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Simulation Analysis of Sealing Performance of Rubber Core of Rotary Blowout Preventer

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Abstract: The performance of rotary control head or rotary blowout preventer will directly affect the success or failure of the underbalanced construction of oil and gas well. Once the failure occurs in the construction process, there may be blowout and other big drilling accidents. Based on the Yeoh constitutive equation, the dynamic sealing model of rubber core is established in this paper, and the sealing process of rubber core during tripping and tripping is calculated and analyzed. Then, the effect of the bubble defect in the core on the sealing performance of the core under different drilling fluid pressure was analyzed. Finally, the effect of metal degumming on the sealing performance of the core was analyzed. The results showed that the larger the initial sealing pressure and contact stress value of the Mises core was, the better the sealing effect of the Mises core was, while the larger the Mises stress value was, the more likely the Mises core was to suffer fatigue failure. The drilling fluid pressure significantly affects the maximum equivalent stress of the core, and the maximum equivalent stress appears in the bubble position inside the core at different times and under different drilling fluid pressure. The degumming position is placed in the contact position between metal and rubber core. When the tensile stress exceeds the limit of rubber core material, radial and circumferential cracks will occur on the upper surface of rubber core. With the increase of drilling times, rubber is prone to fatigue cracks, which eventually lead to mutual tearing.

Keywords: Rotate the blowout preventer, Rubber core, Sealing performance, Simulation analysis.

1. Introduction

Rotary blowout preventer is an important equipment in wellhead safety control system, and it is also one of the necessary equipment in underbalanced drilling, geothermal drilling and CBM drilling. The equipment required for the implementation of underbalanced drilling mainly includes: wellhead control equipment and surface treatment equipment. Among them, the wellhead control equipment mainly refers to the rotating control head or the rotating blowout preventer, which together with the original ring blowout preventer, ram blowout preventer and four pass constitute the wellhead blowout preventer group, whose function is to implement pressure control for oil and gas Wells, prevent and monitor accidents, and ensure the safety of drilling personnel, drilling equipment and oil and gas Wells [1]. As the heart of the rotary blowout preventer, the rubber core is the guarantee of its normal operation, which is particularly important in the process of development. The performance of rotary control head or rotary blowout preventer will directly affect the success or failure of the underbalanced construction of oil and gas well. Once the failure occurs in the construction process, there may be blowout and other big drilling accidents. Due to the working conditions, the rubber core is prone to failure in the form of root damage, wear in the contact area with the drill tool, slip damage, excessive deformation, thermal burn, etc., which becomes the main factor affecting the working performance of the rotary blowout preventer [2-5].

Qiu et al. [6] summarized the research status of rubber fatigue from three aspects: research methods of rubber fatigue, factors affecting fatigue life and crack section. Zhang et al. [7] analyzed the effects of thermal aging and fatigue damage on the fatigue life of rubber under the influence of temperature, and the proposed prediction model could predict the fatigue life of such rubber samples under different temperatures. Wu et al. [8] adopted finite element simulation combined with experiments to optimize the structure of the iron core thickness, fillet radius and inner diameter of the rubber core of the RBOP, which improved the performance and life of the rubber core of the RBOP. In addition, many petroleum scholars have established a finite element model of rubber core seal for rotary blowout preventer, and conducted research and analysis on fatigue failure of rubber core [9-13].

Many scholars have analyzed the influence of core performance on rotary blowout preventer mainly in core structure, drill pipe joint structure, wellhead pressure, trip speed and core material hardness. However, the effects of different drilling fluid pressures and defects in the production and operation of the core on the performance and life of the core were not considered. In this paper, the mechanical analysis of the drilling conditions of intact core and defective core is carried out. The effects of core defects on different drilling fluid pressures were compared and analyzed. The effects of various types of defects on the stress of the sealing surface of the rubber core were summarized in order to provide reference for the defect detection, sealing performance and service life of the rubber core.

2. Finite Element Model of Rubber Core of Rotary Blowout Preventer

2.1. Yeoh model

Many scholars have conducted in-depth research on rubber material constitutive model, which is mainly divided into phenomenological model based on strain energy function and statistical model based on molecular chain network [14]. On this basis, the Arruda-Boyce, Mooney-Rivlin, Ogden and Yeoh models, which are widely used today, were formed by simplifying the model parameters [15]. The Arruda-Boyce model has some limitations in describing the behavior of complex rubber materials. The Mooney-Rivlin and Ogden models are suitable for small and medium deformation of rubber, but cannot accurately simulate carbon black NBR rubber. Yeoh model is suitable for simulating large deformation behavior of carbon black-filled NBR, and has the ability to describe the mechanical behavior of other deformation with simple uniaxial tensile test data.

Rubber is assumed to be isotropic material in the undeformed state. The properties of rubber are described by the strain energy density per unit volume.

$$U = \sum_{i+j=1}^{N} C_{ij}(\bar{I}_1-3)^i(\bar{I}_2-3)^j + \sum_{i=1}^{N}\frac{1}{D_i}(J-1)^{2i} \quad (1)$$

Where N is the polynomial order, D_i parameter represents the compression property of the material, and C_{ij} is the parameter describing the deformation of the material.

By setting the parameters $C_{ij}=0, J\neq 0$, we get the special form of the polynomial model, and when $N=3$, we get the Yeoh form polynomial:

$$U = \sum_{i=1}^{3} C_{i0}\left(\bar{I}_1-3\right)^i + \sum_{i=0}^{3}\frac{1}{Di}(J-1)^{2i} \qquad (2)$$

As the Yeoh model C_{10}, C_{20} and C_{30} coefficient magnitude relationships can better describe the rubber stress-strain curve, when the rubber is under small deformation, C_{10} represents the initial shear modulus, and when the rubber is under medium deformation, the rubber softens due to the C_{20} coefficient relationship. When the rubber has a large deformation, the rubber hardens due to the C_{30} coefficient. The main feature of Yeoh model in *ANSYS* software is that the input parameters are few, and the input parameters can be obtained only by stretching data. A wide range of deformation can be described, and reasonable results can be obtained under large uniaxial tensile and simple shear deformation. Therefore, the Yeoh model has a good ability to fit the large deformation of rubber, and is particularly suitable for describing the deformation under the environmental conditions of the rubber core of the rotary blowout preventer.

2.2. Rubber core finite element model

The core material of the rotary blowout preventer is mainly composed of nitrile butadiene rubber. The core material of the rotary blowout preventer is prepared into dumbbell shape and uniaxial tensile test is carried out. The data curve was fitted between the test data and the Yeoh model in ansys simulation software, and the fitting parameters of the Yeoh model were $C_{10}=1.4285MPa, C_{20}=0.12011MPa, C_{30}=-0.0032135MPa$. In the initial state, the drill pipe is inserted into the rubber core in a static state; When drilling with pressure, in addition to the pre-loading force, the outer cone of the rubber core will also bear the pressure from the drilling fluid at the bottom of the hole. When the drill pipe passes down the rubber core, it will exert a downward friction force on the inner surface of the rubber core. When drilling with pressure, in addition to the preload specific pressure, the rubber core will also withstand the pressure from the drilling fluid at the bottom of the hole. As the drill pipe passes upward through the rubber core, an upward friction force will be exerted on the inner surface of the rubber core. The finite element model is established by ANSYS software. In order to improve the calculation efficiency of the model, the actual structure of drill pipe and rubber core is properly simplified. Yeoh constitutive model was adopted for rubber material parameters, and the stress-strain data measured by tests were used to establish the model. Elastic modulus of drill pipe material was *210GPa*, Poisson's ratio was *0.3*, and density was $7.8*10^3 kg/m^3$. The contact property between rubber core and drill pipe, rubber core body and iron core is defined as limited slip. Figure 1 shows the real rubber core of the rotary blowout preventer, and the finite element calculation model.

Figure 1. Rubber core and finite element calculation model of rotary blowout preventer

3. Simulation Analysis of Sealing Performance of Rubber Core

In environmental conditions, the drill pipe will usually run in reciprocating trips. When the drill pipe joint passes the rubber core sealing surface, the rubber core will be squeezed and expanded, and the contraction will recover after passing due to the elastic properties of the rubber material. At this stage, the alternating cycle load makes the rubber core easy to fatigue failure. ANSYS software is used to simulate the process. Figure 2 reflects the extrusion expansion and contraction deformation of the elastomaterials in the trip operation. Figure 2 (a) and Figure 2 (b) show the change of the overall force on the rubber core during the trip operation. At t_1, the drill rod body passes through the rubber core, the deformation of the rubber core is small, and the maximum equivalent stress of 1.65MPa is concentrated at the outer bottom of the rubber core. At t_2, the drill pipe joint began to pass through the rubber core sealing surface, the rubber core deformation began to increase, the Mises stress on the contact surface of the rubber core seal began to increase, and the maximum equivalent stress was 19.66MPa concentrated in the sealing surface. When the drill pipe joint passes through the contact surface of the rubber core at t_3, the rubber core continues to maintain the maximum expansion by the drill pipe extrusion, and the maximum equivalent stress 19.11 is concentrated in the sealing surface of the rubber core; The Mises stress at t_4 was higher than the Mises contact surface, and the Mises stress at the contact surface was 23.56MPa at most during the whole process. When the drill pipe joint passes through the contact surface of the rubber core at t_5, the rubber core recovers due to rubber characteristics, but the overall stress distribution changes differently from that at t_1, and its maximum equivalent stress is 5.37MPa, slightly greater than the maximum equivalent stress at t_1.

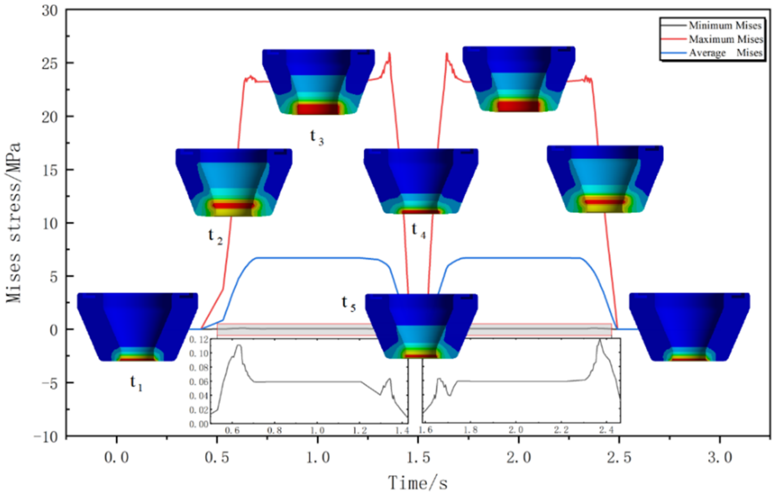

Figure 2 (a) The trip calculation process

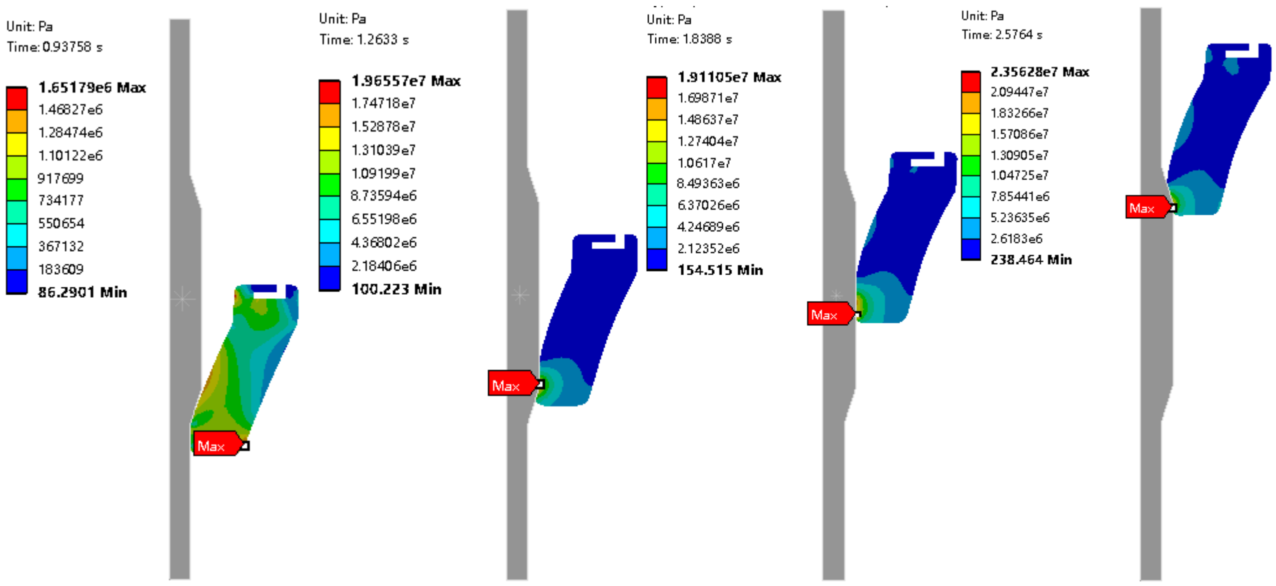

Figure 2 (b) Contact stress between sealing surface and drill pipe

Figure 2. Force analysis of rubber core in trip

Mises stress curves were obtained when the Mises stress surface was in contact with the drill pipe at different positions during trip out, as shown in Figure 2 (b), when the drill pipe joint did not touch the drill pipe surface, the Mises stress was only affected by the preloading force. Mises stress on the sealing surface changed little. When the beveled edge of the drill pipe joint first contacts the Mises stress on the seal surface, the Mises stress change increases significantly, and the Mises stress peak value is relatively large when the drill pipe joint rod body passes through the rubber core seal surface. The beveled edge of the drill pipe joint passes through the rubber core sealing surface twice, and the Mises stress peak value is the largest when the rubber core begins to shrink and recover. The Mises stress increased to the peak value and then decreased when the bevel edge of the drill pipe joint passed through the rubber core sealing surface. The stress change of the sealing surface of the rubber core is mainly concentrated at the bottom of the rubber core during tripping. The stress amplitude is an important factor that reflects the fatigue failure of the rubber core, so the stress changes near the bottom of the rubber core sealing surface, and the fatigue failure of the rubber core is easy to be caused when the hypotenuse of the drill pipe joint touches the two stages of the rubber core sealing surface.

4. The Effect of Stomatal Defects and Metal Degumming

4.1. Effect of bubble defects under different drilling fluid pressures

According to the above force analysis, the sealing surface of the rubber core will show transverse stretching deformation during the process of drilling with pressure, and the rubber core will show upward compression during the process of drilling. It can be seen from Figure 3 that the contact stress of the rubber core is basically the same during drilling. In the process of drilling, the contact stress at the sealing surface is greater than 10MPa (24.649MPa, 17.829MPa, 26.487MPa, respectively), and the sealing effect of rubber core is good. Therefore, the contact stress and contact area of the rubber core when it passes through the joint of the drill pipe are greater than that when it passes through the body of the drill pipe. Generally speaking, the drilling conditions have great influence on the sealing performance of rubber core.

It can be seen from Figure 4 and Figure 5 that the maximum contact pressure still occurs at the junction between the inner cone and the main sealing surface before the core deformation. Under different drilling fluid pressures, as the pressure increases, the drilling fluid pressure increases and the peak pressure increases gradually at the same drilling time. It can be found that with the increase of wellhead pressure, the deformation of the rubber core increases, and the contact length between the inner cone of the rubber core and the drill pipe increases. The contact pressure of the main sealing section is greater than the corresponding wellhead pressure, which can form a good seal, reflecting the self-sealing performance of the conical rubber core. The contact pressure of some nodes in the horn of the inner cone is greater than the corresponding wellhead pressure, which also plays a certain role in auxiliary sealing. The contact area between the core and the drill pipe increases with the increase of pressure, which can increase the wear resistance of the core and increase the service life of the core. However, the size of drilling fluid pressure can not be infinite increase, because under a certain drill pipe equipment, the greater the pressure, the greater the contact pressure of the rubber core to the drill pipe, so the reasonable determination of the size of drilling fluid pressure is very important to improve the life of the rubber core.

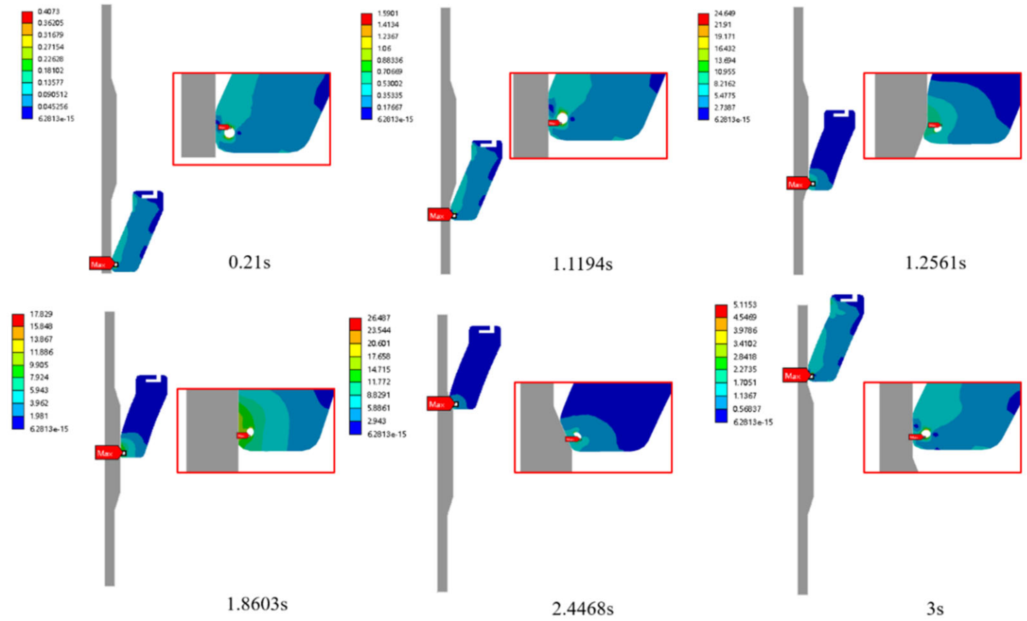

Figure 3. Drilling fluid pressure 1MPa

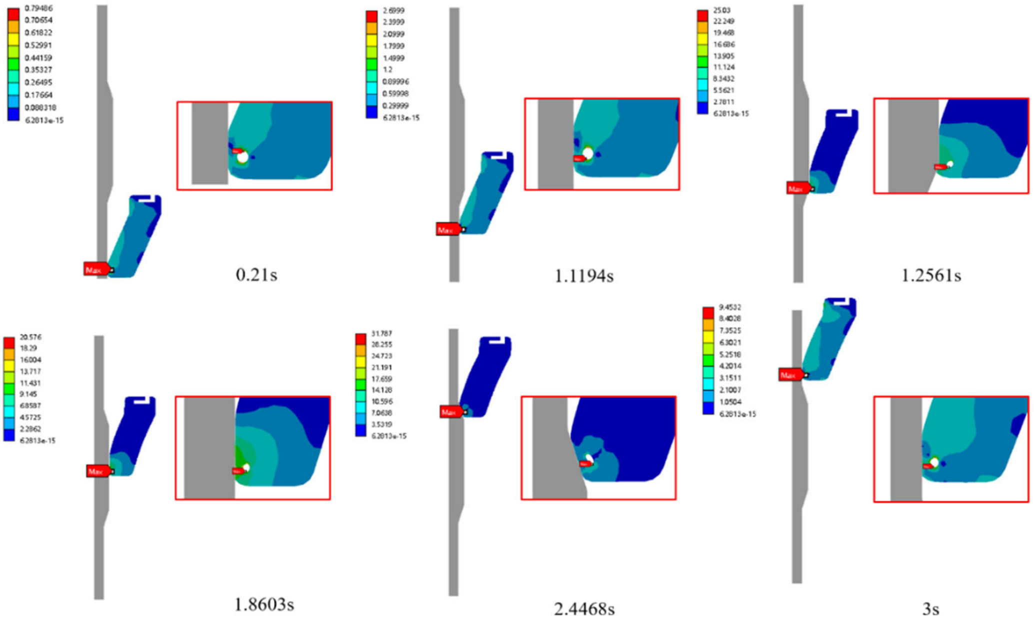

Figure 4. Drilling fluid pressure 2.5MPa

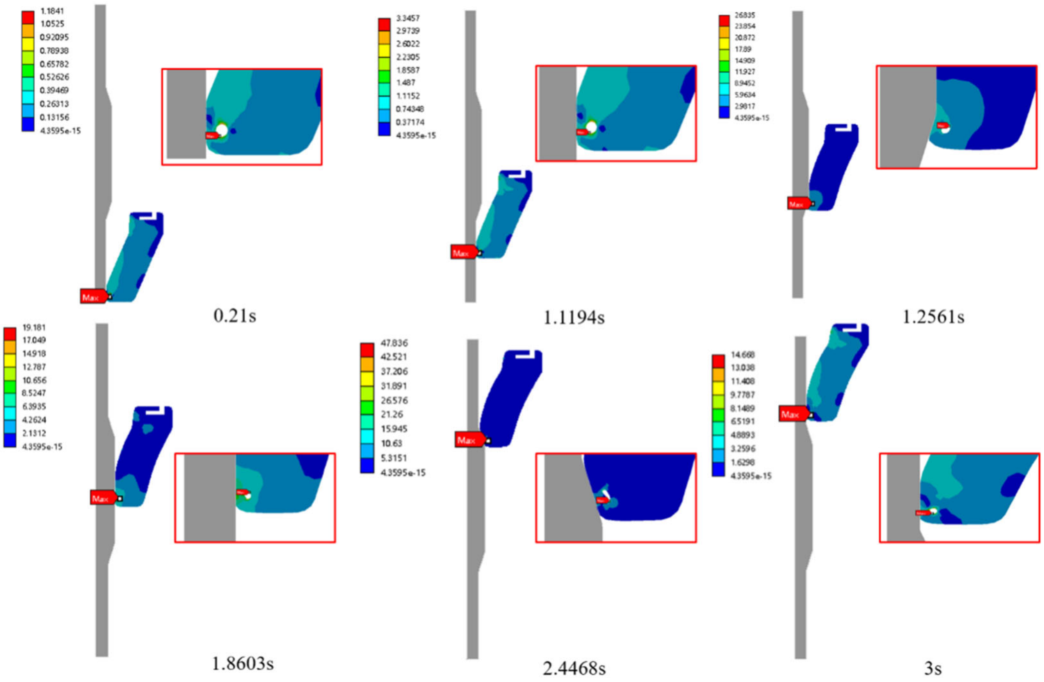

Figure 5. Drilling fluid pressure 4MPa

Table 1 shows the comparative analysis of the maximum equivalent stress of the inner bubble defect core under different drilling fluid pressures. At 0.21-1.1194s, the maximum equivalent stress of the core showed a slow growth trend with the increase of drilling fluid pressure during this period. At 1.1194-1.2561s, during this period of time, the core was squeezed by the drill pipe, and the maximum equivalent stress increased rapidly, and began to change significantly with the increase of drilling fluid pressure. At 1.2561-1.8603s, the maximum equivalent stress tends to be stable. At 1.8603-2.4468s, because the drill pipe size began to decrease and the rubber core began to shrink, the maximum equivalent stress continued to increase significantly during this period, and the greater the drilling fluid pressure was, the maximum equivalent stress mutation was also the largest. After that, the equivalent stress of the core began to decrease sharply with time, but the greater the drilling fluid pressure, the equivalent stress of the core was still the maximum. Therefore, the drilling fluid pressure significantly affects the maximum equivalent stress of the core, and the maximum equivalent stress appears in the bubble position inside the core at different times and under different drilling fluid pressures.

Table 1. Comparative analysis of the maximum equivalent stress of the inner bubble defect core under different drilling fluid pressures

Time/s	Drilling fluid pressure 1MPa	Drilling fluid pressure 2.5MPa	Drilling fluid pressure 4MPa	Maximum equivalent stress position
0.21	0.4073	0.79486	1.1841	Inner bubble
1.1194	1.5901	2.6999	3.3457	Inner bubble
1.2561	24.649	25.03	26.835	Inner bubble
1.8603	17.829	20.576	19.181	Inner bubble
2.4468	26.487	31.787	47.836	Inner bubble
3	5.1153	9.4532	14.666	Inner bubble

4.2. Analysis of Degumming Law of Metal In Rubber Core

There is a fixed metal plate inside the rubber core of rotary blowout preventer, which is prone to metal degumming in the process of rubber and metal vulcanization, which affects the safety of the rubber core. As shown in Figure 6, label 1 is the degumming of the right wall of the metal; Label 2 is degumming of the underside of the metal. Through ansys simulation calculation, the influence of metal degumming at different positions on rubber core was analyzed.

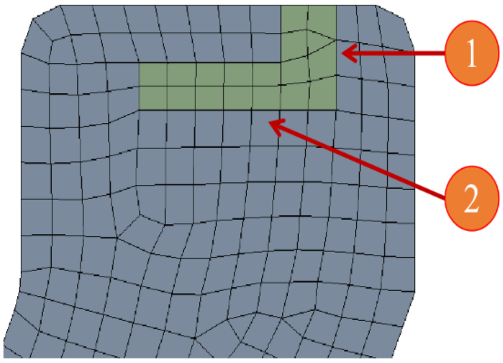

Figure 6. Metal degumming in the core

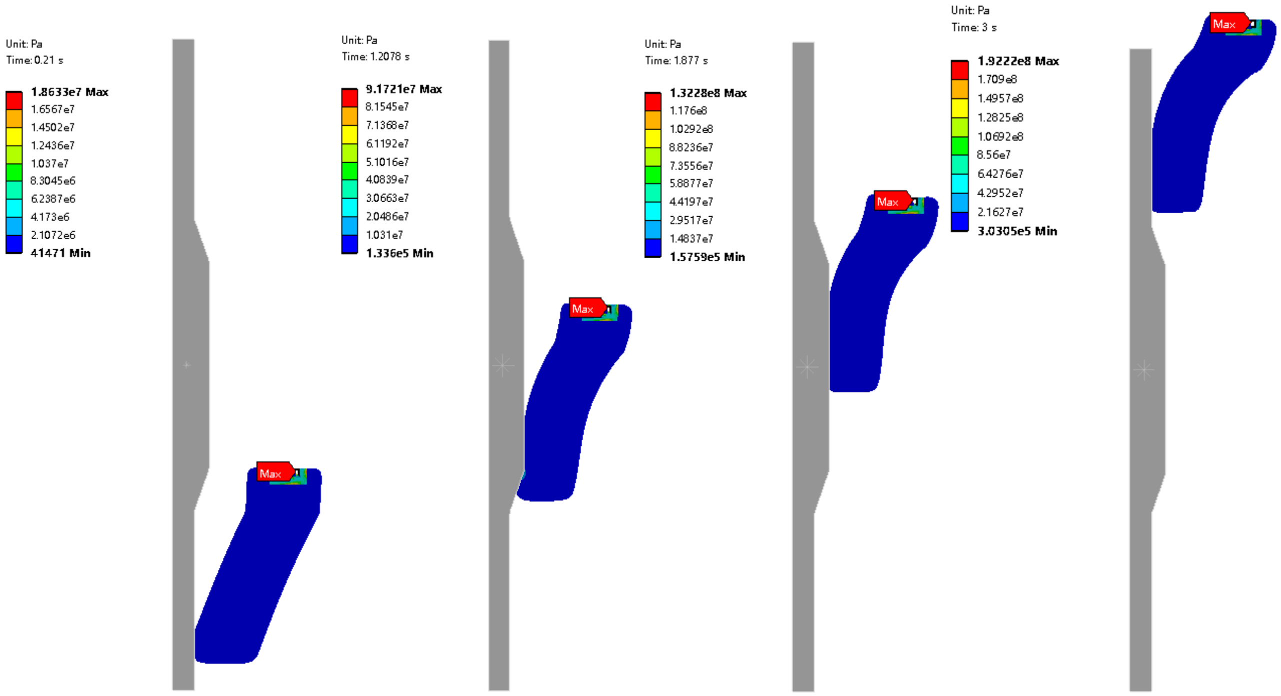

Figure 7. Undegummed core

Figure 7 shows the calculation results of no metal degumming of the rubber core. At different positions where the rubber core contacts the drill pipe, the maximum equivalent stress of the rubber core is in the middle of the metal, and the intact state of the rubber core changes under environmental conditions. Mainly due to the rubber core rubber material is squeezed and expanded, its sealing effect is mainly at the bottom of the rubber core, and the force on the top of the rubber core is less.

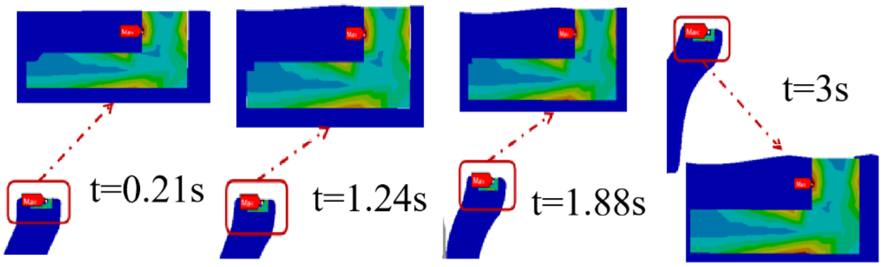

Figure 8. Metal degumming on the right side of the rubber core

Figure 8 shows the calculation results of metal degumming on the right side of the rubber core. At different positions where the rubber core and drill pipe contact, the maximum equivalent stress of the rubber core changes and is not concentrated in the middle part of the metal. Due to the degumming on the right side of the rubber core, the metal begins to squeeze the rubber core, resulting in stress concentration on the left side of the rubber core, and the gap between the rubber core and the metal is obviously seen on the right side.

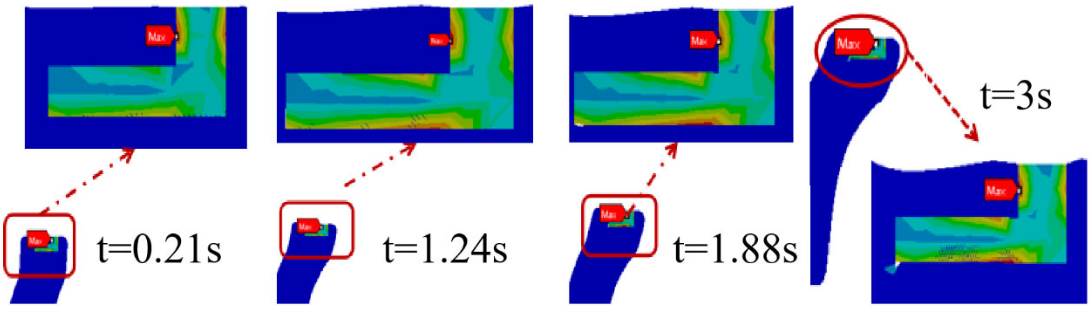

Figure 9. Degumming of metal on the lower side of rubber core

Figure 9 shows the calculation results of metal degumming on the lower side of the rubber core. At different positions where the rubber core and the drill pipe contact, the maximum equivalent stress of the rubber core changes and is not concentrated in the middle part of the metal. Due to the degumming on the lower side of the rubber core, the metal begins to squeeze the rubber core, resulting in stress concentration on the left side of the rubber core, and the gap between the rubber core and the metal is obviously seen on the lower side.

Figure. 8 and Figure. 9 are the calculation results of the degumming of the core of the rotary blowout preventer. It can be seen that the degumming positions are placed in the contact position between the metal and the core. This is because the bottom of the rubber core is subject to the upward translation driving force of the piston, the inner surface of the top cover exerts a pressure on the rubber core pointing to the center of the sphere and the friction force along the tangent line of the sphere. When the rubber core is in contact with the drilling tool, the inner surface of the rubber core produces contact pressure, which plays a role of sealing or self-sealing. Under the action of the above forces, the inner surface of the rubber core will shrink and deform, and the upper surface of the rubber core will show a bulge shape, and the farther away from the support reinforcement, the larger the bulge deformation will be. Due to the influence of the support reinforcement, the tensile stress at the junction of the upper surface of the rubber core and the inner surface of the cylinder is the largest. When the tensile stress exceeds the limit of the core material, the upper surface of the rubber core will produce radial cracks and circumferential cracks. In addition, the part of the rubber core and the support bar contact with the piston ring, due to the sudden change of material properties, will produce stress concentration and large shear stress. When drilling, an upward friction force is added to the inner surface of the rubber core. In this state, when the friction is large, there will be large shear stress or friction and wear phenomenon on the rubber core. If the drilling operation is repeated, the rubber core will also appear fatigue alternating stress.

Due to the sudden change of material properties at the contact point between the rubber core and the metal, there is an obvious stress concentration in the rubber core. When the stress exceeds the ultimate stress of the rubber material, the rubber core degumming cracking will occur. The rubber is extruded from the skeleton, and there is a binding effect of tearing each other inside. With the increase of sealing times, the rubber is prone to fatigue cracks. Eventually they tear each other apart.

In the process of high temperature rotation, rubber expands when heated. Due to the high temperature aging of rubber core material, its high elastic properties and mechanical properties are changed, resulting in cracking, embrittlement and damage at the contact position between rubber core and metal. Due to the excessive permanent deformation and serious elastic hysteresis of the rubber core, the initial sealing pressure of the rubber core is too low, and then the failure occurs. Due to the absence of lubricants or poor lubrication conditions, there will be a very serious friction heat generation phenomenon between the rubber core and the drilling tool, resulting in local overheating of the inner surface of the rubber core, changing the high elastic properties of the rubber material, the rubber core will become soft (that is, viscidity), and even carbonization, resulting in the sealing performance of the rubber core is reduced, and finally high temperature failure.

5. Conclusion

This paper analyzes the sealing process of rubber core and the effect of bubble defect in rubber core on the safety performance of rubber core under different drilling fluid pressures. Finally, the influence of metal degumming in different positions of the core on the safety performance of the core was analyzed. The results show that:

1. The larger the initial sealing pressure and contact stress value of the rubber core on the drill pipe, the better the sealing effect of the rubber core on the drill pipe, and the larger the Mises stress value, the more likely the fatigue failure of the rubber core will occur.

2. The contact stress of the rubber core is basically the same during drilling; In the process of drilling, the contact stress at the sealing surface is greater than 10MPa, and the sealing effect of rubber core is good. Therefore, the contact stress and contact area of the rubber core when it passes through the joint of the drill pipe are greater than that when it passes through the body of the drill pipe. Generally speaking, the drilling conditions have great influence on the sealing performance of rubber core.

3. Under different drilling fluid pressures, with the increase of pressure, the greater the drilling fluid pressure at the same drilling moment, the peak pressure will gradually increase. It can be found that with the increase of wellhead pressure, the deformation of the rubber core increases, and the contact length between the inner cone of the rubber core and the drill pipe increases. The contact pressure of the main sealing section is greater than the corresponding wellhead pressure, which can form a good seal, reflecting the self-sealing performance of the conical rubber core. The contact pressure of some nodes in the horn of the inner cone is greater than the corresponding wellhead pressure, which also plays a certain role in auxiliary sealing. The drilling fluid pressure significantly affects the maximum equivalent stress of the core, and the maximum equivalent stress appears in the bubble position inside the core at different times and under different drilling fluid pressure.

4. The degumming position is placed in the contact position between the metal and the rubber core. When the tensile stress exceeds the limit of the rubber core material, radial cracks and circumferential cracks will occur on the upper surface of the rubber core. If multiple trips are made, the core will suffer from fatigue alternating stress. The sudden change of material properties at the contact point between the rubber core and the metal leads to obvious stress concentration in the rubber core. When the stress exceeds the ultimate stress of the rubber material, the rubber core degumming cracking will occur. With the increase of drilling times, rubber is prone to fatigue cracks. Eventually they tear each other apart.

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