Influences of Casing Wear on Mechanical Behavior of Packer Element

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Abstract. Packer element is made of hyperelastic rubber, and its mechanic performance determines the packer's sealing effect. In oil field, casing wear is often found and in some special circumstance the packer has to set at worn casing section. In order to study the effect of casing wear on element mechanical behavior, contact pressure between element and casing with crescent-shaped wear notch is calculated by use of commercial ANSYS software. The influences of notch depth and diameter of drill pipe joint on contact pressure are discussed in detail. The results show that the contact pressure has a saddle-shaped distribution along axial direction similar to that without wear. But minimum contact pressure decreases rapidly when the notch depth increases. And a larger diameter of drill pipe joint can give rise to lower contact pressure near the notch.

1. Introduction

Packer is one of the most important downhole tools in oilfield production. In packer setting process, axial compression load from tubing string is imposed onto packer. Then the element, which is made of hyperelastic rubber, produces radial deformation and contacts the inner wall of the casing. In this way, the goal of sealing the annulus, isolating the formation and protecting the casing is achieved.

In recent years, many scholars have studied the sealing mechanism of the rubber by the finite element simulation. In the literature, Ma et al. [1] established a finite element simulation model of double elements packer using ANSYS software and analyzed the influences of different friction coefficients. Yu G.J. [2] improved the rubber structure by opening small circular grooves in the middle of the side where the rubber is in contact with the central tube. Through the finite element analysis, it is found that the maximum contact stress of the optimized rubber structure is significantly higher than that of the conventional structure and the contact stress distribution is more uniform. Akhtar et al. [3] studied the changes in volume, thickness, hardness and density of expandable rubber at different expansion stages. Hu G et al. [4] studied the effect of casing wall thickness and setting load on sealing performance. Wen JL et al. [5], based on ABAQUS software and experimental research, carried out study on material selection and structural optimization of rubber under high pressure and high temperature condition. Zhang FY et al. [6,7] analyzed the reliability of the seal and the life span of a packer when considering thermal effect and torsional load, and predicted the fatigue life of various materials under different temperatures.

It can be found that the influence of axial load, friction coefficient and structure on contact pressure between the packer element and the casing was the main research direction, and has an important guiding role in improving the sealing performance of the packer. But the effect of the hydraulic environment and casing wear on packer sealing performance are ignored. With the development of oil and gas exploration, more and more ultra-deep wells were drilled, and casing wear has becoming a
prominent problem. Therefore, people sometimes have to set the packer in the casing wear section. This study highlighted the contact pressure between packer element and casing with crescent-shaped wear notch by use of commercial ANSYS software.

2. Analysis Model

2.1. Structure of Packer

There are a great variety of packers, and the real structure of a packer is very complicated. In order to perform the calculation with finite element method, this paper only considers the compression packer for analysis. Without loss of generality, the model of the packer is simplified as a structure consisting of an element, a central tube and two support rings. The axial section is shown in Figure 1, where casing section is also drawn. The central tube, support rings and casing are made of steel.

![Figure 1. The structure of the packer.](image)

In actual operation, the packer is run to a predetermined well depth and performed setting operation. In the setting process, the element is compressed axially under an axial load which is conveyed by the upper support ring, and takes place radial expansion to contact tightly with casing. During this process, the element and upper support ring slide axially along the central tube, and the element generates contact pressure with casing and central tube, so each component forms a complex relationship with the others.

Taking the Y111 compression packer as an example, in finite element simulation, the elastic modulus of the casing, central tube and support ring are $2.1 \times 10^5$ MPa, and the Poisson’s ratios are 0.3. The other structure parameters of the Y111 packer are given in Table 1.

| Components     | Outside diameter (mm) | Inside diameter (mm) | Height (mm) |
|----------------|-----------------------|----------------------|-------------|
| Central tube   | 80                    | 50                   | 105         |
| Element        | 114                   | 80                   | 70          |
| Support ring   | 114                   | 80                   | 10          |
| Casing         | 139.7                 | 121.4                | 105         |

2.2. Hyperelastic Constitutive Model of the Rubber

The packer element is made of rubber with highly nonlinear mechanical property. The rubber can be regard as an isotropic and incompressible hyperelastic material, and its mechanical properties can be described as different forms of strain energy density equations.

Under isothermal conditions, the strain energy density equation of a rubber material is a function of the right Cauchy–Green deformation tensor invariants $I_1, I_2, I_3$, that is [8]:

$$ W = W(I_1, I_2, I_3) $$

(1)
Where
\[
\begin{align*}
\mathbb{I}_c &= tr C = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \\
\mathbb{II}_c &= \frac{1}{2} \left( (tr C)^2 - tr C^2 \right) = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2 \\
\mathbb{III}_c &= \det C = \lambda_1^2 \lambda_2^2 \lambda_3^2
\end{align*}
\]

(2)

\(\lambda_1, \lambda_2\) and \(\lambda_3\) are the principal stretch ratio ratios.

Based on the stress–strain relationship, Mooney [9] established a constitutive relationship for the rubber material by phenomenological theory. As the rubber materials are isotropic and incompressible, \(\mathbb{III}_c=1\). Rivlin [10] developed the strain energy density model of incompressible materials by Mooney’s theory, that is

\[
W = \sum_{i,j=0}^{\infty} C_{ij} \left( \mathbb{I}_c - 3 \right)^i \left( \mathbb{II}_c - 3 \right)^j
\]

(3)

where \(C_{ij}\) is a mechanical property constant, and \(C_{00}=0\).

The stress-strain relationship of hyperelastic materials can be accurately simulated by a higher-order polynomial model, but more constants should be determined. It is difficult to determine these constants, especially in the case of limited experimental data.

Yeoh [11] gave up the \(\mathbb{II}_c\) part and kept only the first three order terms, and deduced the following common equation.

\[
W_{\text{Yeoh}} = C_{10} \left( \mathbb{I}_c - 3 \right) + C_{20} \left( \mathbb{I}_c - 3 \right)^2 + C_{30} \left( \mathbb{I}_c - 3 \right)^3
\]

(4)

In this paper, the constitutive parameters of Yeoh model are used to simulate the deformation behavior of packer element, they are \(C_{10}=3.4297\) MPa, \(C_{20}=-3.3617\) MPa, and \(C_{30}=2.2005\) MPa.

3. Numerical Calculation of Element in Hydraulic Environment

3.1. Finite Element Model

3.1.1 Model meshing. The 2D axisymmetric model is chosen in modeling because the packer is symmetric around the centerline of the casing. The mesh type of the packer element is set to the hexahedral element by multizone sweep method, and the other parts use the default element.

Element size of the packer element is set to 1 mm, and the element size of the casing, central tube and support ring is set to 3 mm, at the same time, the overall mesh correlation is set from rough to medium.

3.1.2. Constraint conditions. The actual working environment of the packer is a fluid-filled wellbore. In order to analyze the influence of environmental pressure on the mechanical behavior of packer element, a pressure of 30 MPa is applied on the surface of the packer element, the surface of the support rings, the inner and outer surface of the central tube and the inner surface of the casing to simulate the initial environmental pressure, which is roughly equivalent to the liquid column pressure at well depth of 3000 m. According to the structure and working behavior of the packer, the fixed support is set to the outer surface of casing and the inner surface of central tube respectively. The lower support ring is bond with the central tube and so without axial movement. The upper support ring can move downward to convey axial force to compress the element and achieve the sealing behavior.

The friction coefficient between the element and metal parts is set as 0.1.
4. Element Mechanical Behavior with Casing Wear

4.1. Mathematical Model with Casing Wear

Casing wear is a common problem in deep wells, and it can result in blowouts, lost production and other troubles. In order to analyze the mechanical behavior of element in the condition of the casing wear, the model of the casing wear as shown in Figure 2 (a). This model is based on the phenomenon that the rotating drill pipe joints wear the inner wall of casing and form a crescent-shaped notch [12].

In the Figure 2 (a), \( r \) is the inner radius of the casing, \( R \) is the outer radius of the drill pipe joint, and \( t \) is the notch depth.

The analysis model of packer is not axisymmetric any longer when crescent-shaped casing notch exists. Therefore, a three-dimensional model is used, as shown in Figure 2 (b) and Figure 2 (c). According to the material characteristics, complete the meshing of each part, and all the contacts are set face-to-face to simulate the friction between element, casing, central tube and support ring. The friction coefficient between element and metal parts is set as 0.05.

4.2. Mechanical Behavior of Packer Element

An axial load of 80kN is applied to the upper ring to compress the packer element under 30MPa environmental pressure. The outside diameter of drill pipe joint is 111.1mm. Let the maximum notch depth is 1mm and 2mm respectively.

4.2.1. Minimum contact pressure distribution. Extracting minimum contact pressure values along the notch axially, the curves along the axial position are shown in Figure 3. In the figure three curves correspond to notch depth is 0mm, 1mm and 2mm respectively.

According to Figure 3, the following conclusions can be obtained:

1. The results show that the contact pressure has a saddle-shaped distribution along axial direction, and the contact pressure of the loading end is larger than other position.

2. Comparing with no wear curve, it can be seen that when the notch depth is 1mm the contact...
pressure reduces by about 20%; when the notch depth is 2mm the contact pressure reduces by about 47%.

4.2.2. Relationship between minimum contact pressure and setting load. The axial setting load of this type packer is normally from 60kN to 80kN. The minimum contact pressure under different setting load with different notch depth is shown in Figure 4.

![Figure 4. Relationship between setting load and minimum contact pressure.](image)

According to Figure 4, the following conclusions can be obtained:

1) The minimum contact pressure increases with setting load, but this trend becomes less obvious when notch depth increases.

2) When there is no wear, the minimum contact pressure under 60kN is about 5.25MPa, while when the notch depth is 2mm, the minimum contact pressure under 80kN is only about 4.23MPa.

4.2.3. Influence of the diameter of drill pipe joint. In fields, different drill pipe can be used. In 5.5"(139.7mm) casing, drill pipe body is generally 2-7/8"(73mm). But the outside diameter of drill pipe joints may be 111.1mm (type I) or 98.4mm (type III). Then, the notch width is different at the same notch depth.

Considering joint diameter and notch depth, contact pressure distribution along the circumference under setting load 80kN is shown in Figure 5. Where circumferential angle 0° corresponding to the deepest position of notch.

![Figure 5. Contact pressure distribution along circumference.](image)

According to Figure 5, the following conclusions can be obtained:

1) From midpoint of notch to both sides, the contact pressure increases abruptly in the wear range, while it increases slowly outside the wear range.

2) In the case of the same notch depth, a larger drill pipe joint results in a smaller minimum contact pressure.

3) Contact pressure outside the wear range is slightly larger comparing with no wearing, and this phenomenon is more obvious when notch depth is larger.
5. Conclusion
Focusing on the packer element and using the Yeoh rubber material model, the mathematical models were established under the conditions of casing wear. The mechanical behavior of packer element was simulated by ANSYS software, and the following conclusions can be drawn:

(1) When a packer is set in casing section with crescent-shaped wear notch, the minimum contact pressure between packer element and casing occurs at the deepest point of the notch.

(2) Under the parameters in this paper, comparing with no casing wear, the minimum contact pressure reduces by about 47% when the notch depth is 2mm.

(3) When the casing is worn, the minimum contact pressure may not be sufficient to achieve sealing function, even if the maximum setting load is applied.

(4) In the case of the same notch depth, a larger drill pipe joint results in a smaller minimum contact pressure.

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7. Reference
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