

Design and Strength Analysis of Reduction Clutch for a Cable Tail Coiling Device

Kai Bai, Zheng Zhang, Zhanlong Li, Beijun Guo, Zhipeng Li, and Zhiqi Liu

Abstract—The reduction clutch of the cable coiling device in a large open-pit mine can guarantee continuous power supply, improve working efficiency, ensure equipment safety, adapt to harsh environments, and support automated operations. This mechanism plays a vital role in the mine's production operations. This study focuses on the reduction clutch of the cable coiling device. First, the system composition of this reduction clutch is introduced, followed by a new design and calculations conducted for it. A magnetic particle clutch is employed to control the magnetic field strength, enabling the transmission to separate and connect. This ensures smooth operation and precise control of the cable coiling device. Furthermore, ANSYS software is used to analyze the gear shaft strength, demonstrating that the maximum stress on the shafts is below the material's allowable stress. Analysis and verification confirm that the designed reduction clutch achieves flexible start-stop, overload protection, and intelligent speed regulation compared to conventional counterparts. It can not only realize the cooperative linkage of cables but also improve the safety and stability of mining equipment.

Index Terms—Reduction clutch, Structural design, Magnetic particle clutch, Strength analysis

I. INTRODUCTION

The open-pit mining is one of the ways to obtain ore resources and an important way to obtain industrial raw materials in modern society. The development of open-pit mining equipment affects the efficiency of ore mining. Electric shovels are large mechanical excavators widely used in open-pit mining operations, which is one of the key equipment in open pit mining [1,2]. These shovels rely on 6,000–10,000V high-voltage electricity transmitted through cables. In open-pit mining and stripping operations, it is necessary to coil and transport cables. However, cables have

the characteristics of high hardness, heavy mass per unit size, and inconvenient human coiling and uncoiling, and cables being dragged on the ground for a long time will cause serious damage, which will cause great security risks [3]. The level of mechanization and intelligence in smart mines continues to improve. The application of cable coiling devices effectively ensures the work quality of open-pit mining. These devices not only significantly reduce labor intensity for workers but also enhance operational safety and productivity. Cable coiling devices demonstrate promising market potential [4].

Cable coiling devices are subjected to a variety of stresses during operation. These encompass various mechanical stresses, including extrusion and tension, in addition to thermal stresses resulting from repeated motor cycling and operations under heavy load conditions. The synergy of these stress factors promotes the aging and degradation of the cable insulation, which considerably shortens the cable's operational lifespan [5-7]. The reduction clutch in cable coiling devices converts high-speed motor rotation into lower speeds, thereby meeting the requirements for controlled cable coiling, which plays a vital role in ensuring the safe and stable operation of open-pit coal mines. However, there are many problems with traditional reduction clutches: ① Continuous operation causes degradation and a reduced lifespan of the internal components, leading to clutch damage and jamming. To maintain normal operation, this necessitates periodic replacement of friction discs and lubrication, which significantly increases maintenance costs and downtime [8]. ② Conventional clutches exhibit structural flaws: high inertia, excessive friction, and complex transmission chains. Their slow response speed makes them unable to meet the rapid start-up and shutdown demands of cable coiling systems. ③ In the process of torque transmission, there will also be instability [11], which cannot ideally address the problems of synchronization of cable winding, appropriate cable tension, overload protection stability, etc. These problems undoubtedly reduce the production efficiency and safety of mining operations.

Therefore, it is crucial to study latest reduction clutches, aiming to achieve higher stability and precise brake control, thereby enhancing their applicability across diverse scenarios and extending service life. According to Wu [8], the torque in magnetic current reduction clutches is regulated through magnetic field adjustment, enabling precise control and enhanced transmission performance. This not only reduces the power consumption but also improves the stability and safety during operation. When magnetic particle brake is used as a clutch component in a reduction clutch, the current of the excitation coil in the magnetic particle brake has a good linear relationship with the output torque. Dong [9] integrated the magnetic particle clutch into a constant tension linear speed control system. The system realizes automatic

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constant tension control of the rewinding process. Experimental results confirmed that this solution ensures smooth operation and significantly improves operational safety. In addition, O. Mologni [10] studied the variation of cable tension in winch-assisted harvesting, and three planetary gear reducers were used to control the motion of cables inside and outside the drum to improve the safety of winch-assisted operations.

Most literature confirms that the reduction clutches enable efficient motor operation within specific torque-speed ranges. Exceeding these thresholds reduces operational efficiency significantly. Persistent overload may cause motor damage [11,12]. In 2023, Lu [13] developed a novel load-adaptive lifting mechanism. This system automatically adjusts the transmission ratio of the reduction clutch according to the payload. It is capable of performing seamless and continuous adaptive adjustments in response to variations in the payload. Experimental validation confirmed the mechanical feasibility and performance advantage. In the same year, Wu et al. [14] introduced a novel multi-pole magnetic particle clutch design that achieves a transfer torque approximately 2.3 times greater than the conventional design. Meanwhile, Dai et al. [15] proposed a new disc reduction clutch equipped with toothed brake discs. The innovative tooth design significantly enhances torque performance and improves the clutch's transmission capacity. Additionally, it effectively addresses the issues of magnetic leakage and insufficient magnetic field activation in conventional structures. Wang et al. [16] developed a dual-layer control strategy utilizing an automatic clutch actuator. Simulation and experimental results confirmed that this method exhibits greater robustness against external disturbances, substantially minimizing both the impact severity and the frictional work during clutch engagement. Furthermore, Hu et al. [17] engineered a double-disc magnetorheological (MR) brake through enlarging the effective damping gaps and refining the magnetic circuit, both the braking torque and efficiency were markedly increased. More recently, Wang et al. (2024) [18] employing magnetic core materials characterized by low conductivity and high permeability to tackle the slow response time of MR clutches. A. Devi and L. Sivakami [19]

studied the magnetic particle clutch magneto-fluid dynamics, and combined with the vehicle detection algorithm [20] to obtain the unconstrained conditions under which it works well.

The innovative reduction clutches designed and researched in the above literature have been widely used in the fields of automobiles, agricultural machinery, construction machinery and home appliances. But less research has been done on the applications in special mining operating equipment. Therefore, the research and development of reduction clutch for cable coiling and playback cooperative linkage system has become an urgent problem to be solved. To tackle the problems outlined above, this study introduces a novel reduction clutch specifically engineered for cable coiling apparatus. The clutch enables flexible start-stop, overload protection, and intelligent speed regulation, thereby enhancing the stability and control ability of the cable coiling process. Furthermore, the design ensures adaptability to large-scale open-pit mining machinery, meeting the demands of cable coiling and laying.

II. COMPOSITION OF THE REDUCTION CLUTCH SYSTEM

The reduction clutch, as a key piece of equipment in coal mine production, performs the task of dynamically adjusting cable coiling and laying speeds in real time within the cable coiling system. This ensures precise synchronization between the cable coiling speed and the electric shovels movement. Positioned alongside the cable tail line coiling system, its performance is critical for maintaining smooth and reliable coiling and laying operations. The equipment comprises a gear speed-torque control system and a flexible clutch adjustment system. The power transmitted from the motor is decelerated by the three-stage gear train of the gear speed-torque control system. This deceleration mechanism achieves the effect of speed reduction and noise reduction. The output power is regulated by the flexible clutch adjustment system. This regulation enables functions such as flexible start-stop, overload protection, and intelligent speed regulation, ensuring the safe and stable operation of the cable winding device. The overall structure is shown in Figure 1.

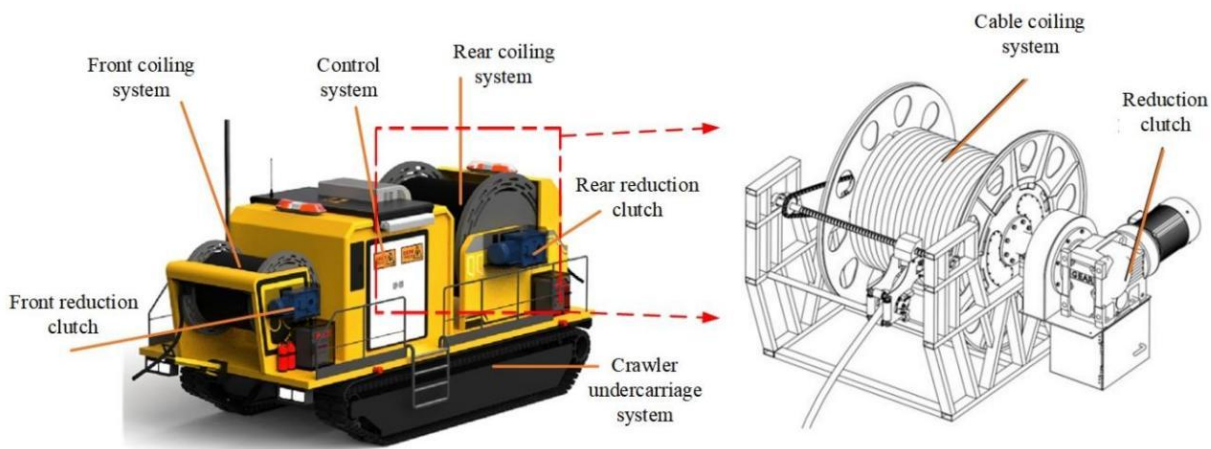


Fig. 1. Reduction clutch in the cable coiling device.

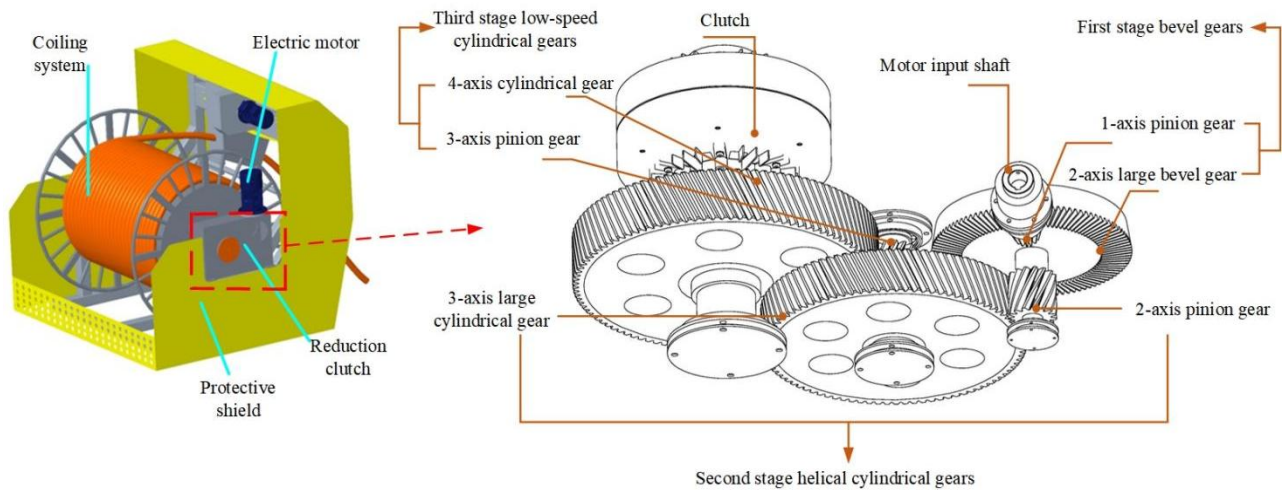


Fig. 2. Structure of geared variable speed torque regulation system.

A. Gear Speed and Torque Control System

The gear speed torque adjustment system consists of a pair of bevel gears, two pairs of helical gears, a magnetic particle clutch, and the gear shafts. The design of the gear reduction clutch requires the selection of an appropriate transmission ratio. It is necessary to consider a variety of factors to deeply analyze a balanced and optimized program. Improper distribution of transmission ratios will result in a bulky structure, high costs, and difficulty in installation, and other problems. The gear speed and torque control system is divided into three levels. The first stage is bevel gear transmission, involving the small bevel gear on 1-axis and the large bevel gear on 2-axis. The second level of helical cylindrical gear transmission, for the 2-axis small cylindrical gear and 3-axis large cylindrical gear. The third level of low-speed cylindrical gear transmission, for the 3-axis small cylindrical gear and 4-axis cylindrical gear, as shown in Figure 2.

The motor couples directly with the input shaft of the reduction clutch, and the output from this clutch is then transmitted to a bevel gear set. The motor of the cable coiling device provides the power to drive the first stage bevel gear, transmitting motion and power between the two parallel shafts. The bevel gear is connected through a helical cylindrical gear to drive the second stage of helical cylindrical gear, transmitting the motion and power between the two intersecting shafts. Through the low-speed cylindrical gear connected to the helical cylindrical gear, driving the third stage of low-speed cylindrical gear, which further reduces rotational speed while increasing torque. Finally, the decelerated power transmits to the flexible clutch system through the output shaft.

B. Flexible Clutch Adjustment System

The gear speed-torque adjustment system and flexible clutch adjustment system are integrated into a unified design. The flexible clutch system controls transmission engagement via magnetic field strength. This ensures smooth operation and precise control of the cable coiling device. During operation, continuous power supply is maintained, work efficiency and equipment safety are improved, harsh environments are withstood, and automation is supported—enhancing the stability and safety of mining operations. The

input side of the reduction clutch is driven by the motor. The gear speed torque regulating system is connected to the input side, rotating under the motor input torque. The system ultimately outputs force to the flexible clutch adjustment system.

The excitation coil is energized in the magnetic particle flexible coupler. Magnetic particles are magnetized within the magnetic circuit under the action of the yoke. This connects the driving and driven components to transmit torque. Power is ultimately output to the input shaft of the unwinding device's reel. The magnetic powder clutch structure is shown in Figure 3.

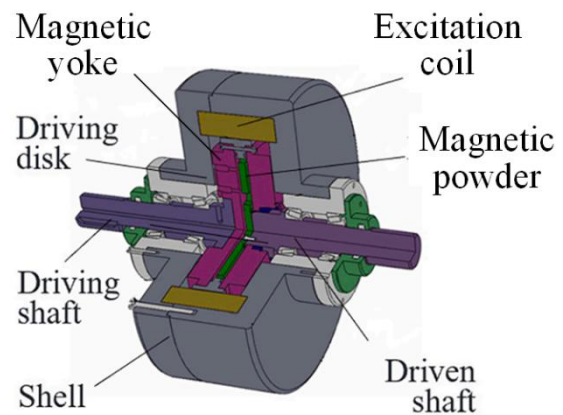


Fig. 3. Magnetic powder clutch composition.

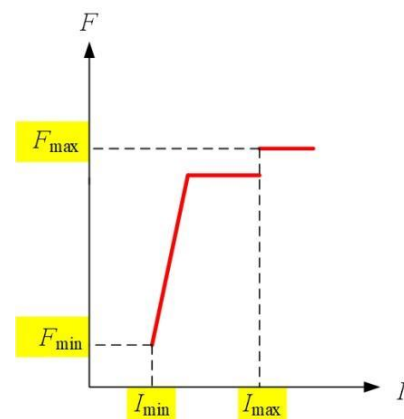


Fig. 4. Current vs. Torque of the reduction clutch.

The flexible clutch adjustment system controls the output torque of the reduction clutch by adjusting the current based on electromagnetic principles during operation. This achieves precise torque regulation for the cable coiling device's reel. When the output torque of the reduction clutch exceeds the maximum allowable value, the detection signal is fed back to the magnetic particle coupler. The magnetic particle coupler switches to the non-operational state. The magnetic powder interrupter automatically cuts power, and the driving and driven components are in a separated state, without transmitting working torque. The working principle is shown in Figure 4.

III. DECELERATION MECHANISM DESIGN AND CALCULATION

A. Three-stage Gear Train Design

The reduction clutch adopts a three-stage reduction mechanism to meet the operational demands of the cable reel, and the gears are used for commutation and torque increase between the input end and the output end. Additionally, the reel operates in a dual-mode configuration: active coiling for controlled cable winding and passive releasing to enable tension-responsive release during operation.

When designing the transmission device, it is necessary to make the distribution of transmission ratios at all levels as uniform as possible. Distribute the ratios according to the principle of equal strength, while keeping the volume and mass of the gearbox relatively small. The designed reduction mechanism is divided into three levels, according to several principles of allocation of transmission ratio. The preliminary design of the transmission ratio is as follows Table I.

TABLE I
DISTRIBUTION OF TRANSMISSION RATIOS

Parameter	Symbol	Value
Total Gear Ratio	i_{total}	247.5
First-Stage Gear Ratio	i_1	6
Second-Stage Gear Ratio	i_2	6
Third-Stage Gear Ratio	i_3	6.875

A small bevel gear with a tooth hardness of 280HB and a large bevel gear with a tooth hardness of 250HB are selected. Bevel gears facilitate the transmission of motion and power between intersecting shafts. Given their prevalent use in practical engineering applications, straight-toothed bevel gears were selected for this design. Table II below summarizes the key design parameters for the three-stage

gear train.

The transmission efficiency of the whole mechanism is:

$$\eta = \eta_1 \eta_2^2 \eta_3 \eta_4 \eta_5 \eta_6 \quad (1)$$

Where η_1 is the bevel gear transmission efficiency, take as 0.97; η_2 is the cylindrical gear transmission efficiency, take as 0.97; η_3 is the efficiency of the magnetic particle clutch, take as 0.98; η_4 is the efficiency of the bearing, take as 0.99; η_5 is the efficiency of the working device, take as 0.96; η_6 is the efficiency of the coupling, take as 0.96. Substituting these data into formula (1), the calculation of η is 0.817.

B. Design and Calculation of Gear Shafts

The first stage involves bevel gear transmission between the small bevel gear on 1-axis and the large bevel gear on 2-axis. The second stage involves helical cylindrical gear transmission between the small cylindrical gear on 2-axis and the large cylindrical gear on 3-axis. The third stage involves bevel gear transmission between the small bevel gear on 3-axis and the bevel gear on 4-axis, resulting in a total of four shafts. The material of the 1-axis and 2-axis is 40Cr steel with tempering treatment; the material of the 3-axis and 4-axis is 34CrNiMo6 with nitriding treatment.

During the operation of the cable coiling device, the reel coils the cable at a speed of 5 r/min. The speed of the motor can be calculated from the total transmission ratio of the working device:

$$n_m = i_{total} \cdot n_{reel} \quad (2)$$

Where n_m is the rotational speed of the motor in revolutions per minute, i_{total} is the total transmission ratio of the device, n_{reel} is the rotational speed per minute of the reel. Substituting the values, the motor speed is calculated as 1237.5 r/min. The shaft rotates at the same speed as the motor. This speed equivalence is expressed as:

$$n_1 = n_m \quad (3)$$

In the formula, it is known that the speed of 1-axis is also 1237.5 r/min, and the speed of 2-axis, 3-axis, and 4-axis can be calculated by the following formula:

$$n_b = \frac{n_a}{i_a} \quad (4)$$

Where $a=1, 2, 3$; and $b=a+1$. Based on the transmission ratios in Table 1, the speed of 2-axis (n_2) is 206.25 r/min. The same can be obtained from the 3-axis speed n_3 is 34.375 r/min, the 4-axis speed n_4 is 5 r/min.

The output power of each axis is calculated:

$$P_1 = P_d \eta_3 \quad (5)$$

$$P_2 = P_1 \eta_1 \eta_4 \quad (6)$$

$$P_3 = P_2 \eta_2 \eta_4 \quad (7)$$

$$P_4 = P_3 \eta_2 \eta_4 \quad (8)$$

TABLE II
THREE-STAGE GEAR DESIGN PARAMETERS

Parameter	Unit	First stage bevel gears	Second stage helical cylindrical gears	Third stage helical cylindrical gears
Number of teeth (Pinion)	-	17	15	15
Number of teeth (Gear)	-	102	90	104
Module	mm	3	4	4
Face width	mm	42	67	80

Where η_1 is the bevel gear transmission efficiency, take as 0.97; η_2 is the cylindrical gear transmission efficiency, take as 0.97; η_3 is the magnetic powder clutch efficiency, take as 0.98; η_4 is the efficiency of the bearing, take as 0.99. P_d for the power of the motor, $P_d = 3$ kW. Substituting the data, the calculated powers are: $P_1 = 2.94$ kW, $P_2 = 2.82$ kW, $P_3 = 2.74$ kW, $P_4 = 2.63$ kW.

Select components such as couplings and bearings according to the engineering requirements and the minimum diameter of the shaft. Then the preliminary estimate of the minimum diameter of the gear shaft is:

$$d_{\min} = C \cdot \sqrt[3]{\frac{P}{n}} \quad (9)$$

In the formula, C is the torsional strength empirical coefficient, 1-axis C_1 is 120, 2-axis C_2 is 99, 3-axis C_3 is 97, 4-axis C_4 is 90. The rotational speed of each axis n_1, n_2, n_3, n_4 and the output power of each axis P_1, P_2, P_3, P_4 into the formula, and bring the data to calculate that the $d_{1\min}$ is 16.01 mm; $d_{2\min}$ is 23.67 mm; $d_{3\min}$ is 41.7 mm; $d_{4\min}$ is 72 mm.

IV. SIMULATION AND ANALYSIS OF GEAR SHAFTS

The gear shaft of the reduction clutch transfers power from the motor's output shaft to the gearbox, thus driving the operation of the entire cable coiling device. Through the reasonable design of the gear shaft, energy transfer efficiency can be effectively improved and energy loss reduced. The gear shaft is a key part of the reduction clutch. Its strength and stiffness must meet the actual requirements. To this end, stress distribution and deformation analyses of the gear shaft were conducted utilizing SolidWorks for 3D modeling and ANSYS for finite element analysis (FEA).

A. Gear Shaft Mesh Models and Delineation

The grid size of 2 mm is selected for meshing of the 1-axis and 2-axis, and the grid size of 5 mm is selected for meshing of the 3-axis and 4-axis. The mesh model of each axis is obtained, as shown in Figure 5 below:

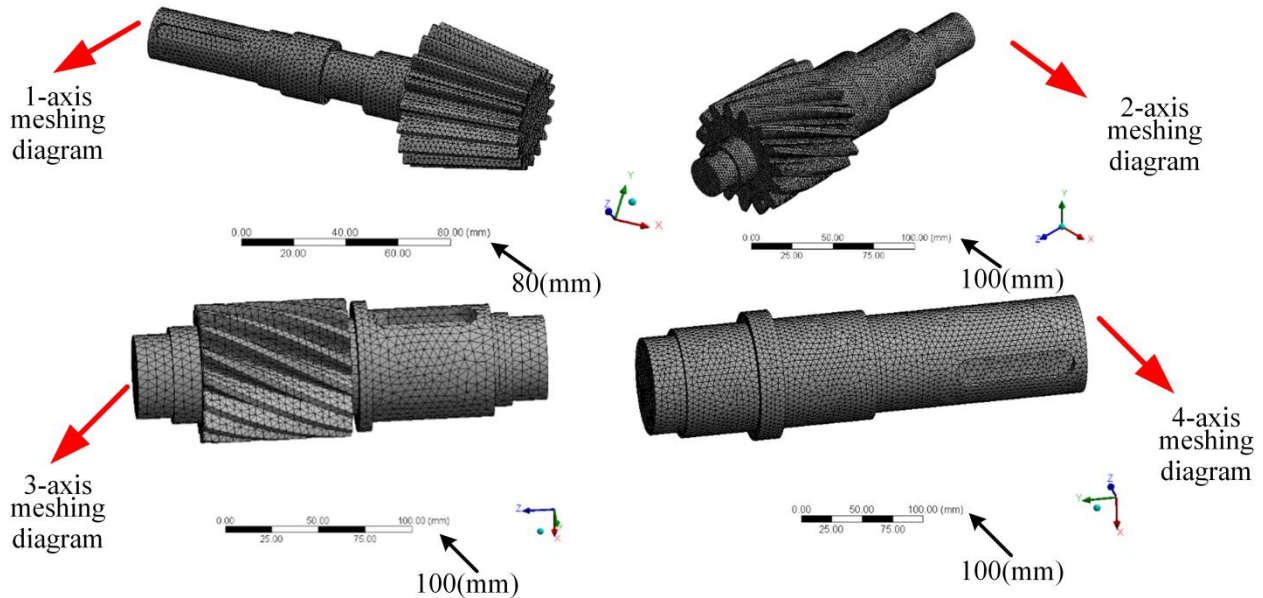


Fig. 5. Mesh models of each axis.

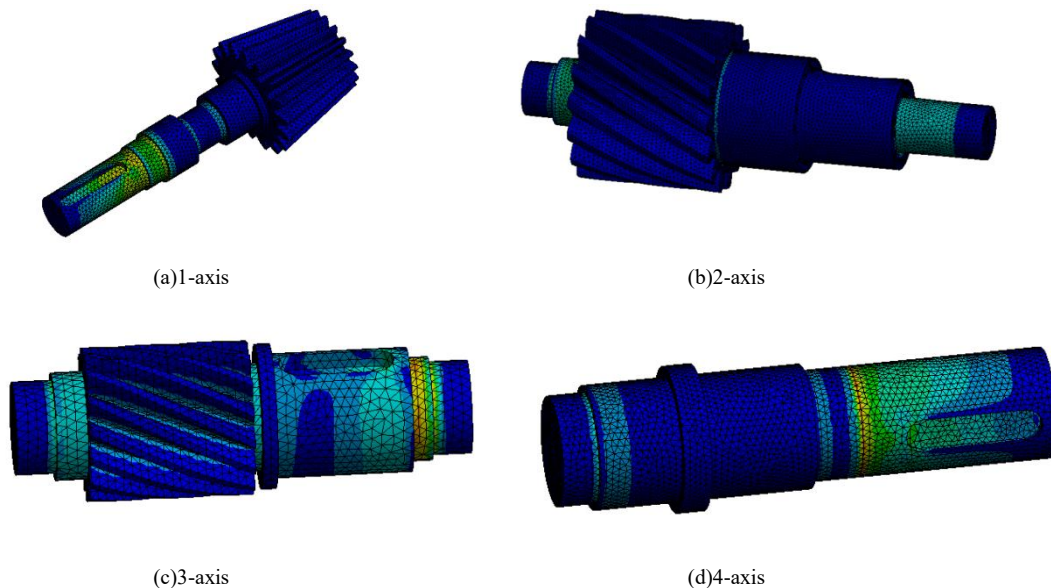


Fig. 6. Stress distribution of each axis.

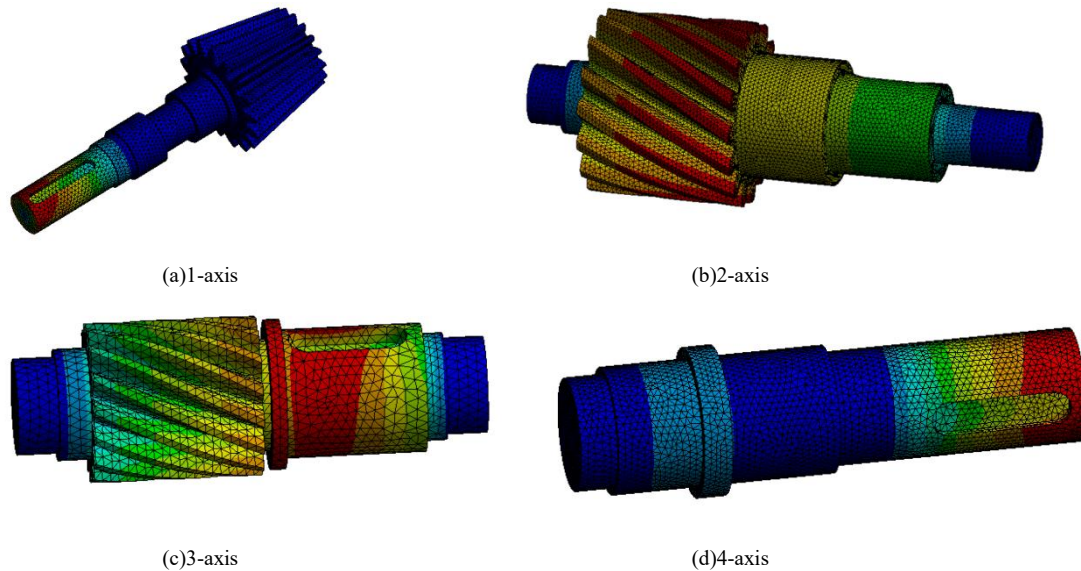


Fig. 7. Deformation diagram of each axis.

B. Gear Shaft ANSYS Analysis Results

Boundary conditions were set based on prior mesh convergence results. Fixed constraints were applied at bearing mounting locations. The simulation was executed, and the obtained stress distribution results in the shaft body are shown in Figure 6.

The material of the 1-axis and 2-axis is 40 Cr steel; the material of the 3-axis and 4-axis is 34CrNiMo6, of which the yield strength of 40 Cr steel is not less than 785 MPa, and the yield strength of 34 CrNiMo6 is not less than 900 MPa. From the simulation results, the maximum stress on 1-axis is 49.621 MPa, the maximum stress on 2-axis is 70.14 MPa, the maximum stress on 3-axis is 100.12 MPa, and the maximum stress on 4-axis is 321.43 MPa. With a safety factor of n is 1.2, the calculated stress is significantly lower than the material's allowable stress. Therefore, the shaft strength can be confirmed to meet the design requirements. Figure 7 illustrates the location and magnitude of the maximum shaft deformation. The simulation outcomes indicate that:

- 1-axis: maximum deformation about 0.010 mm.
- 2-axis: maximum deformation about 0.013 mm.
- 3-axis: maximum deformation about 0.018 mm.
- 4-axis: maximum deformation about 0.065 mm.

These deformations are negligible. Therefore, the design is rational and meets all requirements.

V. CONCLUSION AND ENGINEERING APPLICATIONS

This study designed a new reduction clutch device. Compared with traditional reduction clutches, this design is better suited to cable coiling coordination systems. The simulation analysis results indicate that the maximum stress value is significantly below the material's allowable stress. It can be concluded that the structure and strength of the four gear shafts meet the design requirements. This reduction clutch is operational in large-scale open-pit mining applications. In the research process, we derived the following conclusions:

(1) The device adopts a magnetic particle clutch capable of flexible start-stop, overload protection, and intelligent speed regulation. By modulating the magnetic field strength to enable transmission separation and connection, the

system ensures smooth operation and precise control of the cable coiling device.

(2) The design and calculation of the reduction clutch transmission device were theoretically conducted. By adopting a three-stage transmission with rational power distribution, it meets the requirements for structural bearing capacity and dynamic response performance of the cable reeling cooperative linkage system. This effectively improves the stability and control capability of the cable reeling device, ensuring the production efficiency and safety of mining operations.

(3) This device can be applied not only in the mining field but also to the start-up, stop, and speed adjustment of various mechanical equipment, possessing broad application prospects. We conducted trial production of a prototype and carried out field testing. Feedback confirms that the reduction clutch has a reasonable structural design. Cable-winding torque adjustment demonstrates exceptional convenience. Operational performance remains stable and reliable. Engineering applications show significant effectiveness, as shown in Figure 8.



(a) Cable tail coiling device.



(b) Reduction clutch.

Fig. 8. Diagram of engineering application.

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