Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1900-1911
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

Development of Bionic Dual-Connected Drill Pipe for Horizontal Directional Drilling

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Abstract:

Directional drilling technology is main technical means to control gas and water disasters in coal mines, and drill pipe is an important part of directional drilling tools. However, the broken of the drill pipe is easy to cause the loss of drilling tools and instruments, and even lead to the abandonment of drilling holes. Aiming at the "drilling drop" problem caused by the broken of drill pipe, the animal tendon-bone biological prototype is analyzed, and engineering bionics methods and similar principles are adopted, a dual-connected structure that imitates the form of "tendon-bone" is creatively proposed, which can realize the effect that after the failure of "bone connection pair", the "tendon connection pair" can still be effectively connected, so that the broken drill tool can be lifted out of the hole. The Φ89 mm bionic dual-connected drill pipe was developed and its mechanical properties were tested. The results show that the tensile strength of the drill pipe can still reach 545kN after fracture, which can realize the goal of pulling the measurement instrument, non-magnetic drilling tool, screw and other drilling tools out of the hole after broken. The research of the thesis can provide a new research idea for solving the problem of "drilling drop" caused by the broken of the drill pipe.

***Keywords**: Horizontal directional drilling, Bionics, Dual-connected drill pipe, Drilling drop.*

I. INTRODUCTION

Horizontal directional drilling technology has the advantage of controllable borehole trajectory, high drilling efficiency and short construction period. It is widely used in coal mine gas drainage, water disaster control and other fields, which is of great significance to ensure coal mine safety production. However, due to the actual working conditions of coal mine roadway space size, the drill string is composed with numerous of single drill pipe about 1m long by threaded connection, which leads to enhanced rigidity of the drill string. In addition, drilling pressure can only be applied by drilling rig, so drill pipes bear serious bending during

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near-horizontal drill holes, thus leads fracture frequently at the root of external thread and “drill pipe dropping” accidents. Unfortunately, there are no effective measures to prevent the occurrence of drilling drop accidents by now [1-4].

Relevant experts and scholars analyzed the stress state of horizontal well drill pipes from the perspective of fatigue failure and drill string mechanics, they proposed technical measures to improve the service life of drill pipe from the aspects of improving the structure of drill pipe joint, improving material properties, improving heat treatment process, etc [5-10]. However, the occurrence of joint fracture of drill pipe during use is very random and uncertain, and the "drilling drop" problem caused by drilling pipe fracture has not been solved by the above research ideas. Therefore, this article starts with the study of the force state of horizontal well drill pipe, draws on the animal tendon-bone biological prototype, and creatively proposes a dual-connected structure of drill pipe. Through the double connection structure, the "rib connection pair" can still be effectively connected after the "bone connection pair" fails, so that the broken drill tool can be lifted out of the hole, the "drill pipe drop" problem caused by the fracture of the drill pipe joint can be solved, and the function of changing from passive protection to active prevention of "drilling drop" is realized finally.

II. THE WORKING PRINCIPLE OF THE BIONIC DUAL-CONNECTED DRILL PIPE

Imitation of animal's 'tendon-bone' dual-connection structure, the bionic design of drill pipe was researched to prevent the occurrence of drilling drop accidents [11-14]. During normal drilling, the tendon rod fixed in the central through hole of the box connector is first screwed into the internal box thread of the pin connector, and after screwing for a certain length, the internal pin thread is separated from the internal box thread; then the outer taper thread of the pin connector and the inner taper thread of the box connector begin to screw together, until the end of the box connector contacts the first outer shoulder of the pin connector, the make-up operation is completed. At this time, the taper thread connection between the pin connector and the box connector is equivalent to the "bone connection pair” of the drill pipe, and the connection between the internal pin thread of the tendon rod and the internal box thread of the pin connector is equivalent to the "rib connection pair” of the drill pipe. During the drilling operation, when the "bone connection pair" is broken, the "rib connection pair" will play a role when the drill pipe is lifted. As long as no reversal occurs, the internal pin thread of the "rib connection pair" and the internal box thread of the "bone connection pair” will not be detached, and relying on this connection, the broken drill pipe will be lifted out of the hole. When the drill pipe is unbuckled, the connecting of the taper threads of the pin and box connectors are first separated, then the internal pin and box threads begin to separate, so that the two drill pipes are completely separated and the drilling operation is completed. The connection

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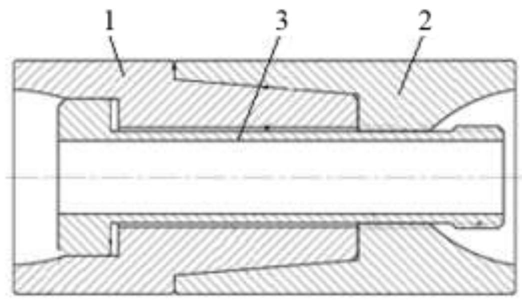
structure of the bionic dual-connected drill pipe is shown in Figure 1.



1-pin connector; 2-box connector; 3-tendon rod

Fig 1: Schematic diagram of the structure of bionic dual-connected drill pipe

III. SIMULATION ANALYSIS OF THREAD PARAMETERS OF TENDON ROD

The core of the development of the bionic dual-connected drill pipe is to use the tendon rod to form a "rib connection pair", so as to realize a "rib-bone" connection structure. Therefore, for the "rib connection pair", it is necessary to design the thread parameters so as to improve its reliability and give full play to its role in preventing "drilling drop".

3.1 Simulation Scheme

When the "bone connection pair" is broken, the tendon rod is subjected to tensile loads during the lifting process. Therefore, in order to ensure the reliability of the tendon rod, the internal pin thread of the tendon rod is required to have strong tensile strength. Compared with triangular thread, rectangular thread has the advantages of high transmission efficiency, strong load-bearing capacity, and strong tensile performance. Therefore, rectangular thread is selected as the tooth shape form of the internal pin thread, and the parameters of the rectangular thread are optimized [15].

The tooth height and pitch are closely related to the strength and force of the thread. The higher the tooth height, the larger the contact area between the tooth sides of pin and box thread, and the greater the thread strength, which is more conductive to reducing the risk of tripping between the pin and box threads, and exerts the lifting effect of “rib connection pair”. However, due to the structural size of the tendon rod joint, the tooth height cannot be infinitely large, considering comprehensively, the tooth height is set to 2mm. Therefore, the priority is to optimize the design of the thread pitch, and a total of four pitch schemes are designed, as shown in Table 1, the four schemes are respectively simulated a by the tension of the tendon

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rod.

TABLE I Internal pin thread parameters of tendon rod

Type	Tooth structure	Tooth height /mm	Pitch /mm
Scheme a	Rectangular tooth thread	2	5.08
Scheme b	Rectangular tooth thread	2	8.467
Scheme c	Rectangular tooth thread	2	12
Scheme d	Rectangular tooth thread	2	16

3.2 Simulation Pre-Processing

The internal pin thread segment of the tendon rod and the internal box thread segment of the pin connector are selected for analysis, and Solid 164 element was used to model. The internal pin thread was screwed into the internal box thread until the internal box and pin thread is completely separated. Figure 2 shows the 3/4 cross-sectional view of the simulation model.

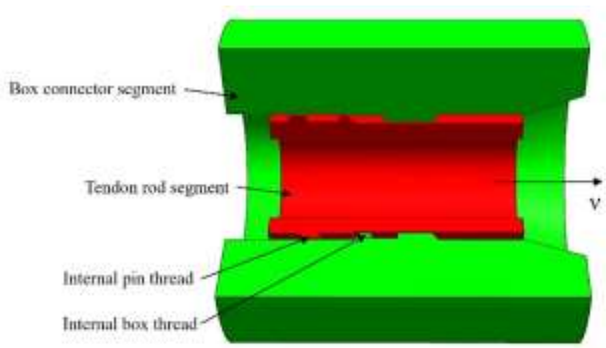
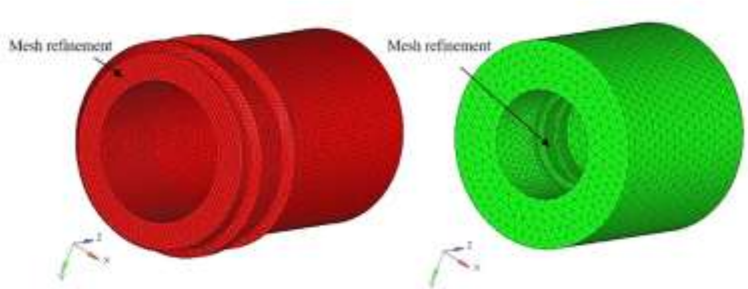


Fig 2: 3/4 section view of simulation model

The tetrahedral mesh element is used to discretize the model, and the mesh of the tooth part is refined to improve the calculation accuracy. Figure 3 shows the meshing model.



(a) internal pin thread (b) internal box thread

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Fig 3: Meshing model

The tendon rod joint is made of 42CrMo material, which is isotropic and uniform in medium. A piecewise linear plastic material model is used to simulate the material proper-ties of the tendon rod [16]. For this material model, the elastic modulus is 185GPa, the Poisson's ratio is set to 0.3, and the yield stress is set to 1085MPa.

The pin connector segment is completely fixed, and the tendon rod moves along the central axis at a uniformly increasing linear velocity ν. Within 0-50s, the linear velocity ν of gradually increases from 0 to 5mm/s. A surface-to-surface frictional contact is set be-tween the internal pin and box threads to realize the transmission of shear stress.

3.3 Simulation Results Analysis

Figure 4 is the equivalent stress cloud diagram of the internal pin thread of the tendon rod. With the movement of the tendon rod, the first buckle flank of the root of the internal pin thread starts to contact the internal box thread of the pin connector, and stress concentration occurs on the flanks and crests of the first thread (figure 4(a)); With the continuous increase of the speed of tendon rod, the contact area of the internal pin and box threads continues to increase, and the equivalent stress borne by the first buckle at the root of the internal pin thread continues to increase until the stress reaches its yield limit. The thread element at the top of the tooth at the cutter groove is the first to fail, then the stress is transmitted to the outer thread along the thread crest path (figure 4(b)).

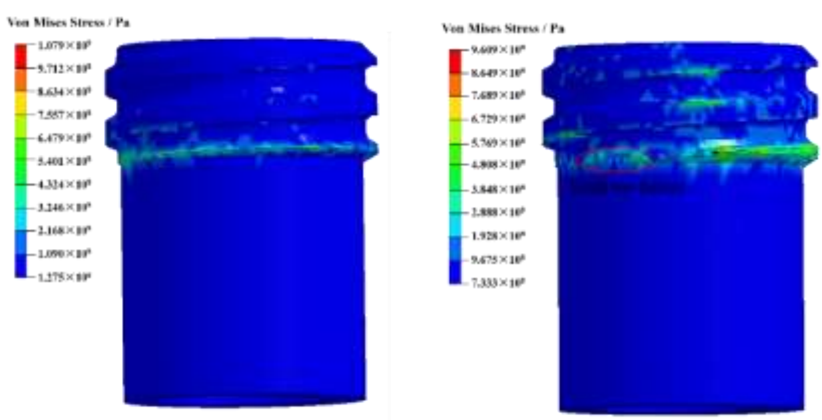

Fig 4: Equivalent stress cloud diagram of internal pin thread

Regardless of the thread structure of the pitch, the tensile load on the tendon rod shows a similar change trend. Figure 5 shows the change curve of the tensile load with time of the

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tendon rod when the pitch is 12mm. In the initial stage, the internal pin thread of the tendon rod is not in contact with the internal box thread, and the tensile load is 0; with the movement of the tendon rod, the sides of the internal pin and box threads begin to con-tact, and the contact area is constantly changing, the tensile load shows the characteristics of oscillation changes. With the continuous increase of the contact area between the internal pin and box threads, the overall tensile load tends to increase sharply. When the tensile load increases to 504.3kN, the tensile load drops abruptly. At this time, the first buckle of the internal pin thread undergoes shear failure and the tendon rod fails.

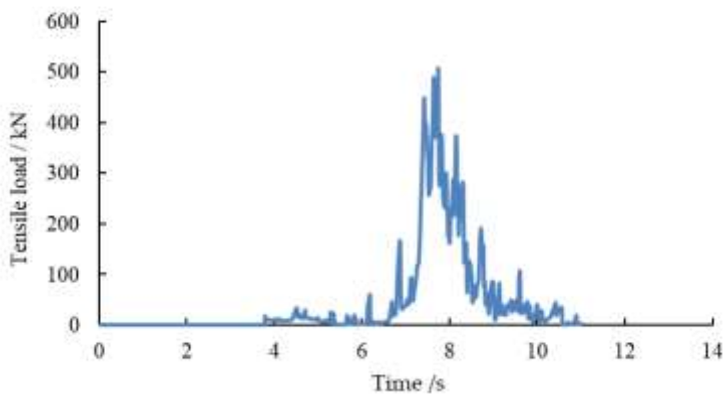

Fig 5: Tensile load with time curve of tendon rod

From this, it can be concluded that when the thread pitch is 5.08, 8.467, 12 and 16mm respectively, the tensile loads when the tendon rod fails are 256.2, 376.4, 504.3 and 571.9kN respectively. When the pitch is 16mm, the tensile load is the largest when the tendon rod fails, so its tensile capacity is the strongest. Therefore, 16mm is the optimal thread pitch parameter of the tendon rod.

IV. DESIGN OF Φ89 MM BIONIC DUAL-CONNECTED DRILL PIPE

4.1 Overall Design

Taking the Φ89 mm bionic dual-connected drill pipe as an example, the design focuses on the following two points: one is to ensure that the strength and toughness of the drill pipe is sufficient to meet the strength requirements during construction; the second is to ensure that after the fails of the taper thread joint, the strength and toughness of the "rib connection pair" can meet the requirements of the maximum pulling force of the drilling rig. Therefore, the overall design idea of the drill pipe is as follows:

1) The overall structure of the drill pipe is an outer flat structure, which is formed by

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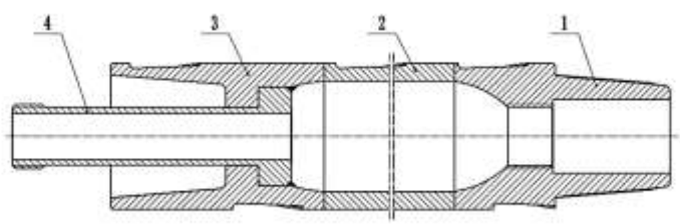
friction welding of pin connector, box connector and the pipe body. The overall structure of the drill pipe is shown in Figure 6. In order to improve the powder discharge ability of the drill pipe, a spiral groove is milled on the surface of the drill pipe [17], the groove depth is 3.5 mm, and the groove width is 22 mm.

2) In order to reduce the drill pipe connection points and reduce the risk of fracture, the drill pipe length is designed to be 3 m.

3) The connection form of the drill pipe joint is a dual-connected structure, and the tendon rod is used to realize the reliable connection of "rib-bone" structure, which plays the purpose of actively preventing "drilling drop".

4) The drill pipe is made of G105 steel grade material, which meets the API drill pipe steel grade requirements. To improve the strength and toughness, the joints and tendon rod are treated with quenching and tempering; the thread surface is strengthened so as to increase its wear resistance and service life.



1-pin connector; 2-box connector; 3-pipe body; 4-tendon rod
Fig 6: Schematic diagram of Φ89 mm bionic dual-connected drill pipe structure

4.2 Design of Joint

According to the design specifications of API drill pipes, a bionic dual-connected drill pipe joint structure was designed. This structure has the following characteristics:

1) The joint adopts the main and auxiliary shoulder double top structure [18], and the squeeze contact of the end face is beneficial to reduce the torque of the thread, reduce the concentrated stress, and increase the joint’s torsion and bending resistance. At the same time, the end face of the main shoulder of the joint is designed to be 75°, which is beneficial to improve the sealing performance of the joint threaded connection and suppress the occurrence of the expansion of the box joint.

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2) In order to ensure the consistency of the starting positions of the internal pin and box threads, special thread processing technology is used to process the internal pin thread of the tendon rod and the box thread of the pin connector, which can ensure the consistency of the phases.

3) The thread of the drill pipe joint is designed as rectangular structure, the tooth height is 2 mm, the thread pitch is 8.467 mm, and the thread taper is 1:12. The thread pro-file can not only increase the contact area of the thread connection, but also improve the centering accuracy and connection rigidity, which is conducive to the uniform thread force and large torque transmission.

4) The tendon rod is designed as rectangular structure with a tooth height of 2 mm.

Table II shows the main technical parameters of Φ89 mm bionic dual-connected drill pipe.

TABLE II Technical parameters of Φ89 mm bionic dual-connected drill pipe

Type		Outer diameter /mm	Inner diameter /mm	Material(Steel grade)	Tooth structure
Outer pipe	Body	89	69	G105	Rectangular
	Joint	89	48		
Tendon rod		42	30	G105	Rectangular with large pitch

V. PERFORMANCE TEST OF Φ89 MM BIONIC DUAL-CONNECTED DRILL PIPE

5.1 Torsion Resistance Test

The torsion resistance of the designed bionic dual-connected drill pipe was carried out with a microcomputer numerical control torsion testing machine. The torsional load was applied to the dual-connected drill pipe at uniform speed. Considering personnel safety and equipment capacity, the upper limit of torsional load was set at 30 kN·m. Figure 7 shows the torque loading curve obtained of the test. When the torque loading reached the upper limit of the equipment (30 kN·m), the drill pipe did not break, and the relationship between torque and loading time was basically linear, which indicated that pin and box joints of the drill pipe was in elastic deformation stage. After unloading the drill pipe, it was found that the drill pipe joint had no obvious deformation, and it was basically intact.

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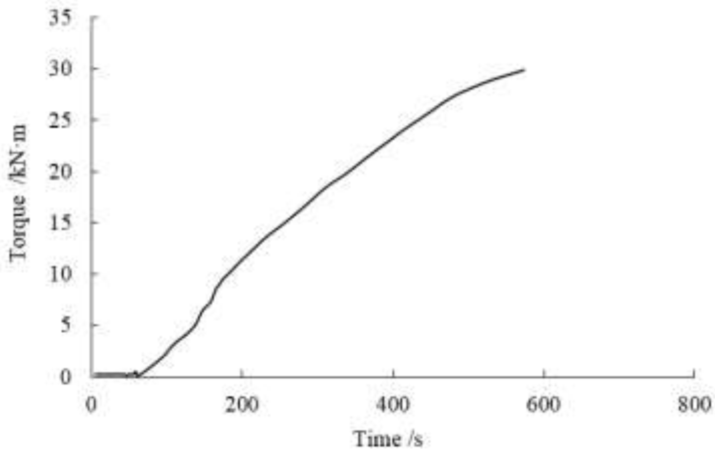

Fig 7: Torque loading curve

5.2 Tensile Performance Test

Horizontal tensile testing machine was used to test the tensile performance of the tendon rod. Before the test, the tendon rod and the pin connector were assembled in advance. During the test, the oil feeding speed was maintained at 0.5~1.5kN/s, and the load was evenly loaded until the sample was broken. Figure 8 shows the tensile fracture morphology of the tendon rod. The fractures of the tendon rod all occurred at the internal pin thread. The failure of the "rib connection pair" was caused by the buckle at the root of the internal pin thread.

Fig 8: Fracture morphology of tendon rod

Figure 9 shows the curve of tensile load of tendon rod with displacement. This curve shows the characteristic of "double peak", that is, the tensile load increases firstly, then decreases and then sharply increases with the increase of displacement. The reasons are summarized as follows: in the initial state, the internal pin and box threads are not in contact, with the increases of tensile displacement, the side of the internal pin and box threads begin to contact, because of the phenomenon of sliding dislocation, the initial contact is not stable, so there will be small fluctuations in the initial tensile load. After the contact between internal pin and box threads is stable, the tensile load increases sharply with the tensile displacement, when the tendon rod breaks, the tensile load drops sharply. This phenomenon is in good agreement with

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the tensile load change phenomenon obtained by simulation.

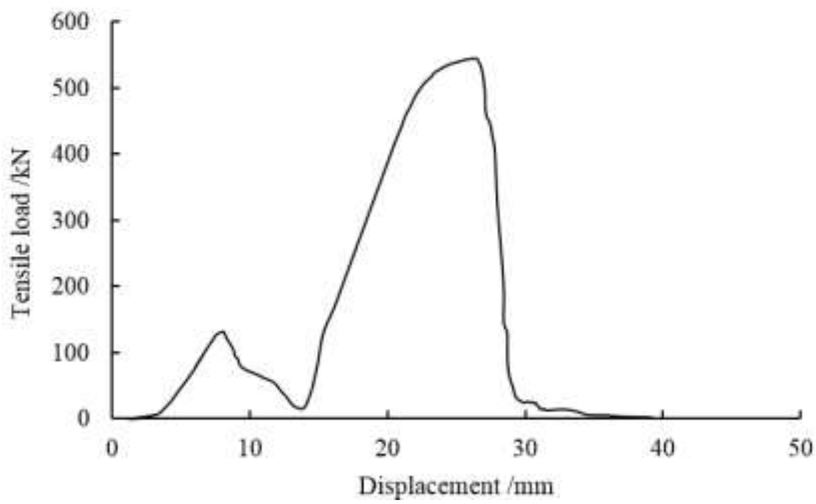

Fig 9: Curve of tensile load of tendon rod with displacement

From the tensile test, it can be concluded that when the thread pitch is 5.08, 8.467, 12 and 16mm respectively, the tensile loads when the tendon rod fails are 219.6, 350.5, 489.5 and 545.5kN respectively. When the pitch is 16mm, the tensile strength of the tendon rod is strongest. The results are in good agreement with the simulation results, which verifies the reliability of the simulation results. When the Φ89 mm bionic dual-connected drill pipe is used for directional long drilling, the corresponding drill pull force is 250 kN. When the pitch is 16mm, the tensile capacity of the tendon rod exceeds the pulling force of the drill rig by more than 2 times, which meets the requirements that the measuring instrument, non-magnetic drilling tool, screw and other drilling tools are put forward outside the hole.

VI. CONCLUSIONS

(1) Aiming at the problem of drill pipe joint fracture during near-horizontal directional drilling, a dual-connected structure imitating the form of "rebar-bone" was creatively proposed. After the drill pipe "bone connection pair" is broken, the broken drill tool can still be lifted out of the hole by the "rib connection pair", realizing the bionic effect of "breaking the bones and connecting the ribs", so as to achieve the bionic effect of "breaking the bones connected to the tendons", and provide a new idea for solving the problem of "drilling drop".

(2) The thread profile and parameters of the tendon rod was optimized the designed through simulation. According to the actual working conditions, the overall structure size is confirmed, the Φ89mm bionic dual-connected drill pipe was developed, and its performance test was

carried out in laboratory. Test results show that, the torsion resistance of the dual-connected drill pipe exceeds 30kN·m, and the maximum tensile strength of the tendon rod reaches 545.5kN, The maximum tensile capacity of the tendon rod is 545.5kN, which is more than 2 times the pulling force of the drilling rig, and it meets the requirements that the measuring instrument, non-magnetic drilling tool, screw and other drilling tools are put forward outside the hole after the drill pipe is broken.

ACKNOWLEDGEMENTS

This research was supported by National Natural Science Foundation of China (Grant No. 42072345), and the Natural Science Basic Research Project of Shaanxi Province (Grant No. 2021 JQ-952).

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