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The sealing mechanism of tubing and casing premium threaded connections under complex loads

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ABSTRACT

With the increase of ultra-deep and extended reach wells, the premium threaded connections (PTCs) of tubing and casing have to withstand extremely high level of combined loads, and often occurs sealing failure under complex loads. In order to solve this problem, the sealing mechanism of PTCs should be analyzed in depth. The existing analytical method can provide the contact stress formula for PTCs, but the extremely nonlinear mechanics of thread interactions under complex load states cannot be captured due to the stringent assumptions. In this article, a nonlinear 3D elastic-plastic finite element model for 7″casing buttress PTCs with the helix angle is established to analyze the stress distribution characteristics on the sealing surface, shoulder and thread. The results show that the preload has important influence on the sealing characteristics of the PTCs, and the sealing performance of the joint depends on the contact stress on the thread, sealing surface and shoulder. The axial tensile load will increase the sealing performance on the thread and weaken the sealing performance on the shoulder and the sealing surface. When a bending moment is applied on the tool joint, the contact stress increases in the compressed side while decreases in the stretched side, and the contact stress and sealing band width of the sealing surface decline, which indicates that the complex loads greatly affect the sealing performance of the sealing surface. Especially, the sealing surface width and the stress obtained with the three-dimensional finite element model are more reasonable than the analytical method due to the consideration of the helix angle of thread and the elastic-plastic characteristics of the material.

1. Introduction

As available oil and gas resources located at deeper depths and harsher environments, tubing and casing threaded connections must withstand extremely high leaves of combined loads, and the API standard threaded connectors would not meet the seal and connection strength requirements in such complex operating conditions. It made many manufactures develop the premium threaded connections (PTCs), which improve the performance of the joint greatly. However, many oilfield cases have confirmed that the seal failure still occurred on the PTCs frequently, and through qualification tests it has been found that the breakdown in connection sealing ability can be traced to the damage of primary seal surface, which can eventually develop into a leak-path and result in a large number of economic losses (Hamilton et al., 2009).

In fact, many research works have been made to study the failure mechanism and develop new kinds of PTCs. Japan Sumitomo Metals Co. was one of the earliest companies to study the PTCs in 1969. In the development process, a lot of leak-proof tests were made to determine the adequate joint sealing structure with reference to the API RP37 evaluation program (Yoshihiro et al., 1974). Since then, the research on PTCs has not stopped (Thomas and Bartok, 1941; Clinedinst, 1965; Weiner and True, 1969; Asbill et al., 1983; Schwind and Wooley, 1989; Assanelli et al., 1997; Reynolds and Summerfield, 1991; Buonodono and Day, 1993; Teodoriu and Badicioiu, 2013; Galle et al., 2014) and was paid more attentions in recent years (Hamilton et al., 2009; Zhang et al., 2015; Cui et al., 2015; Xu et al., 2016; Chen et al., 2015). Hamilton (2007) (Hamilton et al., 2009) assessed the contact stress along the metal-to-metal seal band of the PTCs by the ultrasonic technology, and the leakage resistance of the threaded joint was determined. Zhang et al. (2015) analyzed the stress and contact pressure of PTCs subjected to tension, internal pressure and the combined loads of them with a 2D

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axisymmetric model, and found out that the high stress values appeared on shoulder and sealing surface, and the contact pressure on the shoulder decreased under the tension and the seal performance of the shoulder degraded. Fen Cui et al. (2015) compared the structure characteristics of the two designed buttress PTCs with 3D models neglecting the helix angle and a superior model was chosen to make three experimental tests, i.e. the gas seal test, the failure test and the anti-galling performance test. The results showed that the gas seal performance of tested connections was always well and no thread gluing happened. Xu et al. (2016) made an excellent work and applied a theoretical model to calculate the contact stresses on sealing surface of PTCs with the ball to cone sealing structure based on the Hertz contact mechanics theory, and the influence of taper and spherical radius on the contact width and contact stress of sealing surface were analyzed. The results showed that the taper was in direct proportion to the contact width and contact stress, and the spherical radius was proportional to the contact width and inversely proportional to the contact stress. However, the helix angle was failed to be taken into account and the contact seal structure was considered to be semi-infinite elastic solid due to the difficulty of theoretical analysis.

It is not difficult to find that there are three ways to study the sealing performance of PTCs, i.e. experimental method, theoretical method and numerical simulation method. Full-scale experiment method is the most direct method and can be implemented for the sealing performance test of PTCs, but it is time-consuming and expensive, and sometimes the complicated loads cannot be applied. The theoretical method is easy to use, however, the highly nonlinear mechanics of thread interactions under complex load states and the plastic characteristics of material cannot be described due to the stringent assumptions (Chen et al., 2015). The FEM is an effective way to deal with this puzzle, and there is importance to conduct a 3D full size simulation on seal performance of PTCs with considering the elastic-plastic deformation of material and the helix angle, which were ignored in the 2D FEM and led to the fail to predict the results accurately under complex loaded conditions. The significant difference between a 2D and 3D FEM has been described in detail in the article of Chen et al. and Di et al. (Chen et al., 2013; Di et al., 2012). In this article, the analytical method proposed by Xu et al. (2016) is firstly used to calculate the contact stress of sealing surface, then a nonlinear 3D elastic-plastic finite element model is established for 7″casing buttress PTCs with the helix angle and the stress distribution characteristics on the sealing surface, shoulder and thread under complex loads are analyzed. We will place emphasis on the sealing mechanism of PTCs and the reason which makes the imperfection of the analytical method.

2. Theoretical analysis of sealing characteristics for PTCs

Differing from the API threaded connections, PTCs have specially-designed sealing types except for the thread interference seal, e.g. the radial metal seal, the shoulder auxiliary seal and even resilient seals that act as back-ups to the primary metal seal. Among them, radial metal seal is the critical component to achieve satisfactory gas tight (Bradley et al., 2005). It mainly includes the cone to cone seal, the ball to cone seal, the ball to cylinder seal and the ball to ball seal. In this paper, the ball to cone seal structure is studied.

Based on the thick wall cylinder theory of elastic mechanics and the Hertz contact theory, Xu et al., (2017) established the contact stress analytical model for primary sealing surface of PTCs, in which the ball to cone sealing structure was simplified as the circular arc to the line contact, as shown in Fig. 1. The model was based on the following assumptions:

1) The contact surface was continuous and non-coordinated.
2) The strain was small.
3) The material was assumed as linear elastic.
4) The contact seal structure were considered to be semi-infinite elastic solid.
5) The contact friction was ignored.

The normal contact stress of the sealing surface can be expressed as (Xu et al., 2017)

$$P_{sN}(x) = \frac{E_p E_c \sqrt{2R_s\delta_{sN} - \delta_{sN}^2 - 4x^2}}{4R_s[E_c(1-\nu_p^2) + E_p(1-\nu_c^2)]} \tag{1}$$

Where $P_{sN}(x)$ is the normal contact stress in x position. Ep and Ec is the elasticity modulus of the pin and the box, respectively. ν_p and ν_c is the poisson's ratio of the pin and the box, respectively. Rs is the radius of the sphere. δ_{sN} is the interference value of the initial contact point after the make-up, which can be described as

$$\delta_{sN} = N_s P \sin\gamma_S \tag{2}$$

Where Ns is the additional make-up turn on sealing surface. P is the pitch of thread. γ_s is the half-cone angle of the sealing surface.

According to the assumption 3), the maximum $P_{sN}(x)$ cannot exceed the material yield stress. Taking the 7″casing buttress PTC as an example, the geometric and material parameters of the casing threaded connection are shown in Table 1 and Table 2, respectively. Substituting these parameter values into Eq. (1), $P_{sN}(x)$ can be expressed as

$$P_{sN}(x) = 1910.689\sqrt{30\delta_{sN} - \delta_{sN}^2 - 4x^2} \tag{3}$$

When $x = 0$, $P_{sN}(x)$ achieves the maximum value and varies with δ_{sN}. If $P_{sN}(0)$ equals to the material yield stress, δ_{sN} will reach the critical value and is about 0.006524 mm in this example. By Eq. (2), Ns is only 0.041 turn. However, the optimal make-up torque recommended by Baosteel company is 22.57 kN m for the 7″casing buttress PTC, the corresponding Ns is about 0.244 turn. Therefore, the obtained Ns by the theoretical method is unreasonable, which is mainly attributed to the neglect of the plastic deformation of material. As we know, it is very difficult to solve this problem by the theoretical method, and the most effective way to solve it is to use 3D finite element model with taking the helix angle and the material's elastic-plastic characteristics into account.

3. 3D finite element analysis of sealing characteristics for PTCs

3.1. The 3D finite element model of PTCs

The 3D elastic-plastic finite element model of 7″casing buttress PTC and its boundary condition are shown in Fig. 2. This model is composed of 604,500 nodes and 495,500 elements. The pin end is free and the external loads are applied on it, the box end is fixed and constrained by the distributing coupling technology. Surface-to-surface contacts between the pin and the box are defined on the threads, sealing surfaces and shoulders to simulate the interaction. By using the elastic-plastic material, the mechanic properties of the 7″casing buttress PTC are analyzed.

In order to simulate the loading process of PTCs, three loading steps shown in Table 3 have been set. In the first analysis step (S1), a recommended make-up torque, 22.57 kN m, is applied in the previous 0.15s and released smoothly from 0.15s to 0.2s. Then in the second step (S2), 670 kN axial tension is applied, followed by 27.498 kN m bending moment which corresponds to a bending curvature of 10°/30 m in the third step (S3). The analysis steps are listed in Table 3.

There are two aspects of evaluating the performance of PTCs, one is the connection strength, including the von Mises stress distribution of the whole joint and the contact stress of thread. The other is the seal performance, including the contact stress on sealing surface and shoulder. The sealing capacity of PTCs is determined by the magnitude and distribution of the contact stress that exists over the metal-to-metal seal region under each load condition.

In order to investigate the contact stress distributions, eight critical