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Reliability Analysis of Super 13Cr Tubing in Ultra-Deep Gas Well

Lihu Cao[1], Hongtao Liu[1], Junyan Liu[1], Hailong Geng[1], Haotian Wei[2]

[1]Petro China Tarim Oilfield Company, Korla, China
[2]College of Mechanical Engineering, Yangtze University, Jingzhou, China
Email: lld1210@qq.com

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Abstract

Abnormal oil casing pressure appeared in the process of test production of multiple Ultra-Deep Gas Wells in Tarim Basin. The super 13Cr oil pipe string was used to analyze the causes of pipe string failure in view of the oil casing channeling well during the test and blowout period. The construction process of the well was analyzed in detail. Combined with the review of the operation flow and the detection of fracture string material and fracture morphology, the causes of pipe string fracture were analyzed and calculated in detail. Through field investigation, analysis and calculation, it was found that the main cause of cracking of super 13Cr tubing in this well is the decrease of vibration natural frequency caused by excessive fluid velocity in pipe and too long span of pipe string. At the same time, the mixed failure of stress corrosion cracking and stress load interaction occurred in Cl^{-1} environment and other corrosion environments.

Keywords

Ultra-Deep Well, Gas Well, Pipe String, Vibration, Fatigue Corrosion

1. Introduction

The fracture failure of pipe string is one of the main forms of pipe string failure in oil and gas wells. At present, the single factor method is often used to analyze the failure of pipe string [1] [2], but the comprehensive effect of many factors is ignored. The existing literature focuses on the fracture failure of oil and gas well string, which is generally attributed to the vibration failure of pipe string [3] or corrosion cracking [4]. Among them, the vibration form is mainly based on the study of transverse vibration, and the analyzed pipe string is considered as Bernoulli-Euler beam, neglecting the shear deformation and rotating motion of the pipe string. The movement of each section of the pipe string is represented by the transverse displacement of the axis, while the corrosion failure is mainly studied by corrosion fatigue failure.

During the operation of a well in Tarim, after the Packer was set and ejected, the oil sleeve pressure was abnormal. After subsequent salvage, several super 13Cr tubing cracks were found, and some of the pipe strings were broken. Due to the complexity of on-site operation flow and working load, in order to deeply study the cracking causes of the well string, on the basis of a detailed review of the well before and after the accident, the fracture string material and fracture morphology are analyzed in detail. Combined with the field working conditions and related parameters, the vibration mechanism and corrosion mechanism of pipe string fracture are studied, and the causes of fracture on the outer surface of the well string are discussed.

2. Case Description

The drilling pipe transmission perforation was carried out in the section of 6747.00 - 6840.00 m in oil-based drilling fluid on January 27, 2013. After entering the completion string at 8:00 on February 22, the reverse displacement of 1.50 excess slurry 10 m^3 + density 1.22 isolation fluid 5 m^3 + density 1.38 organic salt 142 m^3, returning oil-based drilling fluid 140 m^3 with 1.86 density, replacing fluid for 22 hours, and then completing the Packer sealing work according to the standard procedure.

At 00:00 on March 2, we will see natural gas after opening the well for 8 hours, release it with 4 mm nozzle, oil pressure 25.92 - 26.32 MPa, casing pressure 3.51 - 1.34 MPa, fold daily gas production 72720 m^3. On March 8, acidizing construction, acid dosage: 481 m^3, pump pressure up to 120 MPa, casing pressure up to 45.5 MPa, maximum displacement 5.8 m^3/min. To March 11, release and ask for production, with 5 mm nozzle spray, oil pressure of 71.67 MPa, casing pressure of 14.72 MPa, daily gas production 251,308 m^3. When the well was closed at 08:00 on 11 March 2013, the oil pressure increased from 71.67 MPa, the casing pressure from 14.72 MPa to 15.87 MPa, the first casing pressure from 15.87 MPa to 20.79 MPa, and the second casing pressure from 20.02 MPa to 25.19 MPa. At 09:02, the casing pressure increased slowly from 24.55 MPa to 28.65 MPa, and the sleeve pressure increased from 28.65 MPa to 25.90 MPa, and then the casing pressure increased sharply, and the oil pressure decreased from 92.25 MPa to 86.89 MPa.

Open the well, release the annular protective fluid from the wellhead, confirm that the oil pressure and casing pressure have been connected, and the oil pipe string has been damaged. The situation was dealt with in time, after the density 1.38 organic salt was used to kill the well, the density 1.86 oil-based mud was used to reverse circulation the well, the oil production tree was removed and the blowout preventer group was replaced, the pipe string was picked up, and the broken pipe string was salvage.

3. Observation of Phenomena and Properties of Pipe

3.1. Fracture Morphology Analysis

After salvage, it was found that the root of the end wire buckle of 418 tubing (3 1/2" × 6.45 mm × 13Cr-110/BEAR tubing) was broken, and the fish top was 4146.14 m at the depth of tubing body, and the root fracture was shown in Figure 1(a). According to the observation of the root of the fracture, it is found that there are scouring marks in 50% of the fracture area of the root of the tubing, and slight necking can be seen on the side of the pipe body in the instantaneous fracture area of the root fracture. Combined with the fracture form, it is considered that the erosion fracture is the first fracture area. In the process of killing well, the erosion trace should be produced by circulating drilling fluid, and the rest of the fracture is the last irregular fresh fracture area.

At the same time, the main fracture surface of 418 tubing is analyzed, as shown in Figure 1(b), 80% of the main fracture surface has scour marks, which is the erosion first fracture area, the fracture is not in the same plane, the local flat fracture depression, the depression depth 4 mm, depression perimeter 9 mm; the other oblique fracture is transient fracture area, slight necking can be seen on the side of the pipe body, the fracture position is both transverse crack and longitudinal crack.

After continuing the salvage of the kava fishing tube, the 432 tubing also broke, and the fracture morphology was shown in Figure 2, and the fracture form was basically the same as that of 418 tubing. In addition, there are many cracks and cracks in the lifting and salvage pipe string, which are mainly concentrated at the screwed end of the pipe string. The forms of cracks include transverse cracks (60 mm, 89 mm, 120 mm, 165 mm, 170 mm, 190 mm) and longitudinal cracks (40 mm, 50 mm). The depth of the cracked string is mainly distributed in the range of 4146.14 m - 4712.41 m.

(a) Root port

(b) Body fracture

Figure 1. Morphology of root break of 418 tubing.

Figure 2. Morphology of root break of 418 tubing.

3.2. Detection and Analysis of Chemical Properties of Pipe String

The chemical composition of the tubing used in the well and the same batch of tubing not entering the well were analyzed. According to the standard of ISO643-2003 "microscopic metallographic determination of Ferrite and Austenite Grain size of Steel", the microstructure of the inspection tubing was examined by Olympus BX51 metallographic microscope. The results show that the metallographic structure of the inspection tubing is martensite, the inclusion is normal, and the grain size is 9.0.

The plate tensile specimen of 19.1 mm × 50 mm was taken longitudinally along the tubing body, the rod tensile specimen of Φ6.25 mm × 25 mm was taken along the longitudinal direction of the tubing body, the Charpy V notch impact sample of 5 mm × 10 mm × 55 mm was taken along the longitudinal direction of the tubing body, the Charpy V notch impact specimen of 7.5 mm × 10 mm × 55 mm was taken along the longitudinal direction of the coupling, and the hardness block sample was taken along the transverse direction of the tubing body and coupling. Through the chemical composition analysis, metallographic examination and mechanical property test of the relevant samples, the results show that the chemical composition, tensile strength, yield strength, extensibility, impact power and hardness of each tubing material meet the requirements of API SPEC 5CT casing and tubing specification, ISO13680 standard and order replenishment technical conditions, and eliminate the abnormal situation of the material itself.

4. Cause Analysis

4.1. Establishment and Analysis of Theoretical Model of Oil Pipe string Vibration

In order to analyze the fracture string of the well, firstly, based on the existing relevant theory [5], combined with the working conditions of an ultra-deep gas well in Tarim, the transverse and longitudinal vibration models of the string are established.

In the wellbore structure, due to the change of well deviation and azimuth, the production casing is bent and extended in three-dimensional space, the tubing string potential must be in contact with the production casing, the casing is like a bow, the tubing is like a string, and the whole tubing is fixed by the casing to form a string that can vibrate freely, so it can be simplified into a string simply supported by multiple ends in series. Simplify a section of the oil pipe string to a simply supported beam strung at both ends.

Because there is fluid action inside and outside the tubing, and the internal fluid velocity is high, the coupling between pipe string and fluid should be considered in modeling. In the analysis, a four-equation model considering the coupling of pipeline and fluid motion is derived by using Newton principle [6].

Equation of axial motion:

$$EA_p u'' - \left(pA_f\right)' - m_f\left(\dot{v}_f + v_f v_f'\right) - mg_z - m_p ii = 0 \tag{1}$$

Equation of lateral motion:

$$EIw'''' + \left(pA_f w'\right)' + m_f\left(v_f w' + 2v_f \dot{w}' + v_f^2 w'' + v_f v_f' w'\right) + mg_w - m\ddot{w} = 0 \tag{2}$$

Equation of continuous motion:

$$\left(pA_f\right)' + m_f C^2 F\left(v' - 2v\dot{u}'\right) = 0 \tag{3}$$

Momentum equation:

$$\left(pA_f\right)' + m_f\left(g^w w' + g_z + \dot{v}_f v_f' + \frac{f}{2D}v_f^2\right) = 0 \tag{4}$$

In the formula, C^2F is the pressure wave velocity, g_z and g_w are the components of gravity acceleration in the two deformation directions, f is the fluid viscous friction coefficient, m is the pipe mass per unit length plus fluid mass, m_p is the pipe mass per unit length, m_f is the fluid mass per unit length, v_f is the velocity, u is the axial displacement, *wis* is the transverse displacement of the pipeline, and p is the fluid pressure.

By using the energy method, the microelement segment d_x is taken as the research object. The total kinetic energy of the microelement segment in the process of vibration is the sum of fluid kinetic energy and pipeline kinetic energy, which can be expressed as follows:

$$dT = \left\{\frac{1}{2}m_p\dot{y}^2 + \frac{1}{2}\rho_l A\left[\left(\dot{y} + vy'\right)^2 + v^2\right]\right\}dx \tag{5}$$

The total potential energy of the microelement segment is:

$$dU = \frac{1}{2}EI\left(y''\right)^2 \tag{6}$$

According to the (Hamilton) principle of Hanston: $\delta\left(T - U\right) = 0$.

The partial differential equation of transverse vibration of pipe string can be obtained:

$$EI\frac{\partial^4 y}{\partial x^4} + \left(m_p + \rho_l A\right)\frac{\partial^2 y}{\partial t^2} + 2\rho_l Av\frac{\partial^2 y}{\partial x \partial t} + \rho_l Av^2\frac{\partial^2 y}{\partial x^2} = 0 \tag{7}$$

In the formula, L is the span length, mp is the pipe mass per unit length, and Di and Do are the inner and outer diameters of the pipeline. ρ is the fluid density, the cross-section area of the pipe at constant velocity$v$ is A, the transverse disturbance of the pipe is $y(x,t)$, and the axial coordinate of the pipe is x. EI is the bending stiffness of the pipe string and the transverse displacement of the pipe string. The third item represents the force needed to rotate the fluid at the angular velocity $\frac{\partial^2 y}{\partial x \partial t}$ at each point in the pipeline, reflecting the fluid-solid coupling between the fluid and the completion string. The fourth represents the force required to change the flow direction of the fluid to meet the curvature of the tube.

According to the boundary conditions of the pipe supported at both ends, the transverse vibration frequencies of the first two stages can be obtained as follows:

$$\omega_1 = i\frac{\pi^2}{L^2\sqrt{a}}\sqrt{1-v^2\frac{L^2\rho A}{\pi^2 EI}} \tag{8}$$

$$\omega_2 = i\frac{2\pi^2}{L^2\sqrt{a}}\sqrt{4-v^2\frac{L^2\rho A}{\pi^2 EI}} \tag{9}$$

According to the above formula, it can be known that the natural frequency of the transverse vibration of the pipe string is related to the fluid factors after considering the fluid-solid coupling factors. The natural frequency of the transverse vibration of the pipe string depends on the bending stiffness of the pipe, the geometric parameters of the pipe (span, overcurrent area), fluid density and velocity in the pipe, and the transverse vibration frequency of the string decreases with the increase of velocity, fluid density and span in the pipe. Combined with the field operation data, the flow of fluid in the pipe string has a great influence on the vibration frequency and stability of the pipeline. In the process of natural gas discharge and removal of residual acid and natural gas mixture, the dimensionless frequency of the pipe string decreases significantly, so it is more likely to cause resonance and aggravate the vibration degree of the pipe string under the above two working conditions.

4.2. Study on Failure in Corrosion Environment

The Cr tubing has good corrosion resistance, but the analysis of the working condition and the subsequent produced fluid shows that there are still Cl-1 and other corrosion factors in the tubing after the residual acid fluid is discharged, and the related corrosion medium will accelerate the fatigue crack growth rate [7].

The double logarithmic coordinates of stress intensity factor amplitude and fatigue crack growth rate are used to represent the general law of fatigue crack propagation.

$$\Delta K = \frac{\Delta P}{1000 \cdot B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{\frac{3}{2}}} \left(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4\right) \quad (10)$$

In the formula, ΔK is the amplitude of the stress intensity factor, Band W are the actual measured values of the thickness and length of the specimen, unit is m, and ΔP is the stress amplitude and the $\Delta P = P_{\max} - P_{\min}$ unit is kN. B and W are the actual measured values of the thickness and length of the specimen, $\alpha = a/Wa$ is the distance from the crack tip to the stress load axis, and W is the length of the specimen in the crack propagation direction.

$$\frac{d\alpha}{dN} = \frac{\Delta\alpha}{\Delta N} \quad (11)$$

In the formula, $\Delta a = a_{n+1} - a_n$ is the growth amount of fatigue crack growth under different loads, and ΔN is the number of stress damage cycles under Δa crack propagation, and the ratio of them is the fatigue crack growth rate.

Based on the Pairs formula and the existing fracture model, combined with the changes of corrosion medium and load frequency, the correlation coefficient is modified, and the life prediction model of Cr tubing is established [8]. The following formula:

$$d\alpha/dN = B\left(\Delta K - \Delta K_{th}\right)^n \quad (12)$$

$$d\alpha/dN = C(f) \cdot B\left(\Delta K - \Delta K_{th}\right)^{D(f)\cdot n} \quad (13)$$

In the formula, B and n are the correction coefficients of corrosion fatigue crack growth rate relative to atmospheric environment for Cr tubing fatigue crack growth rate, $C(f)$ and $D(f)$ respect the correction coefficients of corrosion fatigue crack growth rate relative to atmospheric environment.

Because the pressure fluctuation of the well is obvious, and the pipe string is in a certain corrosion environment before cracking, the cracking of the well is bound to include the results of stress corrosion cracking and the interaction of various corrosion environments and stress loads.

Combined with the above analysis, during the test blowout process of the well, the injected fluid and the produced gas flow in the oil and gas well string, the movement of the string in three-dimensional space is induced by the changes of flow rate, pressure and temperature. At the same time, the instability of fluid flow in the string leads to the pulsation of the pipe wall. When the outer surface of the string is in the corrosion environment, it is the string that produces transverse and longitudinal cracks, which leads to the failure of the completion string.

5. Conclusions and Recommendations

Based on the above analysis and analysis of the causes of cracking on the outer surface of super 13Cr tubing in an ultra-deep gas well in Tarim Basin, the following conclusions can be obtained.

1) The natural frequency of the transverse vibration of the pipe string depends on the bending stiffness of the pipe, the geometric parameters (span, overcurrent

area), fluid density and velocity in the pipe. With the increase of the velocity and span in the pipe, the transverse vibration frequency of the pipe string decreases. In the testing process of the example well, when testing and testing the liquid mixture after discharge, the vibration frequency of the test string is significantly reduced because of the large flow rate and high speed of the internal gas and gas-liquid mixture.

2) During the test operation of the example well, the pressure fluctuation range of the flow in the string is large; the production is high, and the unstable fluid leads to the pulsation of the pipe wall and increases the vibration damage of the string; at the same time, the surface of the string is in a corrosive environment, which will further accelerate the lateral and longitudinal crack propagation of the string, resulting in the failure of the completion string.

3) The outer surface cracking of super 13Cr tubing in the well is due to the decrease of string frequency and the increase of fluid pressure and pressure fluctuation in the casing. At the same time, because the environment of the string contains a variety of corrosion factors, the destruction of the string is promoted, and the comprehensive operation of many factors leads to the serious cracking of multiple pipe strings in the well.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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