Simulation analysis of mechanical properties of key seating and bearing components of multistage water injection packer

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Abstract. Packer is one of the most important downhole tools for successful multistage water injection. In order to understand the mechanical properties of packer setting components and key loading components, a commonly used Y341 packer was studied as an example by simulation mechanical analysis. A three-dimensional model of a full-size Y341 packer was established by SolidWorks software. The finite element analysis software was used to analyze the mechanical properties of key components such as setting piston, circulating piston, mandrel, and lock ring under different working procedures such as setting packer, water injecting and well circulating. Loading the three-dimensional model of the full-size Y341 packer by finite element analysis software, stresses, strains and deformations of each parts were analyzed corresponding to different working procedures. And then, the stresses, strains and deformations of each parts were compared and researched. Based on the analyses and researching, it was found that the stresses near threads, holes and seal grooves were larger due to stress concentration, under axial force, internal and external pressure. But the working stresses of each parts are smaller than part material yield strength during normal working procedures, confirming the requirements of down-hole tool operations. When moving upward under axial force, the contact force and stress between the setting piston and the outer sleeve is relatively larger. So, the design length of setting piston should be appropriately increased to increase the contact area between setting piston and the piston cylinder. When overcoming upward friction to move the circulating piston, the frictional shear stress at the front end is considerable. So, the design area of the front-end of circulating piston should be larger possibly. Due to the uneven force in contact areas between the mandrel and different parts affiliated, the stresses near holes and circulating are also concentrated. So, the design hole diameter should also be also larger possibly. The teeth of the lock ring near the loading end are the main load bearing parts. So, the strength of the lock ring's stressed end can be increased by changing the opening distance of lock ring, the tooth angle, and the number of the teeth. The simulation analysis is useful and helpful to understand the mechanical properties of key setting and loading parts, and provide a basis for improving the design of multistage water injection packer, especially reducing stress concentration.
Keywords: Packer; multistage water injection; setting and loading component; mechanical property; simulation analysis;

1. Introduction
The packer is one of the most important downhole tools [1]. Simulation analysis is an effective way to know its performance [2], and thus provide guidance to tool designing under downhole temperature/pressure conditions [3]. The finite element method (FEM) is one of the most commonly used methods for downhole tool simulation analysis [4-5]. Reference [6-9] briefed the finite element analysis and design method of packer rubber cylinder. Reference [10] provided finite element analysis and simulation to setting of packer. Reference [11-12] is a finite element analysis of packer slips. Reference [13-14] analyzed the necking mechanism of packer. Reference [15] systematically introduced the secondary development of ANSYS finite element analysis software and its application in packer simulation. In the aforesaid references, the Y341 stratified water injection packer, which is commonly used in Dagang Oilfield, is taken as the research object, to implement 3D stress simulation analysis of layered water injection downhole tools. Due to the limited length of the paper, this paper mainly introduces the simulation analysis results of the mechanical properties of the key setting and bearing parts of the layered water injection packer.

2. Simulation Modeling of Layered Water Injection Packer
The Y341 packer is composed of reverse circulation well flushing mechanism, pack-off element (rubber), setting mechanism and other parts. The working principle is that the packer is well connected according to the tubing string structure and the well is drilled according to the requirements of downhole operation rules. Pressure is added by the tubing. When the pressure rises to a certain value, the piston shear nail cuts and then pressurizes the three-stage cylinder to slide and compress the pack-off element. Make it to seal the annular space of the oil sleeve and lock it by the split claw. When the tubing pressure is removed, the pack-off element will still be in the compression state and will not retract. Continue to keep the sealing compression state, thus completed the setting process. When well flushing is needed, such process is carried out from the annular space of oil jacket. At this point, due to the effect of pressure difference, after opening the well flushing valve on the upper part of the packer, the well flushing fluid will pass through the annular space of the inner and outer central tube and then enter the tubing from the lower ball seat to return to the wellhead, forming a well flushing channel, to achieve the purpose of well flushing. For unsealing, pull up the tubing string. Since the pack-off element is attached to the casing with friction, when the inner central tube goes up and drives the upstream contraction of the split claw of the unsealing sleeve. The split claw does not lock the packer. With the packer's resilience function, the packer is pulled back and no longer attaches to the casing, thus unsealed the packer.

SolidWorks was used to build the full size 5-inch Y341 packer 3D model, and finite element analysis software was used to analyze the stress of packer setting, well flushing and other operating conditions. The 3D finite element model of Y341 packer was established by ABAQUS software, as shown in Fig.1.

![Fig. 1 Y341 Packer 3D Finite Element Model](image-url)
will contact with the casing during the process of analysis. The casing is added to the packer rubber during the 3D modeling process.

3. The Boundary Conditions of Layered Water Injection Packer Simulation Analysis

When the finite element model is established, tangential contact and normal contact are configured. The tangential contact friction coefficient is set as 0.15, and the normal contact is set as hard "contact". 20CrMnMo is used for locking ring material, and 42CrMo for other rigid materials. The casing is set to 5"1/2 7.72mm (wall thickness) P110 grade steel. The rubber is made of nitrile butadiene. When the finite element model was established, the Mooney-Rivlin model was selected, and the coefficient of thermal expansion is set to 1.15x10^-8/℃.

Based on the mechanical analysis of the tubing string, the boundary conditions of the packer before setting, in setting and in well flushing were obtained when the temperature was 85℃ and positioned 2,500 meters underground, as shown in Table 1~3.

Table 1. Front Boundary Conditions of Packer Setting

| Upper axial force | Lower axial force | Internal pressure | External pressure |
|-------------------|------------------|-------------------|-------------------|
| 34.837kN          | 34.629kN         | 28.77MPa          | 28.77MPa          |

Table 2. Boundary Conditions of Packer Setting

| Upper axial force | Lower axial force | Internal pressure | External pressure | Setting pressure |
|-------------------|------------------|-------------------|-------------------|-----------------|
| 118.733kN         | 118.524kN        | 46.77MPa          | 28.772MPa         | 15 MPa          |

Table 3. Boundary Conditions of Packer Well Flushing

| Upper axial force | Lower axial force | Internal pressure | External pressure | Well flushing pressure |
|-------------------|------------------|-------------------|-------------------|------------------------|
| 141.57kN          | 141.146kN        | 37.307MPa         | 42.988MPa         | 5MPa                  |

4. Simulation Analysis of Layered Water Injection Packer Rubber

In this study, the overall 3D stress analysis of the packer was performed. The compression process of the rubber is complicated due to the particularity of the materials, initial downhole state of packer rubber, and the stress nephogram and displacement nephogram, under a packer rubber compression of 30mm and 50mm, are shown in Figure 2and 3respectively.

![Initial rubber stress nephogram](image1)

![50mm setting rubber stress nephogram](image2)

**Fig.2** Rubber Stress Nephogram during Setting
It can be seen from Figure 3 and Figure 4 that the axial displacement and compression amount of the lower rubber are the largest in the stress process, followed by the middle rubber and the upper rubber. The stress condition is similar to that of the displacement, and the force received by the lower rubber is larger than the other two. Deformation pattern of the rubber can be seen from the nephogram. The two ends are squeezed and deformed by the shoulder of the compression rubber, and the deformation shape of the rubber has a tendency to affect the sealing performance. The overall stress of the rubber is uneven during the setting process. In the process of extrusion, the overall force on the inside of the rubber is greater than that on the outside, and stress concentration occurs on the shoulder of the rubber. It can be seen from the stress conditions of the 3 rubbers of the packer that the contact pressure and compression force of the rubber at the loading end are relatively large, while the contact stress of the middle and upper rubber changes slightly along the axial compression direction. Therefore, it is suggested that the length of the rubber under the packer can be appropriately increased and the contact area between the packer and casing can be increased during the well flushing. And the lower rubber material should be more pressure resistant than the upper middle rubber.

The contact pressure and friction-shear stress of the packer rubber during setting drawn from the extraction node along a straight line from the contact area between the rubber and the casing are as shown in Fig.4. As can be seen from Figure 5, the overall trend of contact pressure and frictional shear stress of the rubber is the same. The shoulder of the rubber is higher than the middle part of the rubber, and the force of the lower rubber in the three rubbers is the largest, followed by the middle rubber and the upper rubber. The force on the shoulder of the rubber is relatively large in the middle part. And because of the stress concentration due to deformation, in the design of the rubber, a reliable penetration prevention device should be designed to limit the deformation of the packer rubber shoulder, so as to improve and maintain the contact stress.
5.  Simulation Analysis of Layered Water Injection Packer Flushing Piston

Figure 5 shows the stress nephogram of the packer flushing piston under the action of well flushing pressure. Under the action of well flushing pressure, the flushing piston opens the piston channel upstream to achieve the purpose of well flushing. The piston needs to be cleaned during operation to overcome upward friction. The frictional shear stress is larger at the front end of the cleaning piston. Similarly, the equivalent stress here is larger than the other parts. According to this, we can know the main contact force position of the flushing piston. During the process of design, the front area of the flushing piston can be increased appropriately and the edge chamfer can be used to reduce the stress concentration at the piston edge.

6.  Simulation Analysis of Locking Ring of Packer for Layered Water Injection

The initial and final stress of the lock ring are shown in Fig.6. From the figure, it can be seen that the stress of the lock ring are extremely uneven in the engineering work. The front end of the lock ring bears the main stress. Under the 10MPa axial load, the maximum stress of lock ring is 150Mpa, with high strength.
The stress of the lock ring is similar to that of the conventional packer slips. Take the nodes on a straight line along the axial direction to draw the curve of equivalent stress of the lock ring, as shown in Fig. 7. The teeth near the loading end of the lock ring are the main working part, while the teeth far away from the loading end are less stressed. As the locking ring has an unenclosed structure, with large deformation and unbalanced stress, improvements can be made to increase the strength of the bearing end during design by changing the opening distance of the lock ring, tooth angle and tooth number to avoid the release of packer due to the early failure of the lock ring under extreme working conditions.

![Fig. 7 Equivalent Stress Curve of Lock Ring](image)

7. Simulation Analysis of Central Tube of Packer for Layered Water Injection
The central tube is the main working part of the packer. As the central tube of the packer is connected to different parts when working, the stress on each part of the central tube is uneven, as shown in Fig. 9. The figure shows that the stress mode of the central tube at the rubber is different from that at other parts. The axial force on both ends of the central tube at the rubber has a great influence, and the load brought by the components around the other three parts of the central tube is greater than the influence of the axial load on the central tube. In addition, the packer is in the well flushing channel, and the stress concentration occurs at the hole of the central tube, so the bore diameter may be appropriately increased in the design. In addition, according to the stress law on the central tube, the size of the central tube at each position can be adjusted appropriately to increase the strength of the central tube, so as to ensure that the central tube has a better compressive property when bearing internal pressure.

![Fig. 8 Stress Nephogram of Central Tube of Packer](image)

8. Conclusions
Taking Y341 packer as an example, a three-dimensional model of the full-size packer was established to simulate the overall three-dimensional stress of the packer before setting, during setting and under the operating condition of water injection and well flushing using the finite element analysis software. By analyzing the stress condition of whole full-size packer and its key setting and bearing parts, the stress, deformation and distribution of each part under different working conditions can be obtained, and the dangerous point of stress strength can be found, thus giving suggestions for optimal design of the packer and optimal control of construction parameters.
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