Simulation Analysis and Test of the Thread Joint of High Strength Directional Drill Pipe with Large Through Hole

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Abstract: According to the requirements of the directional drilling, the \(\Phi 89\times3000\) type directional drill pipe with high strength and large through hole is designed. The pre-tightening force and axial force acting on the threaded joint of the drill pipe are analysed theoretically, and the finite element analysis model of the screw thread joint is established. According to the three working conditions of directional drill pipe, the stress conditions of threaded joints under different working conditions are simulated respectively. Based on the simulation results, the optimization measures of threaded joints are put forward, the design of threaded joint structure is improved, and the structure type and parameters of threaded joint are adjusted. Finally, the performance test and industrial test of high-strength directional drill pipe with large hole are carried out to verify the rationality of the improved design of drill pipe. The new directional drilling technology of "replacing tunnel with hole" is put forward innovatively, which promotes the popularization and application of directional drilling technology in coal mine gas control and contributes to coal mine gas control.

1. The introduction

The drilling technology of underground gas drainage hole in coal mine is divided into two kinds: ordinary rotary drilling and horizontal directional drilling. Compared with the ordinary rotary drilling, the horizontal directional drilling can effectively control the inclination angle and azimuth angle of the drilling hole, so that it can be constructed according to the pre-designed drilling trajectory. The construction depth generally exceeds 400 m \textsuperscript{[1-2]}. In the 1990s, China introduced more than 9 sets of directional drilling equipment from VLD Company in the United States and Australia successively to carry out downhole tests in Songzao, Huainan, Pingdingshan and other mining areas \textsuperscript{[3-4]}. In 2003, Yamei Daning mine of Shanxi Province introduced the 1000-meter directional drilling rig of Australia VLD Company. The maximum depth of the main hole was up to 1002 m, and a number of branch holes were completed. The test has been successful. Subsequently, Australian kilometer directional drilling rigs have been widely used in Jincheng, Lu’an, Yangquan and other mining areas, and more than 30 units have been sold successively\textsuperscript{[5-7]}.

In order to realize the localization of kilometer directional drilling rig and change the situation of Australian monopoly directional drilling technology, with the support of the major special projects of the National Development and Reform Commission, Xi’an Research Institute Co., Ltd., China Coal Science and Technology Group took the lead in developing the first kilometer directional drilling rig...
in China in 2007, and successfully carried out underground industrial test\cite{8-9}. In 2010, Chongqing Research Institute Co., Ltd, China Coal Technology Engineering Group successfully developed the first external-powered kilometer directional drilling rig, breaking through the hole switching technology, saving hundreds of thousands of battery replacement and maintenance costs for coal mines every year \cite{10-12}, which played an important role in promoting the rapid development of localized kilometer directional drilling rigs.

With the improvement of domestic gas control requirements and the maturity of directional drilling technology, in view of the situation of more gas accumulation in the upper overburden \cite{13}, domestic coal mines put forward the construction requirements of high-position and large-diameter directional drilling of roof. The drilling technology requires high-power directional drilling rigs \cite{14-16}, whose motor power is up to 132 KW, and the output torque is not less than 13000 N\(\cdot\)m. However, the wire-line coring drill pipe structure is widely used in directional drill pipes. The strength of thread joints is low, which may easily lead to the fracture accident of drill pipe joint in the construction process, resulting in drilling pipe, measuring system and screw motor falling off and other accidents in the hole \cite{17-18}, which brings great economic losses to coal mines.

The dangerous section of drill pipe, which is the key part to transfer torque and tension pressure during drilling, is usually located at the joint thread. In order to improve the torsional and tensile strength of directional drill pipes and meet the construction requirements of high-power directional drilling rigs, according to the working characteristics of drill pipes, the thread parameters of drill pipe joints are studied, and the stress of drill pipe joints under different working conditions is analysed by finite method, and the optimization measures of drill pipe structure and thread parameters are put forward.

2. Structural design of the joint thread of drill pipe

In order to meet the requirements of ZYWL-13000DS directional drilling rig, the drill pipe joints need to transmit the maximum static torque of 13000 N\(\cdot\)m, bear the load of 280 KN of the maximum thrust and pull-out force. At the same time, the drill pipe needs to transmit signals and 10 MPa of high-pressure water, so the drill pipe joints should have good sealing performance. On the basis of drawing lessons from the connection structure of directional drill pipe of Australian VLD Company and domestic rope coring drill pipe, the design of the joint thread of directional drill pipe with high strength and large through hole has been completed.

The threaded joint is connected with taper trapezoidal thread, which is helpful to increase the diameter of drill pipe inner hole, facilitate the installation of signal transmission device and transmission of high-pressure water, and reduce the pressure loss of high-pressure water. At the same time, the conical trapezoidal thread connection is convenient for automatic centering of drill pipe, which increases thread connection strength, makes thread force even, and transfers larger torque. In order to ensure the sealing performance of drill pipe, the large end shoulder of the joint is designed into a conical sealing structure. The drill pipe has self-sealing function after pre-tightening. The joint of drill pipe is designed with external thickening structure to improve the connection strength of the drill pipe thread and avoid the buckling of the box. The structural design of drill pipe is shown in figure 1.
3. Force analysis of threaded joints under pre-tightening force

3.1. Analysis of thread pre-tightening force [19-20]

Before any drill pipe is used, box and pin must be tightened before normal drilling, so that the large end shoulders of the threads can be closely contacted to ensure that drill pipe has a good sealing effect, while increasing the rigidity of the connection of the drill pipe to transmit torque and axial load. Pre-tightening moment produced by screw tightening will stretch pin and compress box to produce shoulder load moment. At the same time, it is necessary to overcome the thread friction moment between screw pairs and the friction moment between shoulder contact surface. For this purpose, it is necessary to analyse the force on the thread of the drill pipe joint, as shown in figure 2. Let the spiral rising angle of the drill pipe joint thread be $\beta$, the tooth type angle of the internal thread of the axial section be $\gamma$, and the tooth type angle of the vertical section of the thread be $\gamma'$, then the geometric relationship can be obtained:

$$\tan(\gamma'/2) = \tan(\gamma/2) \tan \beta$$  \hspace{1cm} (1)

After box and pin are screwed together, the axial preloading force $F_a$ will be generated. When box is subjected to the action of tangential force $U_f$ and moves in the opposite direction to $F_a$, the friction force along the spiral line on the thread contact surface is equal to the sum of the forces of $F_a$ in the vertical section of the thread obtained from the relationship between figures 2 (a) and 2 (b). So there are:

$$U_f \cos \beta - F_a \sin \beta = f_1[F_a \cos(\gamma'/2) + U_f \frac{\sin \beta}{\cos(\gamma'/2)}]$$  \hspace{1cm} (2)

Then $U_f$ can be expressed as follows:

$$U_f = \frac{f_1 \cos(\gamma'/2) + \tan \beta}{1 - f_1 \tan \beta \cos(\gamma'/2)} F_a$$  \hspace{1cm} (3)

where $f_1$ is the friction coefficient between screw pairs.

If the middle diameter of the thread is $d$, then the torque required to generate axial force is as follows:
\[ T_i = U \frac{d}{2} \]  

At the same time, after box and pin is pre-tightened, the large end faces should be tightly fitted, and the friction torque will be generated on the two end faces, and its magnitude can be expressed as:

\[ T_2 = \frac{1}{2} F_a d_1 f_2 \]  

where \( d_1 \) is the equivalent contact diameter of the big end face, \( f_2 \) is the friction coefficient of the end face.

Thus, when box and pin are pre-tightened, \( F_a \) will be generated, and the total torque of the joints is:

\[ T = T_1 + T_2 = \frac{1}{2} \left[ f_1 \frac{l}{\cos(\gamma'/2) + \tan \beta} + d_1 f_2 \right] F_a \]  

According to equations (3) and (6), when the preloading torque is known, the preloading force of box and pin can be calculated as:

\[ F_a = \frac{2T}{f_1 \frac{l}{\cos(\gamma'/2) + \tan \beta} + d_1 f_2} \]  

3.2. Axial force distribution of thread

The interface of the internal and external threads of the drill pipe joint is a spiral space surface after the thread connection, and the stress is more complex. Figure 3 shows the assembly drawing of box and pin of the drill pipe after screwing. The joints are acted by the pre-tightening force \( F_a \). Take the first tooth at the right end after box and pin screwing as the coordinate origin, and establish the OX in one-dimensional coordinate system. The force shared by each tooth thread is simplified to the concentrated force, so we can get:

\[ F = \sum_{i=1}^{n} F_i \]  

where \( n \) is the effective tooth number of the thread; \( F_i \) is the axial force on the first \( i \) tooth of the thread.
Figure 3. Axial force analysis of the threaded teeth.

Under the action of axial force $F_i$, the axial force on the vertical section of pin screw thread at position $x$ is $F(x)$. From the properties of acting force and reaction force, it can be known that the axial force on the section at the origin $x$ of the internal screw thread is $F'(x) = F - F(x)$. So it follows that:

$$F(x) = F \left( F_{x_p} + F_{x_{p+1}} + \ldots + F_n \right) = F - \sum_{i=x/p}^{n} F_i = \sum_{i=1}^{n} F_i$$

(9)

Let $F(x)$ the axial force of unit length along the engagement length of thread be $q(x)$, which reflects the distribution of axial force among the screwing teeth, also known as the distribution intensity of axial force. Then, the axial force on the cross section whose distance from the coordinate origin is $x$ can be expressed as:

$$F(x) = \int_{0}^{x} q(x)dx$$

(10)

Therefore, the axial force of any thread can be obtained from equations (9) and (10).

4. Finite element analysis of the threaded joint

4.1. Establishment of the finite element model

In order to accurately analyse the stress on the drill pipe and verify the rationality of directional drill pipe structural design, the 3D geometric model of box and pin and its assembly was established with Inventor software, which was imported into the ANSYS Workbench finite element analysis software to obtain the finite element analysis model. The grid division is shown in figure 4, with 528077 elements and 315661 nodes. The thread and contact surface are refined to ensure the accuracy of the calculation results.

![Assembly model for the finite element analysis.](image)

4.2. Finite element analysis results

In order to ensure the service performance of directional drill pipe, the drill pipe is made of 42CrMoA steel pipe with upsetting joint. After heat treatment, the yield strength is not less than 850 MPa, the
tensile strength is not less than 1080 MPa, and the extension rate after fracture is not less than 15%. According to the working characteristics of directional drilling, it is necessary to preload the drill pipe before use. When the geological conditions are single, the drill pipe almost does not rotate. It can be considered that the threaded joint only bears the action of preloading force and propulsive force. When drilling in complex formation needs to go through the reciprocating hole washing, the drill pipe should bear the rotary torque, thrust or pull of the drill. Therefore, loading can be carried out according to the three working conditions described in table 1. The loading torque of working condition 1 is the buckle torque of drill pipe, which generates axial preloading force of drill pipe.

Table 1. Working condition table of drill pipe threaded joint.

| No. | Description of threaded joint operation | Pre-tightening force /KN | The bearing capacity of the thread joint of drill pipe |
|-----|----------------------------------------|--------------------------|-------------------------------------------------------|
|     |                                        |                          | Torque / N•m |
|     |                                        |                          | Thrust /KN   |
|     |                                        |                          | Pull /KN     |
| 1   | Under the action of the buckle torque, the threaded joint is only affected by the preloading force | 21.546 | 0 | 0 | 0 |
|     | Normal drilling, the drill pipe does not rotate, threaded joints under the role of pretension and propulsion | 21.546 | 0 | 200 | 0 |
| 2   | Handle cross-hole, holing, rotary and reciprocating motion of drill pipe, screw joint bears the action of rotary torque, thrust or tension, and load according to torque and tension at this time | 21.546 | 13000 | 280 | 280 |

Through simulation calculation, under the action of preloading torque, the stress distribution generated by the preloading force on the threaded joint is relatively uniform. The maximum stress occurs in the first buckle at the small end of the joint, which is 56.01 MPa, as shown in figure 5. Working condition 2 is the schematic diagram of the stress distribution of the drill pipe joint in the normal drilling process, and its maximum value is 838.27 MPa, as shown in figure 6. Working condition 3 is the stress distribution map of the threaded joint when the drill pipe encounters complex strata, up to 967.35 MPa, as shown in figure 7.

Figure 5. Distribution of equivalent stress along axial direction under Preloading force.
4.3. Structural optimization of threaded joints

According to the above analysis results, the structure of the threaded joint of drill pipe is optimized as follows to improve the stress condition of drill pipe: (1) The upsetting diameter of the drill pipe was increased from 91 mm to 93 mm to improve the bearing capacity of the box; (2) Increased the thread height from 1.5 mm to 1.8 mm to improve the thread bearing capacity; (3) To improve the stress distribution of the threaded joint, the large end face contact was changed to the double-top inclined plane sealing structure where all end faces are in contact. The small end face is the auxiliary supporting surface to improve the stress distribution of the threaded joint, as shown in the figure 8; (4) In the root of the end faces, add stress unloading groove to reduce the stress concentration on the end faces, as shown in the figure 8.

Working condition 3 is the working condition with the maximum load of drill pipe. Therefore, the modified threaded joint can only be analysed by finite element method under this working condition.
The analysis results are shown in figure 9. The stress at the large end of the drill pipe thread is 593.62 MPa, which decreases by 38.6%, greatly improving the stress condition of the drill pipe joint.

![Graph showing improved stress distribution](image)

Figure 9. Improved the axial equivalent stress distribution of the structure.

5. Experimental study

5.1. Performance test

In order to verify the torsional and tensile properties of drill pipe joints, 10 pairs of optimized drill pipe joints were trial-produced and sent to China Automobile Engineering Research Institute Co., Ltd. for static torque test. The specific test data are shown in Table 2.

From the data in table 2, it can be seen that the maximum torque of drill pipe static torsion test is 24786 N•m, the minimum is 23828 N•m, the average is 24410.8 N•m, which is much larger than the maximum output torque of drill rig (13000 N•m), and has a higher safety factor.

Table 2. Static torque test of directional drill pipe.

| The sample number | Maximum torque / N•m | Pre-tightening torque / N•m | Rotation degree /° | The test results |
|-------------------|----------------------|------------------------------|--------------------|------------------|
| 1                 | 24589                | 3000                         | 775                |                  |
| 2                 | 23828                | 3000                         | 730                |                  |
| 3                 | 24575                | 3000                         | 744                |                  |
| 4                 | 24406                | 3000                         | 765                |                  |
| 5                 | 24687                | 3000                         | 774                |                  |
| 6                 | 24453                | 3000                         | 764                |                  |
| 7                 | 23983                | 3000                         | 736                |                  |
| 8                 | 24786                | 3000                         | 778                |                  |
| 9                 | 24267                | 3000                         | 757                |                  |
| 10                | 24534                | 3000                         | 760                |                  |

The inner thread is severely expanded and buckled, and the top of the first and second teeth of the inner thread is seriously deformed.

5.2. Industrial Test

After the drill pipe performance test finished, the project team trial-produced 600 drill pipes with the model of Φ89*3000 modified structural directional drill pipes, which were sent to B6 4 hengchuan head-on in 43163 roadway of Chengzhuang mine in Jincheng city, and 33(4)13 roadway in Shuangliu mine of Fenxi Group for the construction of large-diameter holes in high roof. The test rig was ZYWL-13000DS crawler type fully hydraulic directional drilling rig developed by Chongqing Research Institute Co., Ltd. of China Coal Science and Technology Group. The maximum output torque of the rig is 13000 N•m, feed force is 280 KN, and the stroke is 1200 mm. Among them, three main holes and nine branch holes with the model of Φ120 were constructed in Chengzhuang mine, the deepest hole 810 m, expansion Φ193 high large-diameter hole 1 (track construction as shown in figure...
10), 450 m deep. The test lasted for 3 months, total footage 2980 m. The construction of Φ120 main hole and Φ153 high large-diameter hole in Shuangliu mine has 4 each, 12 branch holes, lasted 52 days, and the total footage is 3574m (No.1 drilling site construction track as shown in figure 9). A set of construction technology suitable for high large-diameter directional drilling has been explored, and a new technology of "replacing the roadway with the hole" has been created, which has saved a lot of manpower and material resources and production costs for the coal mine. No fracture failure of the drill pipe joint occurred during the test, and the drill pipe signal test was normal, which could fully meet the requirements of directional drilling with high height and long diameter boreholes.

![Construction track of 810 m main hole in Chengzhuang mine.](image_url)

![Construction track of No.1 drilling site in Shuangliu mine.](image_url)

**Figure 10.** Trajectory construction drawings.
6. Conclusion

1) A kind of high-strength directional drill pipe with big hole was designed, and the pre-tightening force and axial load distribution of the drill pipe were analysed and studied, and the calculation method of pre-tightening force and axial load was deduced.

2) According to the operating conditions of directional drill pipe, the threaded joint of drill pipe was simulated and analysed by finite element method. The results showed that the stress distribution of the joint was relatively uniform under the pre-tightening force, but the stress distribution on the joint became extremely uneven with the application of tension pressure, rotating torque and other loads. After box and pin threads were meshed, the first and second buckles of the large end of the threaded joint were the parts with the greatest load-bearing stress.

3) According to the bearing capacity of drill pipe, the threaded connection structure was improved, the stress relief groove and auxiliary support surface at the small and large end of the threaded joint were increased, the contact stress of the threads was reduced, and the maximum stress was reduced by 38.6%. At the same time, the sealing performance and torsion resistance of the drill pipe were improved.

4) Performance test and field industrial test showed that the structure design of high strength large through-hole directional drill pipe was reasonable and reliable, which could well guarantee the construction requirements of directional drilling, created a new technology of directional drilling of "replacing roadway with hole", and provided an application model for coal mine gas control.

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Author introduction:

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