Lightweight Drill Pipe Based on Composite Carbon Fiber Material

Keyue Jiang*, Ruiheng Xie*, Hanfang Yun
School of Mechanical and Electrical Engineering, Wuhan University of Technology, Wuhan 430070, Hubei Province

*corresponding author’s email: jkyyy@whut.edu.cn, xieruiheng@whut.edu.cn

Abstract. At present, our country's drilling platforms mainly use alloy high-speed shafts. Due to the long transmission torque of drill pipes, drill collars and so on, the drill pipes are subjected to excessive torque and torque during operation, which often lead to fracture failure. The working environment of the drill pipe is wet underground, which is easy to corrode due to chemical reaction with the surrounding environment, thus causing the strength of the high-speed shaft to reduce and corrode, accelerating the fracture of the drill pipe, causing a large amount of waste of engineering materials and causing more serious environmental pollution problems. Based on the defects of the metal main shaft mentioned above, carbon fiber material is used as the main material of the high-speed shaft to avoid the corrosion of the main shaft caused by the changeable environment during drilling operation. Meanwhile, it has higher compressive strength, torsional strength and high temperature resistance. The invention can reduce the cost of transportation and installation parts, consume less electric energy during operation, reduce the weight of the drilling platform itself, and reduce a large amount of unnecessary cost in the drilling industry.

1. Introduction
With the accelerating process of social industrialization, the demand for industrial raw materials, especially crude oil, is increasing day by day. China's oil and gas resources are generally 7,000 to 9,000 meters deep and some of them are below 10,000 meters. This has led to the current situation that a large number of drill pipes are needed to exploit oil and gas resources. In this case, the problems in the actual use and production process of traditional rotary rods are also increasingly exposed. Due to the problems of single metal used and production process defects in the drill string combination of the traditional drilling platform, the drill shaft has defects such as excessive mass, low strength and gravity, poor corrosion resistance and micro-magnetism, etc., which bring great problems in the transportation and installation parts of the drilling engineering and increase the unnecessary cost of crude oil collection.

At present, our country's drilling platforms mainly use alloy high-speed shafts. Due to the long transmission torque of drill pipes, drill collars, etc., the drill pipes are subject to excessive torque and torque, which often lead to fracture failure and need to be replaced regularly. As the working environment of drill pipe is wet underground, it is easy to corrode due to chemical reaction with the surrounding environment, which leads to the strength reduction and corrosion failure of high-speed shaft. Due to corrosion, the cross-sectional area of the drilling tool is reduced or small corrosion pits are formed.
to cause stress concentration points, which greatly reduce the fatigue strength of the drilling tool, accelerate the fracture of the drilling rod, cause a large amount of waste of engineering materials and lead to more serious environmental pollution problems. With the development of China's industry, the number of drilling platforms is increasing and the intensity of drilling work is also increasing. Therefore, new materials are urgently needed to replace metal drill pipes.

2. Brief Introduction of Equipment
The device mainly uses carbon fiber materials to realize the light weight of the main shaft of the drilling platform and improve the corrosion resistance of the main shaft, thereby prolonging the service life of the main shaft and reducing the energy consumption of the active motor. The carbon fiber material and the metal material are not compatible with each other, and the main shaft of the original metal entity and the synthetic carbon fiber sleeve are connected through interference fit. At the same time, the main component of the spindle is light carbon fiber long sleeve, which has better mechanical properties and environmental adaptability. The main contents of this device are as follows:

1) The matching mode of metal shaft and carbon fiber sleeve is designed, and stress simulation analysis is carried out to verify the feasibility of the new spindle.
2) The quality of the traditional shaft and the new main shaft are compared and analyzed, the load of the connecting bearing is calculated, and the transmission energy consumption is analyzed.
3) The corrosion forms and corrosion states in deep well drilling are studied, and anti-corrosion design is carried out for the new carbon fiber spindle.

The device calculates and simulates various parameters for the new carbon fiber composite spindle to verify the feasibility of the bearing. The main shaft consists of a carbon fiber sleeve and a metal material which are mutually matched and connected to form a composite carbon fiber transmission shaft. In this matching mode, when the rotation speed of the main shaft is too high and the resistance at the front end of the drill bit cannot rotate at the same speed with the main shaft, the carbon fiber sleeve will no longer transmit torque, thus realizing the overload protection function of the main shaft. At the same time, we further optimized the feasibility of the new bearing through stress simulation analysis and strength check, calculated the reasonable transmission speed and working conditions of the new spindle, and improved its environmental adaptability and working life.

![Fig. 1 Design flow chart of carbon fiber drilling spindle](image)

The device can effectively improve the defects of high energy consumption, high damage rate and the like when the existing drilling platform works, and realize the energy-saving and environment-friendly goals of low cost and long-term utilization of the drilling platform main shaft. According to a certain proportion, carbon fiber material is compounded with the original metal, and the advantages of light weight, corrosion resistance, excellent mechanical properties and the like of the carbon fiber material are utilized, so that the main shaft is more suitable for harsh working environments under deep drilling platforms, and the drilling quality and the working life of main shaft components are improved.
3. Device Design

3.1. Design of connection mode between carbon fiber sleeve and metal stepped shaft

The device is designed to be formed by alternately connecting a carbon fiber main shaft and a metal shaft, wherein the metal shaft is provided with a journal to realize interference fit with a carbon fiber hollow sleeve, so as to realize long overlapping. The device is shown in the following figure. Two sections of metal shaft and one section of carbon fiber sleeve, because the carbon fiber sleeve has certain ductility, the carbon fiber sleeve is taken as the outer shell, and at the same time, the anticorrosion design of the joint of the metal shaft can be realized.

![Fig. 2 Detail drawing of interface between metal stepped shaft and carbon fiber sleeve](image)

Due to certain connection difficulties between the metal shaft and the carbon fiber sleeve, it is impossible to simply connect through shape. At the same time, the existing difficulty is to ensure the reliable bonding between the carbon fiber drill rod body and the metal joint, including the tightness of the rod body and the joint, and the strength of the bonding place. The device uses the adhesive between the inner walls in a way of shaft neck sleeving to prevent the adhesive from directly contacting with the external environment and reduce the problems of melting and swelling of the polymer adhesive caused by factors such as sudden change of external temperature, stress change and the like. In order to ensure the tightness, the metal shaft and the carbon fiber sleeve are in interference fit so that the bonding is effective and reliable. At the same time, if the adhesive fails and other problems occur, the ductility of carbon fiber can ensure its normal operation and is more effective and reliable.

3.2. Lightweight research and design of new spindle

When drilling the main shaft, the main shaft of the machine tool moves at a high speed and feeds continuously, which is mainly affected by the torque opposite to the direction of rotation of the main shaft and the reaction force opposite to the direction of feeding, causing the working motor to generate additional power consumption. In addition, the main shaft generally uses alloy with higher quality as the main load-bearing and torque transmission unit, resulting in excessive load on the drive motor during drilling operations, requiring a large starting torque and starting voltage when the drill pipe is started. Under certain special circumstances, excessive starting voltage may cause overheating or damage to the motor.

The new carbon fiber drill string is composed of carbon fiber-alloy composite material. Through the structure and interference connection design, it can not only ensure the good stress fatigue resistance of the main shaft, but also greatly reduce the quality of the main shaft and reduce the starting torque of the motor. While reducing energy consumption in operation, the risk of motor overheating and damage during startup is also reduced.

According to the data, the density of common alloy steel is 7.9g/cm³, the density of carbon fiber is about 1.8g/cm³, and the density of carbon fiber is about one quarter of that of common alloy steel. Using carbon fiber can reduce the quality of drill string by three quarters. Moreover, the torque of the new drill shaft is about one eighth of that of the traditional shaft, the starting torque is small, the damage to the motor during starting is low, and the motor can be effectively prevented from overheating during starting and excessive energy consumption for maintaining rotation.
3.3. Assembly and product design of carbon fiber drill pipe

In order to improve the adaptability of drill pipes under various conditions and enhance the integrated production level of new carbon fiber drill pipes, the device designs carbon fiber drill pipes as discrete production mode. The male and female joints of the drill rod and the connecting part are processed respectively at the same production source. Among them, the sizes of male and female joints are designed in a standardized way so that their diameters can meet the requirements of all kinds of above-ground platform power devices. The thickness of carbon fiber wound carbon filament and the transverse and longitudinal winding methods of drill rod are designed in a standardized way.

| Standardized parameters | Drill pipe diameter, carbon fiber winding carbon filament degree, transverse and longitudinal winding mode | Male/female connector Double interface diameter, metal material, Connection length |
|-------------------------|------------------------------------------------------------------|--------------------------------------------------------------------------------|

According to the above standardized parameter table, different combination modes of carbon fiber drill pipes can be generated to achieve different use effects. For example, on different hard lands, the performance of drill pipes can be changed by using the combination of drill pipes with different parameters and male-female joints to meet the use requirements.

After the discretization processing is completed, the drill rod and the male-female joint are packaged respectively. Due to the low quality of carbon fiber materials, a large amount of transportation costs can be saved during transportation. Meanwhile, the discretization packaging transportation can save transportation space to a certain extent. After the carbon fiber products are transported to the target site, the drill pipes can be assembled for use. The specific use process is as follows:

Fig. 3 Flowchart of carbon fiber drill pipe product application

4. Research Foundation and Feasibility Analysis of the Device

4.1. Benefit analysis

4.1.1. Cost analysis. The traditional drill pipe materials are mainly made of S135, G105 or P105 steel. When several drill pipes are spliced together, the drill pipes have sufficient torsion resistance, tensile resistance and other mechanical properties, and can meet the safety performance requirements. The traditional drill pipe materials are mainly made of S135, G105 or P105 steel. When several drill pipes are spliced together, the drill pipes have sufficient torsion resistance, tensile resistance and other mechanical properties, and can meet the safety performance requirements. The drill pipe material in the device is mainly composed of carbon fiber, which is a new type of fiber material with carbon content of 95%, lighter in mass than metal aluminum, but higher in strength than steel, and has the characteristics of corrosion resistance and high modulus. Carbon fiber is the main part, metal material is used at the joint of drill pipe, and interference fit is used for the connection between metal material and carbon fiber. After the splicing is completed, the carbon brazing filler metal drill pipe has the advantage of corrosion
resistance under the condition of meeting the mechanical performance and safety performance. Now, the cost of the two drill pipes is checked.

The production cost is calculated according to the manufacturing cost method. On the premise of mass production, the production method of carbon fiber is directly used to produce carbon fiber, and finally the production cost is obtained. Taking standard drill pipe 23/8" as an example, compared with traditional metal drill pipe and carbon fiber drill pipe, the cost analysis is shown in the following table:

|          | Drill pipe body $S_1$/Yuan | Drill pipe connection $S_2$/Yuan | Processing fee $S_1$/Yuan | Total cost $S$/Yuan |
|----------|---------------------------|-------------------------------|---------------------------|--------------------|
| Traditional drill pipe | 716.72                    | 126.48                       | 31.62                     | 874.82             |
| Carbon fiber drill pipe | 6861.51                   | 126.48                       | 23.63                     | 7011.62            |

The traditional drill pipe body uses G105 carbon steel as the material body, accounting for 85% of the whole drill pipe. The traditional drill pipe of 23/8" size is 7-9m, here 8m is taken as the length of each drill pipe, and the mass per meter is 10.54kg. The market price of G105 is 7-13 yuan/kg. Here, 10 yuan/kg is taken as the unit price of G105. The traditional price cost of drill pipe body is:

$$S_1 = 8 \times 10.54 \times 85\% \times 10 = 716.72 \text{ Yuan}$$  \hspace{1cm} (1)

The main part of the carbon fiber is 40% carbon fiber plus 60% substrate, and the density of the carbon fiber is 1.76~1.80g/cm³, G105 steel is 7.85g/cm³, The cost price of carbon fiber is about 1000 yuan/kg, the base is resin, the market price is 45 yuan/kg, and the main price cost of carbon fiber is:

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$$S_{11} = 8 \times 10.54 \times 85\% \times \frac{1.76}{7.85} \times 1000 \times 40\% = 6427.65 \text{ Yuan}$$  \hspace{1cm} (2)

$$S_{12} = 8 \times 10.54 \times 85\% \times \frac{1.76}{7.85} \times 45 \times 60\% = 433.86 \text{ Yuan}$$  \hspace{1cm} (3)

$$S_1 = S_{11} + S_{12} = 6427.65 + 433.86 = 6861.51 \text{ Yuan}$$  \hspace{1cm} (4)

The joints of drill pipes are all made of original metal materials, and the cost is 126.48 yuan. The processing cost of steel on the market is about 3,000/ton. The processing cost of traditional drill pipes is 31.62 yuan. Carbon fiber is directly formed by wrapping with carbon fiber cloth, gluing and then high-temperature treatment. The processing cost is about 10 yuan/kg.

$$S_1 = 10 \times 10.54 \times \frac{1.76}{7.85} = 23.63 \text{ Yuan}$$  \hspace{1cm} (5)

After accounting by manufacturing cost method, we can get the approximate cost of two kinds of drill pipes under the condition of mass production. The manufacturing cost of traditional drill pipes:
\[ S_{\text{old}} = S_t + S_a + S_1 = 716.72 + 126.48 + 31.62 = 874.82 \text{ Yuan} \] (6)

Manufacturing cost of carbon fiber drill pipe:

\[ S_{\text{new}} = S_t + S_a + S_1 = 7011.62 + 126.48 + 23.63 = 7161.73 \text{ Yuan} \] (7)

4.1.2. Analysis of transportation benefits. Taking the total length of a single drill pipe as 5.5m (in feet), the outer diameter as 60.3mm, and the total length of the loading part of the transport vehicle as 12m, the total number of conventional drill pipes that the transport vehicle can load is about 3200. After standardized processing, the total length of new drill pipes after removing male and female joints is about 3.3m, the total number of new drill pipes that can be transported is about 4800, and the ratio of transportation efficiency occupied by transporting male and female joints to the original transportation efficiency is removed. According to the calculation of the same number of transport vehicles at the same time, the transportation efficiency that can be improved by using the new drill pipe is as follows:

\[ \alpha = \frac{\eta_1 - \eta_2}{\eta_2} \times 100\% - \frac{\eta_3}{\eta_2} \times 100\% = 42.7\% \] (8)

According to calculation, the transportation efficiency of the utility model drill pipe is higher at the same time.

4.1.3. Energy saving benefit analysis. According to the definition of the rotational inertia of the cylinder, the starting torque of the drill shaft in the actual movement process and the energy required to maintain the steady state in the rotation process vary with the magnitude of the rotational inertia. According to the formula:

\[ I_v = mr^2 \int \int dv \] (9)

The moment of inertia of the two kinds of drill pipes has a linear relation with the mass only once under the volume integral, taking the same radius of the two kinds of drill pipes as an example. Using the average formula of rotational inertia, the rotational inertia of the two types of drill pipes is calculated as follows:

\[ J = \frac{1}{2} m(R_1^2 + R_2^2) \] (10)

The inner diameter and outer diameter of the two kinds of drill pipes are equal. According to API drill pipe standard specifications, the outer diameter R1 is 88.9mm and the wall thickness is 11.4mm, so the inner diameter R2 is 77.5mm and the mass of G105 carbon steel drill pipe is 10.54kg per meter. The main part of the carbon fiber is 40% carbon fiber plus 60% substrate, and the density of the carbon fiber is 1.76~1.80g/cm³, G105 steel is 7.85g/cm³. According to the formula

\[ 10.54 \times \frac{1.76}{7.85} \] (11)

The obtained carbon fiber drill rod has a mass of 2.36kg per meter and an average length of 8 meters. Finally available \( m_1 = 84.32\text{kg}, m_2 = 18.88\text{kg} \), Calculating the moment of inertia is available
\[ J_1 = 586422 \text{kg} \cdot \text{mm}^2 \]  
(12)

\[ J_2 = 131305 \text{kg} \cdot \text{mm}^2 \]  
(13)

To calculate the torque of drill pipe, we take the rotation speed of drill pipe as 60r/min, according to the formula

\[ T = 2\pi nJ \]  
(14)

The available torques for the two types of drill pipes are

\[ T_1 = 221.1N \cdot m \]  
(15)

\[ T_2 = 49.5N \cdot m \]  
(16)

We choose the standard drilling rig with the rotating speed of 1200r/min. According to the formula:

\[ P = \frac{T \times n}{9550} \]  
(17)

The available rig power required for different drill pipes are

\[ P_1 = 27.8kw \]  
(18)

\[ P_2 = 6.2kw \]  
(19)

According to the calculation of 8 hours of work per day, the energy that the traditional drill pipe needs to consume per day is

\[ W_1 = 800640kJ \]  
(20)

The energy consumed by the drill pipe using carbon fiber every day is

\[ W_2 = 178562kJ \]  
(21)

According to the summary, the daily benefits that can be saved by using carbon fiber drill pipes are about

\[ \Delta W = 622078kJ \]  
(22)

4.2. Simulation and analysis of mechanical performance of drill pipe

The device has carried out a preliminary stress simulation analysis of the model. INVENTOR software is used to carry out a drill pipe drilling process simulation experiment. The feasibility of the innovative device is preliminarily verified. The structure design is simple and the modification is easy, which can ensure the successful production of the prototype.

In order to verify the anti-overload effect of the spindle, we carried out comparative experiments. During the experiment, the conditions need to be simplified in consideration of the limitations of the conditions. We have established models of drill shafts, drill pipes and friction torque limiters made of
carbon fiber. In the experimental environment, we successively fixed the drill shaft, drill rod and carbon fiber sleeve on the same axis. The drill shaft and carbon fiber friction torque limiter and the drill rod and carbon fiber friction torque limiter are connected in a transitional fit manner to fix the bottom of the drill rod. In order to verify the feasibility of the scheme, we added a friction torque limiter made of special alloy steel and applied the same constraint conditions. Our experimental scheme is shown in the following table:

Table 3 Contrast analysis table of friction torque limiter stress

| Connecting material of two drill pipes | Fixed position | Torque   | Positive pressure |
|---------------------------------------|----------------|----------|-------------------|
| Carbon fiber                          | Bottom of drill pipe 2 | 20000N·m | 12000KN           |
| Special alloy steel                   | Bottom of drill pipe 2 | 20000N·m | 12000KN           |

Fig. 4 Stress analysis diagram of friction torque limiter made of carbon fiber in experimental group

When the carbon fiber friction torque limiter is used as the connecting part between the drill pipe and the drill shaft, the bottom of the drill pipe is fixed, pressure is applied from the top of the drill shaft and a torque is applied to the whole parts, and we obtain the compression condition and stress analysis diagram of the whole parts.

Fig. 5 Compare with the stress analysis diagram of the friction type torque limiter made of composite gold
The friction torque limiter made of alloy steel is used to fix the bottom of the drill pipe when it is used as the connecting part between the drill pipe and the drill shaft. Pressure is applied from the top of the drill shaft and a torque is applied to the whole parts. We also obtain the compression condition and stress analysis diagram of the whole parts.

Experimental data show that the carbon fiber friction torque limiter has less harmful torque transmission when connecting two drill pipes, and the drill pipes have less stress, high safety factor and alloy steel friction torque limiter. When two drill pipes are connected, harmful torque is transmitted more, drill pipes are stressed more, and safety factor is low. From the experimental simulation results, it can be known that it is feasible to selectively transmit torque between metal shaft and carbon fiber sleeve by interference connection to prevent the main shaft and its connecting part from being damaged due to high rotation speed overload.

5. Summary
1) Through interference fit, the metal stepped shaft is connected with the carbon fiber sleeve to form a composite carbon fiber main shaft, carbon fiber is taken as the main component material of the drill rod, and the corrosion resistance of the main shaft is effectively improved;
2) The composite application of carbon fiber material and metal material can reduce the weight of the long shaft of the drilling platform and reduce the energy consumption required for motor transmission.

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