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Structure Design of Grooved Joint Drill Pipe and Self-balancing Continuous Unscrewing Device

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Abstract: ***In the process of unscrewing the traditional drill pipe, the huge gripping force and friction on the outer surface of the joint often lead to the wear of the drill pipe joint. In order to solve the problems of the joint being eliminated and the pump or stuck caused by the wear of the drill pipe joint, a kind of grooved joint drill pipe and self-balancing continuous unscrewing device is designed in this paper, and the strength of the device is checked by numerical simulation. The design idea, structure principle and strength checking are introduced. The unscrew device can continuously tighten or unscrew the drill pipe without applying radial pressure to the drill pipe in the process of tripping and drilling pipe unscrew, and will not cause any damage to the surface of the joint, and the wear of the joint is only produced in the well and the wall, so it can effectively improve the overall service life of the drill pipe, reduce the probability of accidents such as drill pipe and stuck pipe, so as to improve the efficiency of drilling. It is of great significance to save the drilling cost. At present, the self-balancing screw unloading device has not been prepared, and it will be tested and put into practice in the future, hoping to achieve successful application in the field of intelligent drilling.***

Keywords: Drill pipe joint wear, Grooved joint drill pipe, Self-balancing continuous unscrew device, Strength check, No radial pressure is applied, Intelligent drilling**.**

1. Introduction

Drilling technology, as a crucial link in energy exploration and development, directly impacts the acquisition of oil and gas resources through its efficiency and safety. In this process, the drill pipe, serving as an essential downhole tool connecting the drill bit to the drilling rig, undertakes multiple tasks such as transmitting power, bearing pressure, and conveying drilling fluid. The structural design and material selection of the drill pipe are vital to the success of the entire drilling operation. This paper aims to discuss the wear issue of drill pipe connections and its influence on drilling efficiency and safety, while also exploring novel solutions to enhance the wear resistance of these connections. The drill pipe connection, a key component linking each section of the drill pipe, primarily consists of a pin connection, a box connection, and the connected drill pipe body. The outer diameter of the connection is typically larger than that of the body to facilitate the clamping of screwing and unscrewing tools. However, traditional drill pipes have certain limitations in practical operations. Significant clamping force must be applied by the screwing and unscrewing tools to generate enough friction for tightening or loosening the connections. During this process, the tool jaws penetrate the outer surface of the connection, leaving circumferential scratches. These scratches can produce burrs or protrusions when contacting the wellbore, leading to wear. As the outer diameter of the drill pipe connection gradually decreases, its wear resistance and safety also diminish, ultimately resulting in the replacement or elimination of the connection. Furthermore, under specific geological conditions, such as in formations prone to hole shrinkage and mud packing, the wellbore diameter may closely match the connection size. This not only increases the risk of downhole incidents like pump sticking or pipe sticking but also narrows the mud circulation channel, increasing the frictional loss along the mud circulation path and, consequently, the circulating pump pressure, thereby affecting drilling efficiency.

To address these issues, technicians have developed welded wear bands containing hard particles like tungsten carbide to enhance the wear resistance of the connections. Although these wear bands have improved connection durability to some extent, they have not fundamentally solved the wear problem.

Therefore, modifying the existing structure of drill pipe connections and the method of screwing and unscrewing represents a significant direction for addressing the aforementioned issues. This paper presents the design of a drill pipe with axial deep-groove wear-resistant connections (hereinafter referred to as grooved drill pipe) and its accompanying self-balancing continuous screwing and unscrewing device. This device enables continuous tightening or loosening of the drill pipe without applying radial pressure to the surface of the connections during tripping and pipe handling. As a result, it does not cause any damage to the connection surfaces, and wear on the connections only occurs when they come into contact with the wellbore wall. Consequently, this design can extend the overall service life of the drill pipe, reduce the likelihood of drilling tool failures, pipe sticking, and other accidents, thereby improving drilling efficiency and saving drilling costs.

2. The principle of the Screwing and Unscrewing Device

2.1 The Principle of Traditional Drill Pipe Screwing and Unscrewing

Based on different operating principles, traditional drill pipe screwing and unscrewing mechanisms can be classified into clamp-type mechanisms and gripping-type mechanisms. The clamp-type mechanism operates through a clamp cylinder that drives the clamping jaws to grip and release workpieces such as drill pipes. When the clamp cylinder is activated, the clamping jaws either grip or release the drill pipe, enabling the tightening or loosening operation. The gripping-type screwing and unscrewing mechanism typically consists of two grippers located at either end of the drill pipe. These grippers, controlled by hydraulic cylinders, can clamp and release the drill pipe. Once both grippers have clamped the drill pipe, one of them, powered by a hydraulic cylinder, rotates the clamped drill pipe while the other remains fixed. This relative rotation between the two drill pipes causes the threaded connections to loosen, as illustrated in Figure 1 (+ represents N as the normal force). The gripping mechanisms clamp the connections of two adjacent drill pipes, and under the clamping force N between the screwing/unscrewing mechanism and the male connection of the drill pipe, as well as the frictional force F generated on the connection surface, the torque M produced by the frictional force F completes the screwing or unscrewing process. Traditional drill pipe screwing and unscrewing require significant frictional and clamping forces to achieve proper tightening and loosening, which often leads to surface wear on the drill pipe connections. This wear can result in reduced diameter of the connections or even reach dimensions that necessitate their replacement.

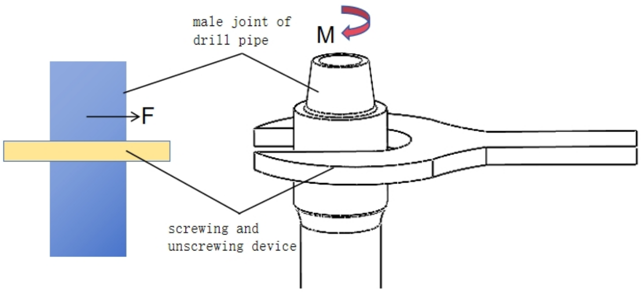


Figure 1: The principle of traditional drill

1.2 The Principle of Screwing and Unscrewing Grooved Drill Pipes

After the grooved drill pipe (with dimensions conforming to national standards for drill pipes) is connected via male and female connections, the screwing and unscrewing mechanism, along with the clamping mechanism, fixes the drill pipe by clamping the screwing and unscrewing groove and the anti-wear ridge of the connection. Then, driven by the torque M applied by the torque motor, the screwing and unscrewing mechanism rotates the clamped drill pipe while the other drill pipe remains fixed under the action of the clamping mechanism, thereby tightening or loosening the drill pipe threads, as illustrated in Figure 2. The screwing and unscrewing mechanism rotates the drill pipe under the action of torque M without needing to contact the outer diameter surface of the connection, thus completing the entire screwing and unscrewing process without causing any damage to the outer diameter surface of the connection. The wear on the outer diameter surface of the connection only occurs when it comes into contact with the wellbore wall, significantly reducing wear on the connection, extending the overall service life of the drill pipe, and lowering the likelihood of drilling tool failures, pipe sticking, and other accidents.

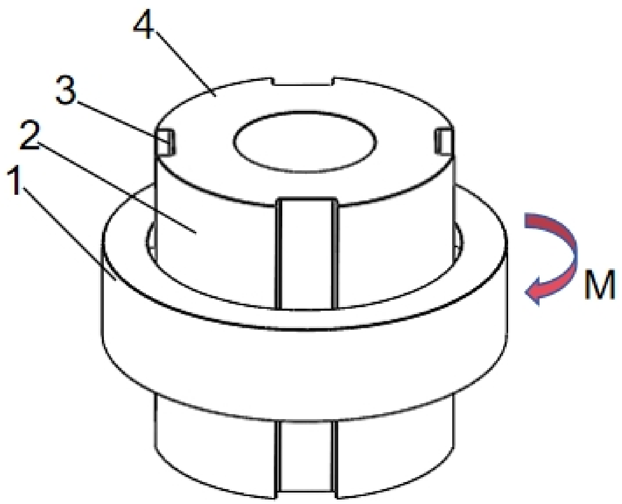


Figure 2: The principle of screwing and unscrewing grooved drill pipes

Notes: 1) Screwing and Unscrewing Mechanism 2) Anti-wear Ridge 3) Screwing and Unscrewing Groove 4) Drill Pipe Connection

3. The Structure of Self-balancing Screwing and Unscrewing Device

3.1 The Structure of Grooved Drill Pipe

The structure of the grooved drill pipe mainly consists of three parts: the drill pipe body, the male connector, and the female connector (with dimensions conforming to national standards for drill pipes), as shown in Figure 3. Similar to traditional drill pipes, the bottom of the male connector is equipped with a male connector connection part with external threads, and the female connector is internally fitted with internal threads that match the male connector connection part. However, unlike traditional drill pipes, the male and female connectors of the grooved drill pipe are circumferentially distributed with multiple connector screwing and unscrewing grooves extending along their axial direction. The spaces between adjacent connector screwing and unscrewing grooves form connector anti-wear ridges, which are equipped with wear-resistant materials or multiple blind holes for installing convex spherical caps. The smooth and wear-resistant convex spherical caps are fixedly connected within the blind holes, with the highest point of the spherical cap coinciding with the outer surface of the anti-wear ridge. The drill pipe body, male connector, and female connector are all hollow structures that run through.

The male connector with external threads and the female connector with internal threads can connect individual drill pipes together. The connector screwing and unscrewing grooves and the connector anti-wear ridges primarily serve as clamping features to achieve a fixed connection between the drill pipes, allowing for continuous screwing and unscrewing of adjacent drill pipes.

The transitional edges between the connector screwing and unscrewing grooves and the connector anti-wear ridges are designed with smooth fillets to reduce stress concentrations during the continuous automatic screwing and unscrewing of the drill pipes. The smooth and wear-resistant convex spherical caps are made of smooth, ultra-hard, and wear-resistant composite materials, which offer extremely high wear resistance and low abrasiveness. The blind holes for installing convex spherical caps on adjacent connector anti-wear ridges are staggered in the circumferential direction, ensuring that the smooth and wear-resistant convex spherical caps are evenly distributed along the axial direction of the connector without gaps when the drill pipe connector rotates. This design allows for continuous tightening or loosening of the drill pipes without applying radial pressure during the processes of tripping in and out, as well as screwing and unscrewing the drill pipes.

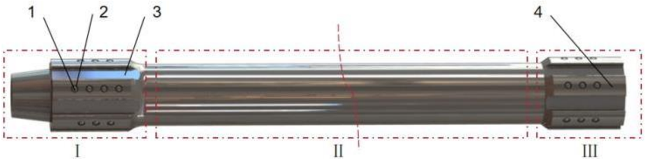


Figure 3: Grooved Drill Pipe
Notes: I Male Connector; II Drill Pipe Body; III Female Connector; 1) Smooth and Wear-resistant Convex Spherical Cap; 2) Blind Hole for Installing Convex Spherical Cap; 3) Connector Screwing and Unscrewing Groove 4.Connector Anti-wear Ridge

2.2 The Structure of the Self-balancing Screwing and Unscrewing Device

The structure of the self-balancing screwing and unscrewing device mainly consists of the following components: a screwing and unscrewing mechanism, a clamping mechanism, a tong body, an extension mechanism, a motor, a clamping block, a torque transmission gear, jaws, a cover plate, and other components, as shown in the 3D diagram in Figure 4.

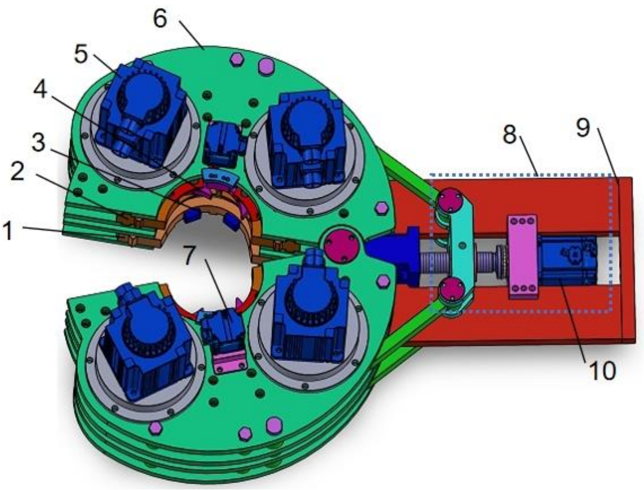


Figure 4: Self-balancing Screwing and Unscrewing Device
Notes: 1) Clamping Mechanism 2) Screwing and Unscrewing Mechanism 3) Clamping Block 4) Jaws 5) Torque Transmission Motor 6) Cover Plate 7) Motor I 8) Extension Mechanism 9) Tong Body 10. Motor II

When the self-balancing screwing and unscrewing device is used for screwing and unscrewing, it first opens to an appropriate angle under the thrust transmitted to the extension mechanism by Motor II. Then, the device is moved so that the drill pipe is positioned within the annular space of the entire device. Next, Motor II is reversed to apply a pulling force to the extension mechanism, causing the self-balancing screwing and unscrewing device to close. Under the force applied by Motor I, the jaws rotate the drill pipe, allowing the clamping blocks of the clamping mechanism to precisely align with the screwing and unscrewing grooves of the drill pipe. The result after alignment is shown in Figure 5. Once the clamping blocks are aligned with the screwing and unscrewing grooves, the torque transmission motor applies force to the screwing and unscrewing mechanism, driving the upper end of the drill pipe to rotate while the lower end remains fixed due to the clamping mechanism. This allows for easy and continuous loosening and tightening of the drill pipe threads.

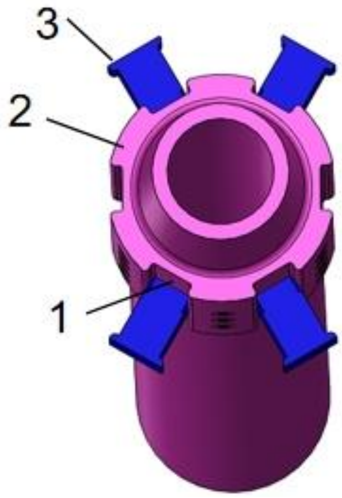


Figure 5: Principle of Drill Pipe Clamping
Notes: 1. Screwing and Unscrewing Groove 2. Drill Pipe Male Connector 3. Clamping Block

The main function of the clamping mechanism is to fix the drill pipe by aligning the clamping blocks with the screwing and unscrewing grooves. The screwing and unscrewing mechanism can rotate one of the drill pipes through the jaws, thereby achieving the purpose of screwing and unscrewing the drill pipe. The torque transmission motor provides torque to the screwing and unscrewing mechanism, enabling it to complete the screwing and unscrewing process. The tong body primarily serves to support and connect the entire self-balancing screwing and unscrewing device. The cover plate mainly provides support and protection, reducing the entry of mud and debris into the interior of the iron roughneck. The extension mechanism's primary role is to enable the opening and closing of the screwing and unscrewing device, allowing it to better fix and release the drill pipe during the screwing and unscrewing process.

4. Strength Verification of the Grooved Drill Pipe

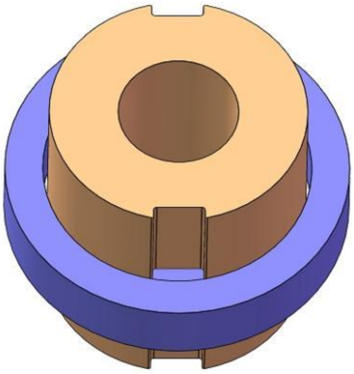
4.1 Finite Element Analysis Approach

The main function of the clamping mechanism is to fix the drill pipe by aligning the clamping blocks with the screwing and unscrewing grooves. The screwing and unscrewing mechanism can rotate one of the drill pipes through the jaws, thereby achieving the purpose of screwing and unscrewing the drill pipe. The torque transmission motor provides torque to the screwing and unscrewing mechanism, enabling it to complete the screwing and unscrewing process. The tong body primarily serves to support and connect the entire self-balancing screwing and unscrewing device. The cover plate mainly provides support and protection, reducing the entry of mud and debris into the interior of the iron roughneck. The extension mechanism's primary role is to enable the opening and closing of the screwing and unscrewing device, allowing it to better fix and release the drill pipe during the screwing and unscrewing process.

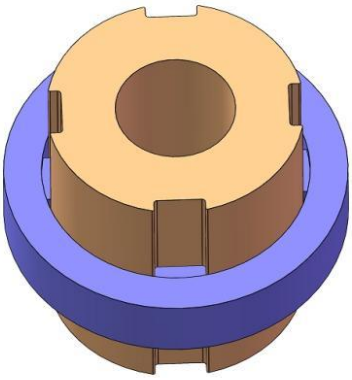
4.2 Strength Analysis of Drill Pipe Structures with Different Numbers of Grooves

4.2.1 Three-dimensional model of grooved drill pipe

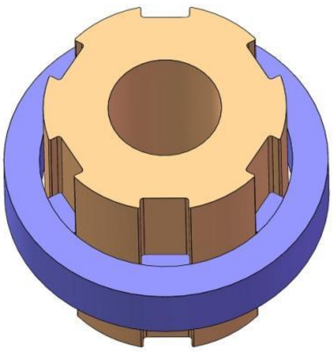
This paper employs Abaqus for structural strength simulation analysis. To ensure the accuracy of the analysis results, careful attention must be given to model simplification, mesh generation, and the setting of contact conditions. While ensuring that the analysis results are not negatively affected, this paper has simplified the model to the greatest extent possible, aiming to shorten computation time while maintaining the accuracy of the results. During the screwing and unscrewing of the drill pipe, the main stress-bearing area is the anti-wear ribs of the connector. The threaded portion of the male connector and the main body of the drill pipe can be removed, and then the upper and lower surfaces of the drill pipe can be fixed. Figure 6 shows the three-dimensional models of grooved drill pipes with different numbers of grooves (hereinafter referred to as D, where D2 indicates 2 grooves).



a) D2 Drill pipe model



b) D4 Drill pipe model



c) D6 Drill pipe model

Figure 6: Three-dimensional models of grooved drill pipes with different numbers of grooves.

3.2.2 Material parameter settings for grooved drill pipe

Both the grooved drill pipe and the screwing and unscrewing mechanism are made of 45 steel, with specific parameter settings shown in Table 1.

Table 1: Material Parameter Table for Grooved Drill Pipe

Material Name	Elastic Modulus （N/m^2）	Poisson's Ratio	Mass Density （kg/m^3）	Yield Strength (MPa)
45 Steel	2.0910^{11}	0.269	7850	355

3.2.3 Setting of Boundary Conditions

Before the drill pipe is unscrewed, the connector is considered fixed, and the screwing and unscrewing mechanism completes the task under the action of torque. Therefore, the boundary conditions can be set as follows: the upper and lower surfaces of the drill pipe are fixed, and a torque M is applied at the center of the screwing and unscrewing device. The magnitudes of M are 3000, 5000, and 7000 N·m, respectively. The screwing and unscrewing mechanism is set as a rigid body. The boundary conditions for the grooved drill pipes with three different numbers of grooves are the same. Taking D4 as an example, the boundary conditions are shown in Figure 7 below.

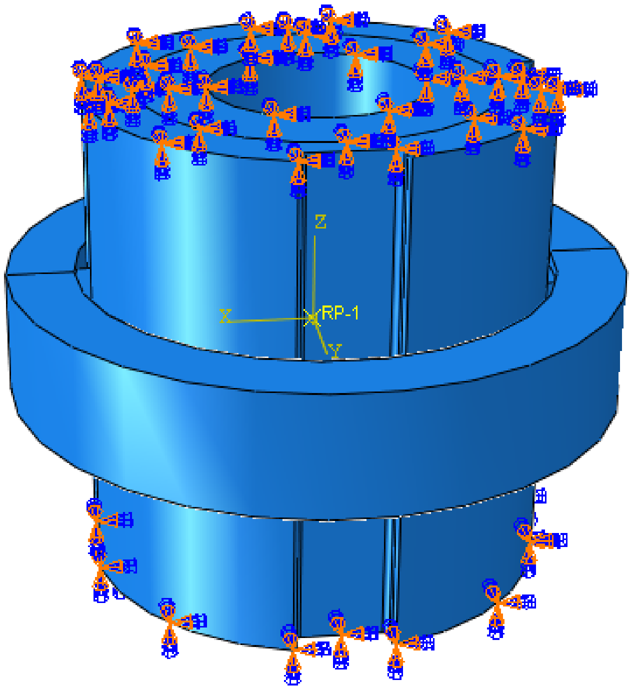


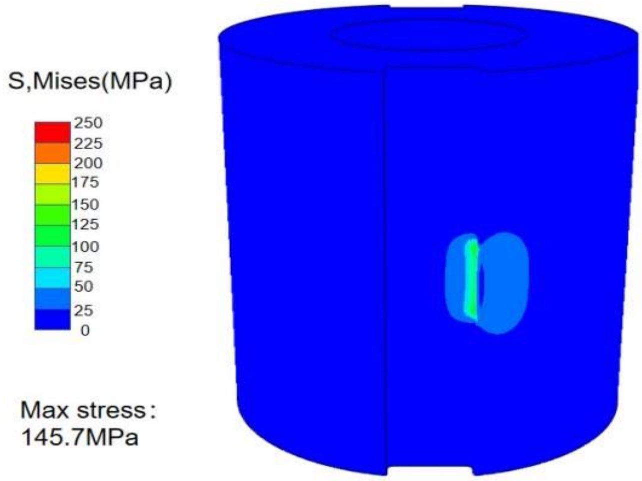
Figure 7: Setting of Boundary Conditions

3.2.4 Finite element results and analysis

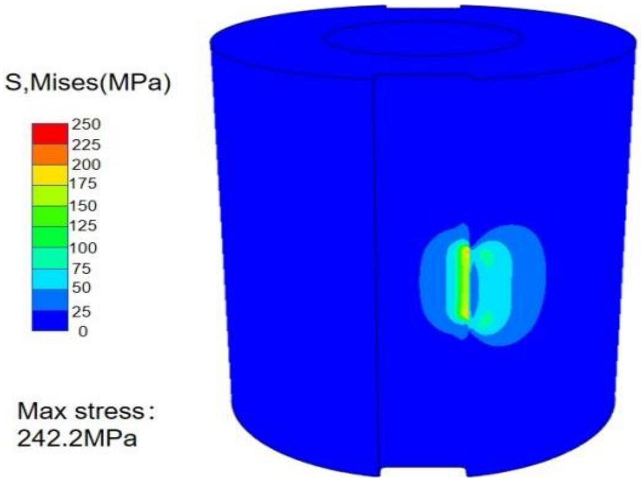
Since the structure of the self-balancing screwing and unscrewing device is symmetrical, the number of grooves should be even. This paper selects grooved drill pipes with 2, 4, and 6 grooves as the research objects.

(1) D2 Drill Pipe

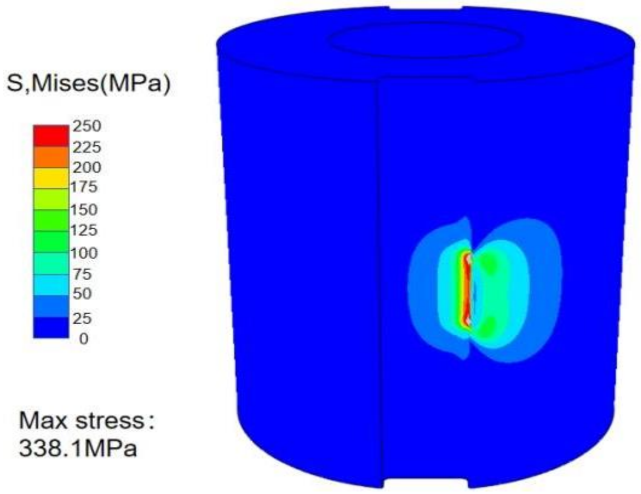
Figure 8 below shows the stress nephograms of the D2 drill pipe under torques of 3000, 5000, and 7000 N·m, respectively.



a) The stress nephogram of 3000N·m



b) The stress nephogram of 5000N·m



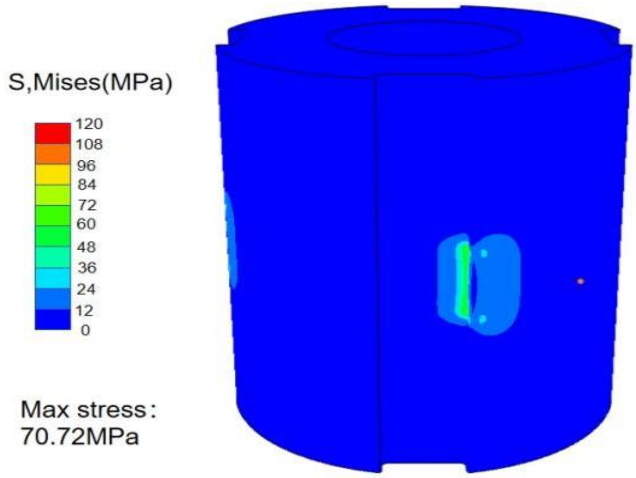
c) The stress nephogram of 7000N·m

Figure 8: Stress nephogram of the D2 drill pipe during screwing and unscrewing at different torques

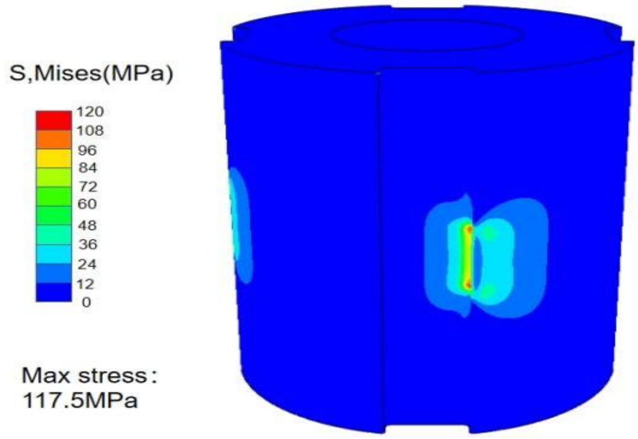
For easy comparison, the same legend is used for drill pipes with the same number of grooves. From the stress nephograms, it can be seen that as the torque increases, the stress on the D2 drill pipe increases significantly. At a torque of 3000 N·m, the stress range of the D2 drill pipe is mainly concentrated between 0-150 MPa, while at 7000 N·m, it is mainly distributed between 100-338 MPa. For every increase of 2000 N·m in torque, the maximum stress increases by about 100 MPa. At a torque of 7000 N·m, the maximum stress of the D2 drill pipe is 338.1 MPa, which is very close to the yield strength of the drill pipe, 355 MPa. The maximum stress appears at the fillet of the screwing and unscrewing groove, so the strength of the D2 drill pipe does not meet the requirements.

(1) D4 Drill Pipe

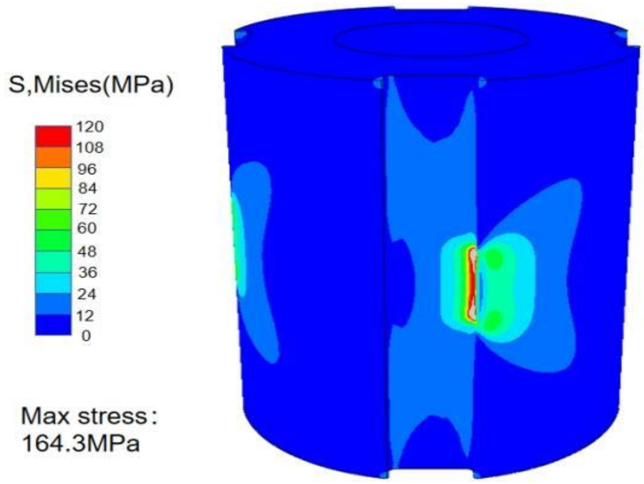
The D4 drill pipe is identical to the D2 drill pipe in all conditions except for the number of grooves. The stress during screwing and unscrewing under different torques is shown in Figure 9.



a) The stress nephogram of 3000N·m



b) The stress nephogram of 5000N·m



c) The stress nephogram of 7000N·m

Figure 9: Stress nephogram of the D4 drill pipe during screwing and unscrewing at different torques.

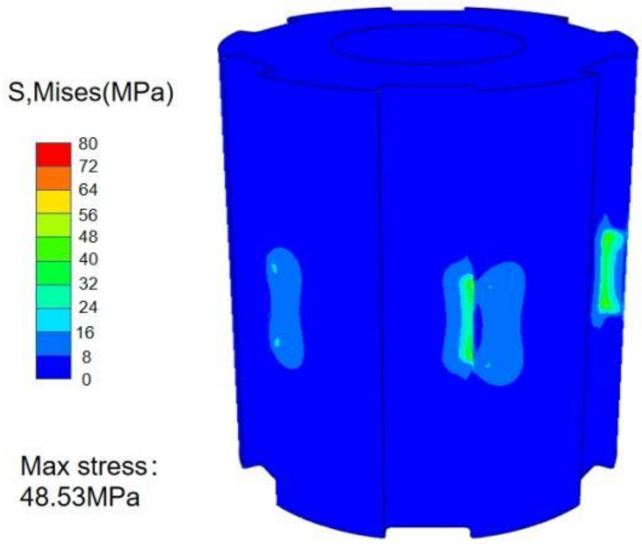
Comparing Figure 8 with Figure 9, it can be seen that compared to the D2 drill pipe, the maximum stress on the D4 drill pipe is twice that of the D2 at the same torque. Since the drill pipe is symmetrical, the maximum stress borne by the drill pipe in practice is proportional to the number of grooves, which is consistent with the simulation results. When the torque is 7000 N·m, the maximum stress on the D4 drill pipe is 164.3 MPa. The formula for calculating the material safety factor is as follows:

$$S = \frac{\delta_s}{\delta_{max}} \quad (1)$$

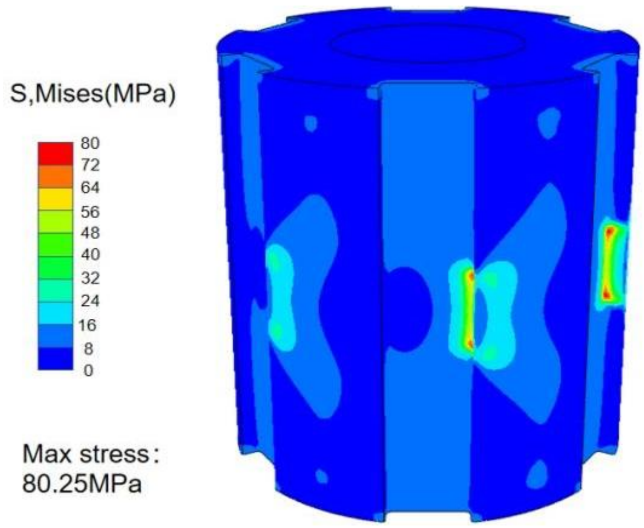
Calculating this, the safety factor for the D4 drill pipe is 2.17, which is greater than 1.5, indicating that the strength of the D4 drill pipe meets the requirements.

(1) D6 Drill Pipe

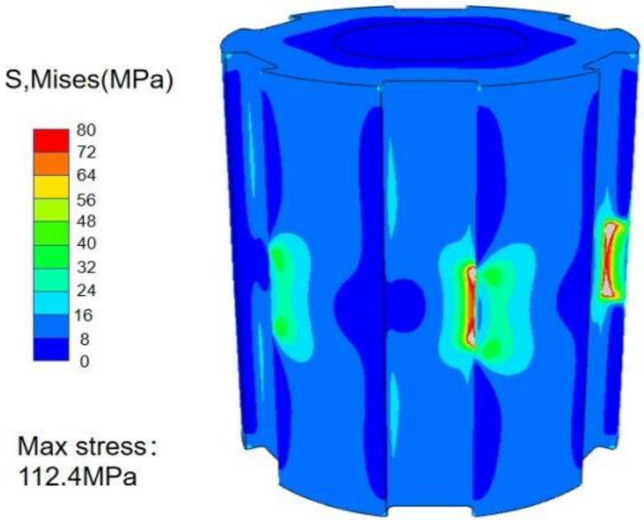
The D6 drill pipe is identical to the D2 drill pipe in all conditions except for the number of grooves. The stress during screwing and unscrewing under different torques is shown in Figure 10.



a) The stress nephogram of 3000N·m



b) The stress nephogram of 5000N·m



c) The stress nephogram of 7000N·m

Figure 10: Stress nephogram of the D6 drill pipe during screwing and unscrewing at different torques.

From a structural perspective, both the drill pipe and the screwing/unscrewing mechanism are symmetrical. At the same torque, the maximum stress experienced by the D6 should be one-third of that experienced by the D2. As can be seen from the stress nephograms of the drill pipes in Figures 8 and 10, the maximum stress values for the D2 at the three different torques are all one-third of those for the D6, which aligns with expectations. Calculations show that the safety factor for the D6 drill pipe at 7000 N·m is 3.15, indicating that its strength meets the requirements. To more intuitively represent the maximum stress experienced by the three types of drill pipes with different numbers of grooves at various torques, a bar chart of torque versus maximum stress has been created, as shown in Figure 11. It can be seen from the figure that, at the same torque, the stress experienced by the drill pipe is proportional to the number of grooves.

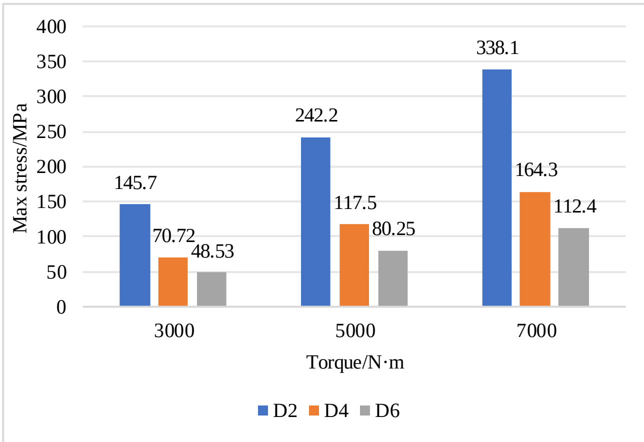


Figure 11: Maximum stress experienced by three types of drill pipes at different torques.

3.3 Strength Analysis of Partially Ejected Clamping Block

Since the clamping block is connected via a spring, there may be situations in actual operation where the block is not fully ejected and does not make complete contact with the inner surface of the screwing/unscrewing groove. Therefore, it is essential to analyze the stress conditions when there is a certain distance between the clamping block and the groove surface under the same torque. Taking the D4 drill pipe as an example, under the same torque conditions, we analyze the stress situations when there is a gap of 2, 4, and 6 mm between the clamping block and the inner surface of the screwing/unscrewing groove. The three-dimensional model is shown in Figure 12 below.

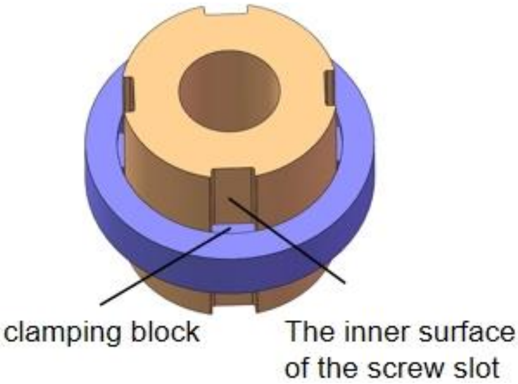
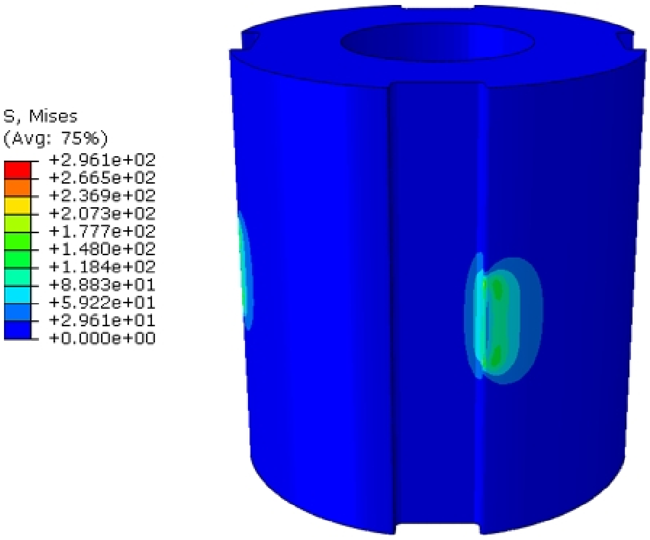
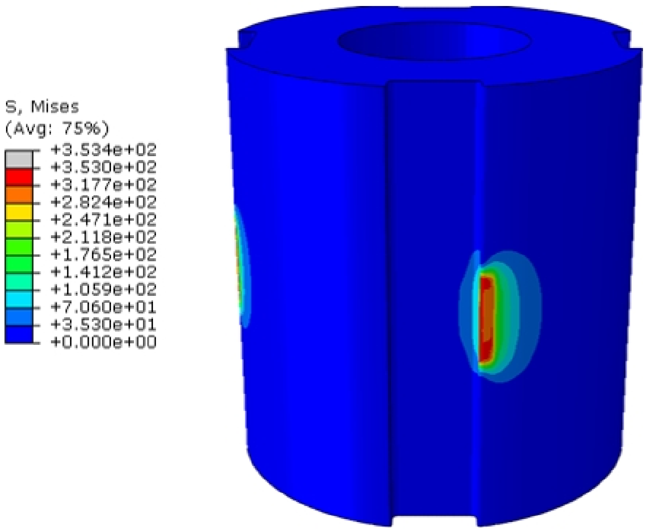


Figure 12: Three-dimensional model of the partially ejected clamping block

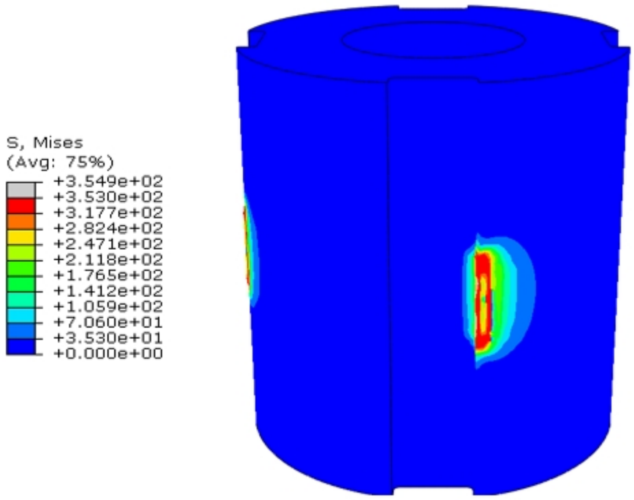
The boundary conditions are set the same as those for the D4 drill pipe when the torque is 7000 N·m (with a distance of 0). Figure 13 below shows the stress conditions when the distances are 2, 4, and 6 mm, respectively.



a) The stress condition of 2mm



b) The stress condition of 4mm



c) The stress condition of 6mm

Figure 13: Stress conditions of the drill pipe at different distances

From the above nephograms, it can be seen that under a torque of 7000 N·m, the maximum stress experienced by the D4 drill pipe at distances of 4 and 6 mm has already reached the yield strength of the drill pipe, resulting in strength failure. At a distance of 2 mm, the maximum stress is 296 MPa, while at a distance of 0 mm, the maximum stress experienced by the D4 drill pipe is only 164.3 MPa. To determine the torque at which strength failure occurs at different distances, the following simulation was conducted: a linearly increasing torque was applied to the screwing/unscrewing mechanism, with the curve shown in Figure 14 below, and the strain curve of the drill pipe was analyzed.

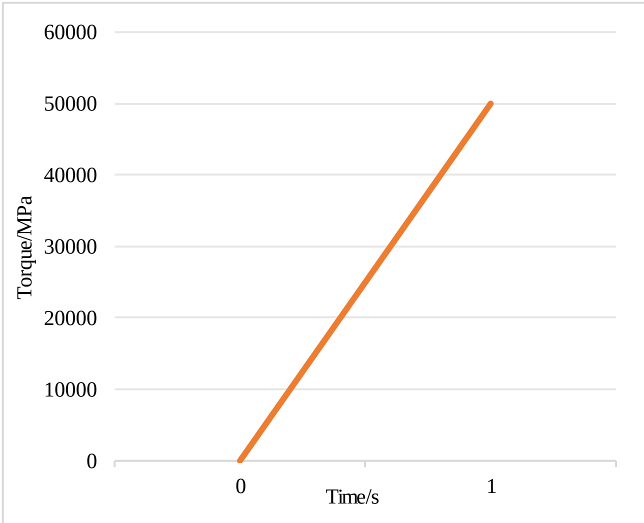


Figure 14: Time-torque curve

Through simulation analysis, the time-angular displacement curves of the center of gravity of the screwing/unscrewing mechanism at different distances were obtained, as shown in Figure 15.

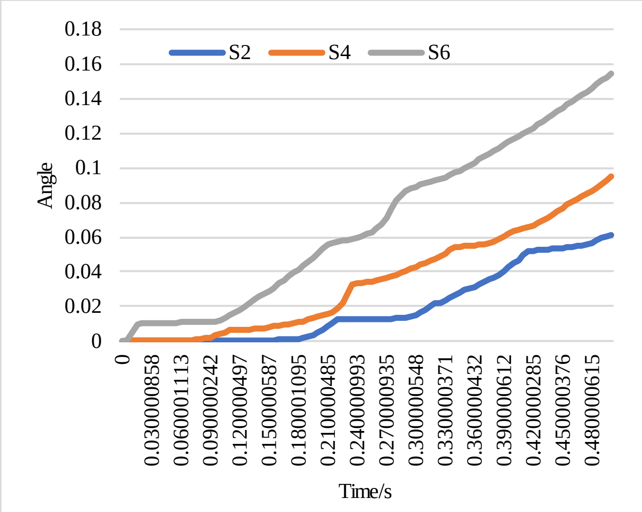


Figure 15: Time-angular displacement curve

As can be seen from Figure 15, the farther the distance between the clamping block and the screwing/unscrewing groove, the weaker the clamping ability of the screwing/unscrewing mechanism becomes, and the more easily the structure is damaged. S2 fails at 0.2 seconds (where 's' represents the distance between the inner surface of the screwing/unscrewing groove and the clamping block), and according to the time-torque curve, the torque at this point is 10,000 N·m. S4 fails at 0.1 seconds, with a torque of 5,000 N·m. Due to insufficient contact, S6 has too little clamping force at the beginning, causing the screwing/unscrewing mechanism to slip and fail to function properly.

5. Conclusion

1) When the torque is the same, the stress on the drill pipe decreases exponentially with the increase in the number of screwing/unscrewing grooves, meaning there is a linear relationship between the stress on the drill pipe and the number of grooves. When the number of grooves on the drill pipe is 2, the structure does not meet the strength requirements at a torque of 7000 N·m. When the number of grooves is 4 or 6, the self-balancing screwing/unscrewing device can complete the entire screwing/unscrewing process normally within 7000 N·m.

2) When the clamping block is not fully ejected and the number of screwing/unscrewing grooves on the drill pipe is 4, the clamping ability of the screwing/unscrewing mechanism is significantly reduced as the distance between the inner surface of the screwing/unscrewing groove and the clamping block increases. When the distance is 6 mm, the mechanism cannot function properly at all. When the distance is 4 mm, the drill pipe starts to slip at 5000 N·m, seriously affecting the entire screwing/unscrewing process. When the distance is 2 mm, the screwing/unscrewing mechanism can function normally within 7000 N·m. Therefore, before screwing/unscrewing, it is essential to ensure that the clamping block can eject properly, perform lubrication, or replace the spring.

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