.	Factors affecting the bit balling sticking are: - Clay calcite content, - High weight on bit, and - Poor projection of bit cutting structure.
Wellbore instability	- Properties of the drilling mud and its interaction with the formation. - Mechanical properties of the formation, and - Magnitude and distribution of the forces around the wellbore.	Sloughing or swelling shales and abnormal pressured shale formations are also affected the wellbore instabilities.
Wellbore sliding/shear failure	Mud weight along borehole trajectories, and drilling orientations.	–

Additionally, number of studies proposed some points for preventing drillstring failure. For instance, the drillstring should be ensured to be in a good shape before entering the borehole. Also, shock adsorption device made with advanced alloys is a highly recommended to be installed on a high-strength drillstring to compensate the negative effect due to absence of drilling mud in air drilling process; and furthermore design of a novel drillstring for efficient drilling process or modified the drillstring surface with advanced coating technique.

References

[1] K.A. Macdonald, J.V. Bjune, Failure analysis of drillstrings, Eng. Fail. Anal. 14 (2007) 1641–1666.
[2] H. Fang, M. Duan, Offshore oil and gas drilling engineering and equipment, Offshore Operation Facilities: Equipment and Procedures, Elsevier Science Limited 2014, pp. 141–340.
[3] M.Z. Lukawski, B.J. Anderson, C. Augustine, L .E.C. Jr., K.F. Beckers, B. Livesay, et al., Cost analysis of oil, gas, and geothermal well drilling, J. Pet. Sci. Eng. 118 (2014) 1–14.
[4] P.M. Bommer, A Primer of Oilwell Drilling, seventh ed. University of Texas at Austin - Petroleum Extension Service, 2008.
[5] Y. Fan, Z. Huang, D. Gao, Q. Li, Experimental study of an Al2O3/WC–Co nanocomposite based on a failure analysis of hammer bit, Eng. Fail. Anal. 18 (2011) 1351–1358.
[6] R.-h. Wang, Y.-b. Zang, R. Zhang, Y.-h. Bu, H.-z. Li, Drillstring failure analysis and its prevention in northeast Sichuan, China, Eng. Fail. Anal. 18 (2011) 1233–1241.
[7] H. Liao, Z. Guan, Y. Shi, Y. Liu, Field tests and applicability of downhole pressurized jet assisted drilling techniques, Int. J. Rock Mech. Min. Sci. 75 (2015) 140–146.
[8] P.A. Patil, C. Teodoriu, A comparative review of modelling and controlling torsional vibrations and experimentation using laboratory setups, J. Pet. Sci. Eng. 112 (2013) 227–238.
[9] R. Caenn, H.C.H. Darley, G.R. Gray, Drilling fluid components, Composition and Properties of Drilling and Completion Fluids 2011, pp. 535–616.
[10] M.J. Knight, F.P. Brennan, Fatigue life improvement of drill collars through control of bore eccentricity, Eng. Fail. Anal. 6 (1999) 301–319.
[11] Y. Lin, X. Qi, D. Zhu, D. Zeng, H. Zhu, K. Deng, et al., Failure analysis and appropriate design of drill pipe upset transition area, Eng. Fail. Anal. 31 (2013) 255–267.
[12] L. Yonggang, L. Fangpo, X. Xin, Y. Biyu, L. Caihong, Simulation technology in failure analysis of drill pipe, Procedia Eng. 12 (2011) 236–241.

[13] X. Zhu, L. Dong, H. Tong, Failure analysis and solution studies on drill pipe thread gluing at the exit side of horizontal directional drilling, Eng. Fail. Anal. 33 (2013) 251–264.
[14] S. Luo, S. Wu, Effect of stress distribution on the tool joint failure of internal and external upset drill pipes, Mater. Des. 52 (2013) 308–314.
[15] W.C. Chin, Drillstring vibrations: classic ideas and modern approaches, Wave Propagation in Drilling, Well Logging and Reservoir Applications 2014, pp. 109–256.
[16] F. Poletto, J.M. Carcione, G. Pinna, Flexural waves in drill-string tubulars with variable loads, Geophys. Prospect. 61 (2013) 955–972.
[17] S.M. Sahebkar, M.R. Ghazavi, S.E. Khadem, M.H. Ghayesh, Nonlinear vibration analysis of an axially moving drillstring system with time dependent axial load and axial velocity in inclined well, Mech. Mach. Theory 46 (2011) 743–760.
[18] A. Ghasemloonia, G. Rideout, S. Butt, Analysis of multi-mode nonlinear coupled axial-transverse drillstring vibration in vibration assisted rotary drilling, J. Pet. Sci. Eng. 116 (2014) 36–49.
[19] M. Kapitaniak, V. Vaziri Hamaneh, J. Páez Chávez, K. Nandakumar, M. Wiercigroch, Unveiling complexity of drill-string vibrations: experiments and modelling, Int. J. Mech. Sci. 101–102 (2015) 324–337.
[20] A. Ghasemloonia, G. Rideout, S. Butt, A review of drillstring vibration modeling and suppression methods, J. Pet. Sci. Eng. 131 (2015) 150–164.
[22] A. Chi, J. Zhang, W. Ge, B. Guo, Prediction of fatigue life of drillstring under axial-torsional combined vibrations, SPE Gas Technology Symposium, Society Of Petroleum Engineers, 15–17 May, Calgary, Alberta, Canada, 2006.
[23] E. Kreuzer, M. Steidl, Controlling torsional vibrations of drill strings via decomposition of traveling waves, Arch. Appl. Mech. 82 (2012) 515–531.
[24] C.E. Agostini, R. Nicoletti, Dynamic modeling and vibration analysis of oilwell drillstring during backreaming operation, in: T.i.M.A. I (Ed.), Society for Experimental Mechanics Series 2014, pp. 123–131.
[25] V.I. Gulyaev, P.Z. Lugovoi, E.I. Borshch, Self-excited vibrations of a drillstring bit, Int. Appl. Mech. 49 (2013) 350–359.
[26] L. Tang, X. Zhu, Effects of the difference between the static and the kinetic friction coefficients on a drill string vibration linear approach, Arab. J. Sci. Eng. 40 (2015) 3723–3729.
[27] A. CunhaJr, C. Soize, R. Sampaio, Computational modeling of the nonlinear stochastic dynamics of horizontal drillstrings, Comput. Mech. 56 (2015) 849–878.
[28] Q. Xue, H. Leung, R. Wang, B. Liu, L. Huang, Shenglai Guo, The chaotic dynamics of drilling, Nonlinear Dyn. 83 (2016) 1–16.
[29] H. Hakimi, S. Moradi, Drillstring vibration analysis using differential quadrature method, J. Pet. Sci. Eng. 70 (2010) 235–242.
[30] J.S.D. Mehdi Hajianmaleki, Advances in critical buckling load assessment for tubulars inside wellbores, J. Pet. Sci. Eng. 116 (2014) 136–144.
[31] Y. Sun, Y. Yu, B. Liu, Closed form solutions for predicting static and dynamic buckling behaviors of a drillstring in a horizontal well, Eur. J. Mech. A. Solids 9 (2015) 362–372.
[32] Y. Sun, Y. Yu, B. Liu, Closed form solutions for predicting static and dynamic buckling behaviors of a drillstring in a horizontal well, Eur. J. Mech. A. Solids 49 (2015) 362–372.
[33] S. Moradi, K. Ranjbar, Experimental and computational failure analysis of drillstrings, Eng. Fail. Anal. 16 (2009) 923–933.
[34] M.J. Knight, F.P. Brennan, W.D. Dover, Controlled failure design of drillstring threaded connections, Fatigue Fract. Eng. Mater. Struct. 26 (2003) 1081–1090.
[35] J.J. Azar, Drilling Problems and Solutions, Petroleum Engineering Handbook, SPE International Publication 2015, pp. 433–454.
[36] V.I. Gulyaev, I.L. Solovev, I.V. Gorbunovich, Stability of drillstrings in ultra-deep wells: an integrated design model, Int. Appl. Mech. 45 (2009) 772–779.
[37] J.M. Kamel, A.S. Yigit, Modeling and analysis of stick–slip and bit bounce in oil well drillstrings equipped with drag bits, J. Sound Vib. 333 (2014) 6885–6899.
[38] S. Xu, Y.-z. Liu, L.-y. Zhou, Y.-m. Yan, H.-w. Zhu, Failure analysis of the 18CrNi3Mo steel for drilling bit, J. Fail. Anal. Prev. 14 (2014) 183–190.
[41] D. Harris, T. Jur, Classical fatigue design techniques as a failure analysis tool, J. Fail. Anal. Prev. 9 (2009) 81–87.
[42] W.H. Wamsley Jr., R.F. Smith, Introduction to roller-cone and polycrystalline diamond drill bits, Petroleum Engineering Handbook, SPE publication 2015, pp. 221–264.
[43] D. Che, K. Ehmann, Experimental study of force responses in polycrystalline diamond face turning of rock, Int. J. Rock Mech. Min. Sci. 72 (2014) 80–91.
[44] M. Karakus, S. Perez, Acoustic emission analysis for rock-bit interactions in impregnated diamond core drilling, Int. J. Rock Mech. Min. Sci. 68 (2014) 36–43.
[45] P.K. Katiyar, P.K. Singh, R. Singh, L. Kumar, Modes of failure of cemented tungsten Carbide tool bits (WC/Co): a study of wear parts, Int. J. Refract. Met. Hard Mater. 54 (2016) 27–38.
[46] M. Javidi, M. Saeedikhani, R. Omidi, Failure analysis of a gas well tubing due to corrosion: a case study, J. Fail. Anal. Prev. 12 (2012) 550–557.
[47] J.P. Yongjiang Luo, Lijia Li, Jiangfu He, Xin Gan, Kun Yin, Zhiqiang Zhao, Development of a specially designed drill bit for down-the-hole air hammer to reduce dust production in the drilling process, J. Clean. Prod. 112 (2016) 1040–1048.
[48] K. Ranjbar, M. Sababi, Failure assessment of the hard chrome coated rotors in the downhole drilling motors, Eng. Fail. Anal. 20 (2012) 147–155.
[49] M.E. Zeynali, Mechanical and physico-chemical aspects of wellbore stability during drilling operations, J. Pet. Sci. Eng. 82-83 (2012) 120–124.
[50] L. Cheng, D. Tianhuai, W. Peng, An experimental rig for near-bit force measurement and drillstring acoustic transmission of BHA, Measurement 44 (2011) 642–652.
[51] S. Akhtarmanesh, M.J.A. Shahrabi, A. Atashnezhad, Improvement of wellbore stability in shale using nanoparticles, J. Pet. Sci. Eng. 112 (2013) 290–295.
[52] J. Zhang, Borehole stability analysis accounting for anisotropies in drilling to weak bedding planes, Int. J. Rock Mech. Min. Sci. 60 (2013) 160–170.