Fatigue failure analysis of drilling tools for ultra-deep wells in shunbei Block

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Abstract: The ultra-deep wells in the north of the Shunbei block have a vertical depth of about 7500m. During the drilling process, the upper drilling tools often fail. The failure modes are based on the fatigue damage of the drill joint surfaces and threads. The causes of failure are analyzed from the axial and bending stresses and the high temperature and corrosion environment of ultra-deep wells. The major axial stress is the main feature of ultra-deep well drilling. The step surfaces and threads are the stress concentration sites, and the maximum load is close to the material yield limit. The bending stress is the main factor that causes the fatigue load, its size increases with the increase of the rotational speed. The high temperature and the corrosive environment will cause the drilling material to reduce the fatigue limit. The NCODE software was used to perform fatigue finite element simulation on the drilling tool, and the fatigue life of the drilling tool under different stress conditions was analyzed. The main influencing factors of drilling tool failure during ultra-deep well drilling in the north of the area were pointed out, providing a reference for drilling tool design in this area.

1. Introduction

Ultra-deep well drilling tools have large loads and the downhole environment is complex. Drilling tool failures occur from time to time during drilling. Drilling tool damage occurred at the beginning of the development of Shunbei Block and caused heavy losses. Based on the failure mechanism of the drilling tool, the failure situation of the ultra-deep well assembly in the Shunbei block was analyzed. It was found that the failure of the ultra-deep drilling tool occurred mostly in the joints of the upper drill pipe and the lower drill collar, and the failure causes were mostly fatigue damage. This article mainly focuses on the fatigue failure analysis of the upper drill pipe.

2. The Basic Situation Of Ultra-deep Wells In North

2.1 Well Structure
The Shunbei block is located in the territory of Shaya County, Xinjiang, and is located in the Gobi Desert in the northern part of the Taklamakan Desert. The block area is about 3000 km², and the reservoir depth is about 7500 m [1]. In the north of the Shunbei block, a six-well well structure was used in advance. During the drilling process, complex downhole conditions occurred several times. After optimization, the wellbore structure is simplified to the new fourth level. Taking the North Well X as an example, the wellbore structure is shown in (Figure 1).

2.2. Drill Assembly
In the north of the ultra-deep well in the north block, the vertical section is opened, and the fourth section is the horizontal section. During the drilling process, the drilling tool was found to be damaged many times through the pre-drilling inspection. Drilling tool failures typically occur when drilling to a depth of more than 6,000 meters. The failure mode is based on the fatigue damage of the stepped surface and the thread at the drill pipe joints. The occurred parts are located in the upper 139.7 mm drill pipe. One of the two drilling tools is as follows:

Ф250.88mm PDC bit + Ф203mm extruding short joint + Ф197mm screw + Ф177.8mm drill boring 1 + Ф248mm centralizer + Ф177.8mm drill boring 11 + Ф127mm weight the drill pipe 141m + Ф127mm drill pipe 1644 m + Ф139.7 drill

3. Analysis of Fatigue Failure Factors of Ultra-deep Well Drilling Tools
Different from conventional drilling, ultra-deep well drilling tools can withstand higher drill string weight, higher downhole temperature, and longer drilling fluid corrosion time. Therefore, drilling tools have a higher chance of failure. Taking X well of Shunbei as the research object to analyze the failure cause of drilling tool fatigue.

3.1. Bending Stress
According to the literature [2], most of the drilling tool failures are caused by fatigue, and the reverse movement of the drill string is the direct cause of the alternating stress. The maximum bending stress of the drill is calculated as follows:

\[
\sigma_x = \frac{\gamma A R a f L^2}{8g(T/c)} \left[1 + 1.032 \times \left(\frac{(\omega_f + \omega)}{a f} + \frac{a f}{a f}ight)^2 \frac{a f}{a f} \frac{E}{E} \right]^{1/2} (1)
\]
It can be known from equation (1) that part of the bending stress of the drill string comes from the reversal motion of the drill string with \( R \) as the radius, and the other part comes from the forced vibration of the drill string under the self-excited transverse vibration.

Due to the large axial stress in the upper part of the ultra-deep well, forced vibration is hardly to occur. Therefore, the maximum bending stress of the drilling tool can be approximately equivalent to:

\[
\sigma_{b0} = \frac{\gamma_s R \omega^2}{8g(I/c)}L^2 = 9.37 \text{ MPa} \tag{2}
\]

When the drilling tool and borehole size are certain, the bending stress of the drilling tool is proportional to the square of the speed of the drill string. Therefore, the greater the speed, the greater the bending stress on the drill string, as shown in (Fig 2).

![Fig. 2 Variation of bending stress of upper drill pipe with rotating speed](image)

### 3.2. Axial Stress

The large axial load is the most distinctive characteristic of ultra-deep well drilling, especially the drill pipe near the wellhead, which almost bears all the drill string weight. The axial stress of the drill string mainly comes from the drilling pressure, the weight of the drill string and the buoyancy of the drilling fluid, and the axial tensile stress of the 139.7mm drill pipe at the wellhead when the North X-well drilled to the well depth of 6840m [3].

\[
\sigma_{a0} = L \gamma_s K_j - P_a/A = 486.23 \text{ Mpa} \tag{3}
\]

Drill pipe joints are the places where the drill tool has high stress concentration, especially at the shoulders and threads, and the local stress is far greater than the theoretical average. When the stress concentration factor is 1.89 [2], the maximum axial tensile stress is:

\[
\sigma_{a0} = \sigma_{a0} \times K_p = 918.97 \text{ Mpa} \tag{4}
\]

The ultra-deep well drilling upper drill generally adopts S135 steel grade, its tensile strength is 1137.46 MPa, and its yield strength is 1049Mpa. It can be stated that the static load of the drill string during normal drilling can meet its performance requirements.

When calculating fatigue damage, too high a static load will result in a reduction in the fatigue limit of the drill. The existing indoor fatigue test results show that the fatigue limit in the air of S135 drill rod steel [4] is 553 MPa. From the analysis of the size of the cyclic load, the cyclic load on the upper drill is far less than the fatigue limit, and no fatigue failure occurs. However, the indoor test is to use the fatigue limit measured by symmetrical cyclic load, without considering the influence of axial stress, and the fatigue limit of asymmetric cyclic stress will gradually decrease with the increase of static load, especially when the static load strength approaches the yield limit. Fatigue life will be greatly reduced.
3.3. High Temperature and Corrosion Environment

Drilling tools are inevitable during drilling. Due to the long operation time of drilling in ultra-deep wells, drilling tools are in a corrosive drilling fluid environment for a long time. Under the action of alternating stress, slippage occurs between metal crystal lattices, and the protective film on the metal surface is destroyed. At the same time, due to electrochemical corrosion, microscopic corrosion will occur at the slip point. The micro-etching gradually forms an etch pit under alternating stress. The etch pit is the source of micro-crack formation, and the crack eventually fractures under alternating stress. Under the corrosion conditions, the bending fatigue test was performed on the S135 drill rod steel and its critical fatigue strength was 409 MPa.

The bottom-hole temperature of ultra-deep wells is higher than 180°C at 7000m. During the drilling process, the fluid temperature in the wellbore is generally higher than the surface temperature with the circulation of drilling fluid. As shown in (Fig 3), the effect of temperature on the fatigue life of the drill string is significant, which is mainly reflected in the fact that the corrosion rate of metal materials increases with increasing temperature, and the fatigue limit decreases [5].

\[ \sigma_1 \] is the fatigue limit at room temperature; \((\sigma_1) _t\) is the fatigue limit at temperature \(t\)

![Fig. 3 Effect of temperature on fatigue limit of different materials](image)

Under the combined effect of high temperature and corrosion, the corrosion fatigue limit of S135 drill pipe steel at 170°C is 376Mpa.

Based on the above analysis, it can be seen that ultra-deep well drilling tools are more prone to fatigue failure under the combined influence of high axial load, high temperature, corrosion, and bending stress.

4. Fatigue Failure Finite Element Simulation

In order to further analyze the causes of fatigue failure of ultra-deep wells, the life of the drills was predicted using the Design Life module in the NCODE software [6].

4.1. Static Analysis

Using SolidWorks software to establish a 139.7mm drill pipe model, in order to eliminate the influence of the end face constraint on the check result of the middle drill pipe joint, three connected drill pipes were taken as the research model and imported into the workbench module. The structure of the joint is shown in the (Figure 4).
It mainly considers the influence of axial stress and bending stress to ensure that the drilling tool bears the alternating load in the axial direction. In the static analysis of the drilling tool, the axial static load at one end of the drill string is equal to the average stress value, and the other end is fixed at the end. In the calculation results, the distribution of the maximum principal stress of the drill string is shown in (Figure 5). It can be found that there is a significant stress concentration phenomenon at the corner of the shoulder and the maximum axial stress is 862.5 MPa.

4.2 Fatigue Life Prediction
The material properties were set and the fatigue limit of drill pipe material was taken as 376 MPa. The Gutemann cycle coefficient was selected and the maximum principal stress was used to calculate the standard S-N calculation model. The applied variable load was 7.37 MPa, and the fatigue life prediction was performed. The calculated results are shown in (Figure 6).

From (Figure 6), it can be seen that the service life of the drill stem shoulder stress concentration is the lowest (6.33×105). The simulation results show that under the high load, the drilling tool has a low fatigue life at the stress concentration point. Although the drilling tool's stress meets the requirement of static strength, it does not reach the fatigue strength. Therefore, in designing the drill string, it is necessary not only to verify whether the static strength of the drill is satisfied, but also to meet the influence of the static strength on the fatigue life of the drill.

4.3 Fatigue Factor Analysis
In order to verify the influence of the average stress (axial load) and stress amplitude (bending stress)
on the fatigue life of the drill, the fatigue life of the model under different stress states was simulated. (1) Take the stress amplitude of 9 MPa, change the average stress of the drill string, and the calculation result of the drill string fatigue life is shown in (Figure 7).

![Figure 7](image)

As can be seen from (Figure 7), under the condition of constant stress amplitude, the fatigue life at the drill string danger point gradually decreases as the average stress increases. When the average stress is close to 500 MPa, the maximum stress at the stress concentration point is close to the yield limit, and the drill string weight at this time has a significant influence on the fatigue life of the drill string.

(2) Take the average stress of 450 MPa and change the stress amplitude of the drill string. The calculated results of the fatigue life are shown in (Figure 8).

![Figure 8](image)

From (Fig 8), it can be seen that as the stress amplitude of the drill string increases, the fatigue life at the drill string danger point gradually decreases. The higher the drill string speed, the greater the bending stress and the lower its fatigue life.

5. **Conclusions**
(1) The main causes of failure of ultra-deep well drilling tools are fatigue damage due to large axial force, long corrosion time and high temperature inside the well.

(2) Finite element fatigue analysis was performed on ultra-deep well drilling tools in the North Well X. The results showed that the higher weight of the drilling tool and the faster rotation speed of the drill were the main factors leading to the decrease of its fatigue life and the lowest life of the drill pipe stress concentration site.
(3) The average stress of the drill string increases and the fatigue life at the drill string danger point gradually decreases. The higher the drill string speed, the greater the bending stress and the lower its fatigue life.

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