

Disk cutter wear prediction of TBM considering sliding and rolling friction

Yuanjun Huang¹, Rujiang Hao^{1,*}, Jie Li¹, Jingbo Guo¹, Yankun Sun¹, Jiangran Liu¹

¹School of Mechanical Engineering, Shijiazhuang Tiedao University, Shijiazhuang City, Hebei Province 050043, China

Considering the serious wear of disk cutters in tunnel project and the low prediction accuracy of existing methods, a new method for wear prediction of disk cutters from an energy perspective was proposed. Based on contact mechanics, the rock breaking process of cutters was analyzed, and the combined action of sliding and rolling friction was considered. Furthermore, the wear prediction model of disk cutters was established, which realized the predicted wear of disk cutters under different geological conditions throughout the construction line. In addition, considering the influence of penetration on the wear prediction model, the predicted wear values under different penetrations were obtained, and their average values were taken as the predicted wear values of disk cutters considering penetration. Finally, the predicted wear values were compared with the actual wear value of disk cutters. The results showed that the average relative error between the predicted wear value of disk cutters considering sliding and rolling friction and the actual wear data was 12.8%. The average relative error between the predicted value of wear considering only sliding friction and the actual value of disk cutters is 18.3%. The average relative error between the predicted value of disk cutter wear considering penetration and the actual wear data was 12.2%, which proved the feasibility and accuracy of the prediction model. Meanwhile, it is more accurate than the model only considering sliding friction. The research results provided a scientific theoretical basis for the design of a tool change scheme in tunnel construction.

Keywords: *tunnel boring machine (TBM), disk cutter, sliding friction and rolling friction, wear prediction*

1. Introduction

With the continuous development of underground spaces, the tunnel boring machine (TBM) has become the leading tunneling equipment [1]. The disk cutter is the primary rock breaking tool that has directly contact with rock during tunnel construction. The structure of the TBM and disk cutter is shown in Figure 1. When the cutter head is pushed forward, it also rotates with its central fixed axis, and the cutter installed on the cutter head also moves with it. Therefore, a series of concentric circular grooves are formed on the rock face, as shown in Figure 2 [2]. During the working process of the TBM, the disk cutter shears, compresses, and cracks the rock. The rock is broken into fine particles, which are then rolled into powder by the continuous disk cutter to form a dense core. The internal energy of the rock is transferred to the surrounding area through the dense core, creating new cracks in the rock. Figure 3 shows the failure dia-

gram of the rock under the action of the disk cutter. The cracks are divided into lateral cracks and radial cracks due to their different propagation paths in the rock. The lateral cracks extend to the free surface of the rock, causing rock fragmentation, and the radial cracks cause the failure and fracture of the deeper part of the rock, completing the one-time rock breaking process of the disk cutter [3]. In this process, the force on the cutter can be generally divided into mutually orthogonal three-way forces, as shown in Figure 4 [4]. As a result of this construction method, the disk cutter wears under the friction of rocks, and the wear of the disk cutter leads to inefficient tunneling or even stops the machine to replace the cutter, which directly affects the tunneling efficiency, especially in tunnel construction with a large span and complicated geological conditions. The frequency of the disk cutter change chiefly relies on the judgment of human experience. The failure form of the disk cutter includes normal wear and non-uniform wear [5]. Normal wear refers to the uniform wear of the disk cutter along its axis,

* E-mail: 13931131098@139.com

as shown in Figure 5. According to the statistics in an undersea tunnel of the Qingdao subway, the construction section is mainly composed of moderately and highly weathered granite, and the maximum uniaxial compressive strength can reach 140 MPa. In addition, diabase is interspersed in the middle. The TBM with a diameter of 6,300 mm and 41 disk cutters were used. During the construction, the cutters were frequently changed due to severe wear. The use of the cutters was statistically analyzed. The normal wear of disk cutters accounted for 87.93% of the total failure, which is the main failure. The prediction of disk cutter wear is particularly important for well adjusting and controlling the maintenance cycle and for reducing the risk of cutter change in subsea tunnels, as well as for controlling the whole project period and cost.

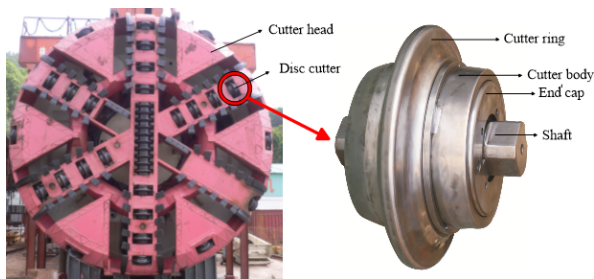


Fig. 1. TBM and disk cutter structure. TBM, tunnel boring machine

Many researchers have conducted extensive research on disk cutter wear. Most scholars used a large amount of actual construction data and cutter wear data to fit data from the perspective of force. Yang et al. [6] and She et al. [7] believed that abrasive wear is the primary form of disk cutter wear. When acquiring the load of the cutter, the former used the Colorado School of Mines (CSM) model [8], while the latter considered the dense core theory [9], and established the model for predicting disk cutter wear, which had passed the engineering verification. Liu et al. [10]. established an empirical model using a 20-inch cutter made of granite based on the actual data of a tunnel. They formed a database for statistically analyzing disk cutter wear data and rock properties of the tunnel. Rong et al. [11] established a prediction model of disk cutter wear based on tunneling parameters. The relation-

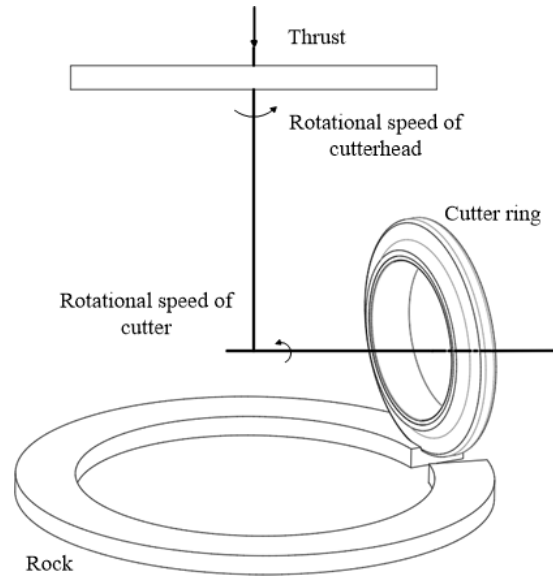


Fig. 2. Motion decomposition of disk cutter

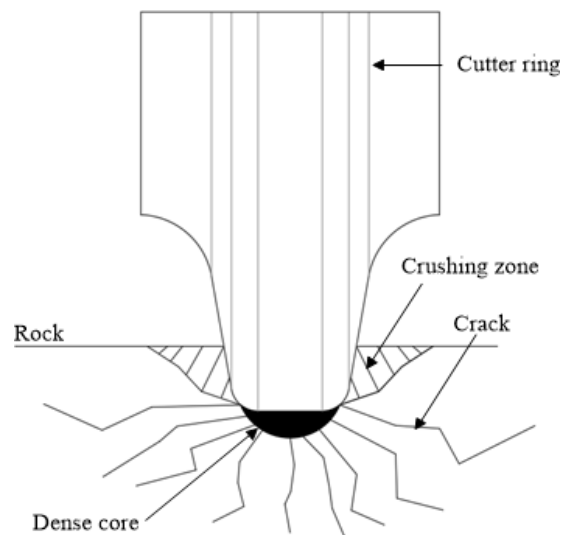


Fig. 3. Rock breaking mechanism of disk cutter

ship between foam volume, tunneling parameters, and cutter wear data was analyzed. Some scholars used artificial intelligence (AI) to predict the wear of cutters. Li and Su [12] established the Elman neural network prediction model by using the tunneling parameters of disk cutters in the normal wear stage after tool change and realized the prediction of wear according to the tunneling speed of the prediction model and the actual comparison error, which was verified by the project. Elbaz et

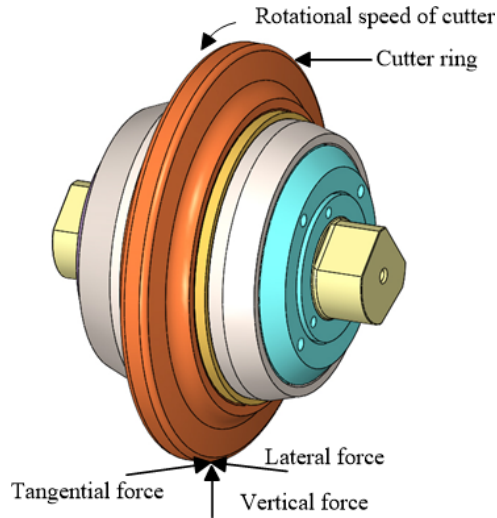


Fig. 4. Force diagram of disk cutter



Fig. 5. Disk cutter with normal wear dismantled on site

al. [13] studied the correlation between the construction data and disk cutter wear, optimized the group method of data handling (GMDH) network structure through the genetic algorithm (GA), and established a prediction model of disk cutter wear, which was verified by the project.

Only a few scholars considered disk cutter wear from the perspective of energy during TBM construction. They analyzed the wear mechanism of cutters according to the law of energy conservation: Shen et al. [14] established a prediction model for disk cutter wear considering energy conversion and uneven thrust distribution and proposed a method to determine the energy conversion rate and thrust distribution coefficient, which was verified by the

project. Song [15] suggested the superiority of the energy principle in the study of TBMs and the layout design of disk cutters. He also pointed out that the work done by the kinetic energy and force of the disk cutter is theoretically equivalent to the breaking energy of rock mass and the damage energy during rock breaking. Geng [16] put forward the concepts of unit wear work and equivalent wear function of the disk cutter based on actual data. The regression analysis between wear data and friction work was carried out. However, when the relative wear data of each cutter position is predicted by using the unit wear work of regularized cutter edge, its reliability largely depends on the length of the tunnel section.

To sum up, the current research mainly focuses on regression analysis and in-depth learning methods to achieve wear prediction by the construction data and disk cutter wear data from the perspective of force, and there are few studies that used energy methods to predict cutter wear. Most studies from the perspective of energy only considered cutter wear caused by sliding friction, resulting in low prediction accuracy and inconsistent with actual cutter wear. Therefore, in view of the low prediction accuracy of the existing prediction model, which is difficult to guide the scientific tool change, combined with a subway tunnel project in Qingdao, based on contact mechanics, it comprehensively analyzed that the reason for the cutter wear in the rock breaking process is the result of sliding and rolling friction, established a new model for predicting disk cutter wear based on the energy method, and realized the wear prediction of the cutter under different geological conditions in the entire construction. The feasibility and accuracy of the model were verified by actual project data.

2. Project overview

Based on the background of a cross-sea tunnel project in the East China area, the total length of the line was about 8.2 km. The TBM construction method and drilling and blasting method were adopted, and the TBM construction length was about 1.2 km. The tunnel geological profile of this bid section is shown in Figure 6.

Table 1. A 19-inch disk cutter with basic parameters

Material name of cutter ring	Outer diameter of cutter ring (mm)	HRC	Width of the cutter edge (mm)	Cutter spacing (mm)
4Cr5MoSiV1	483	50–54	19	80
HRC, hardness of cutter ring				

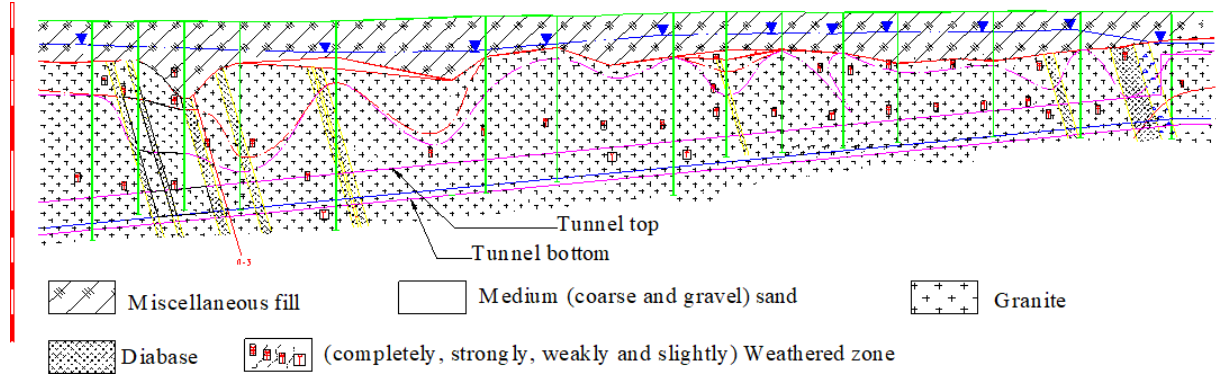


Fig. 6. Geological profile of the tunnel

As can be seen from Figure 6, granite is the main stratum along the line, interspersed with diabase, which accounts for more than 90% of the range. As the construction line passes through the depth of rock weathering, the rock condition is relatively intricate.

This construction section uses a 6,300-mm-diameter TBM, as shown in Figure 7. A total of 41 disk cutters were installed on the cutter head, and the installation radius of 0.8–2.4 m comprised 19" disk cutters. The basic parameters and performance information of disk cutters are shown in Table 1.

The wear diameter of the cutter affects the construction efficiency and cost. According to the tool damages report on the construction site, recorded manually with the measuring caliper when the TBM was stopped, and the wear value of the cutter was measured as shown in Figure 8. When the wear radius of the cutter exceeds the specified value, it is considered a failure and the machine needs to stop to replace the cutter. The narrow and harsh construction environment leads to great safety risks during measurement [17]. Through sorting out and from statistics of wear data, the wear data and installation radius of disk cutters in the whole construction were recorded, as shown in Figure 9.

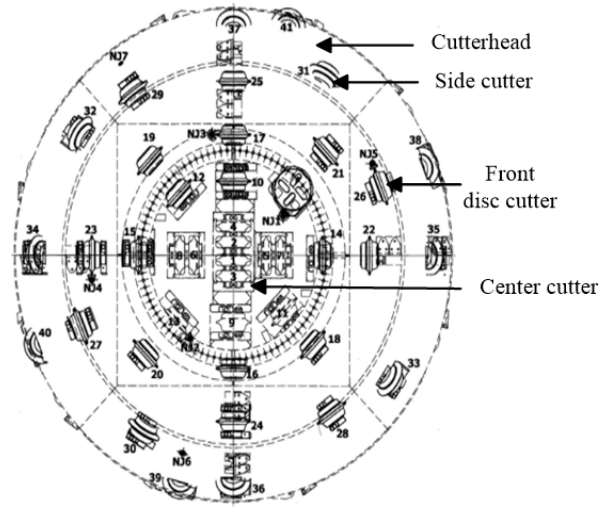


Fig. 7. Introduction of cutter head and cutter

3. Disk cutter wear prediction model considering sliding friction and rolling friction

According to the energy wear theory put forward by Fleisher [18], it was analyzed that the energy between the material molecules of the cutter ring counteracts the work done by the friction between the cutter and the rock during the rock break-

ing process of the disk cutter, resulting in the wear of the cutter ring material. To achieve accurate prediction of disk cutter wear, it should be considered that cutter wear is the result of the joint action of



Fig. 8. Disk cutter wear values were measured on site

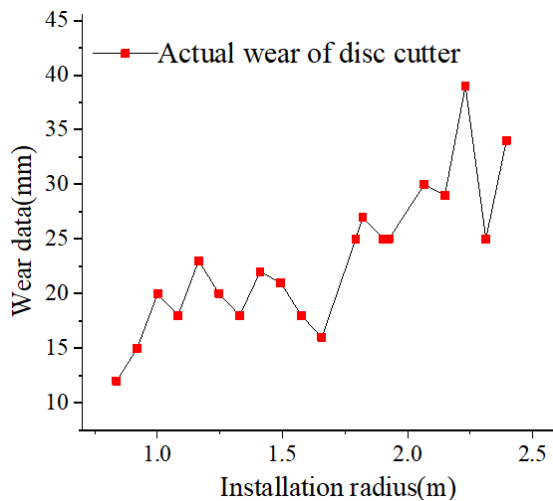


Fig. 9. Actual wear data and installation radius of disk cutter



Fig. 10. Normally worn disk cutter ring and test piece

sliding friction and rolling friction. The cutter ring brought back from the construction site was used to conduct material performance tests. Based on the actual engineering data, the energy conversion of cutter wear was analyzed according to the rock breaking movement process of the disk cutter, and a model was established for predicting disk cutter wear and to achieve accurate prediction wear.

3.1. Material test of disk cutter ring

The cutter ring interacts directly with rock and completes the rock breaking process. The material properties of the cutter ring directly affect its wear. How to improve the service life of the disk cutter and the efficiency of tunnel construction remains to be determined. There are different requirements for the cutter ring under various geological conditions. Generally, the cutter ring material should have high hardness, high strength, and good toughness. The normally worn disk cutter ring brought back from the site was cut linearly, as shown in Figure 10. A material performance test was performed on the disk cutter with the test piece.

3.1.1. Hardness test

According to GB/T230.1-2004, a hardness test was conducted on the test piece with an HR-150A Rockwell hardness tester. As shown in Figure 11, five groups of data was measured on the material, and the average values were taken as the hardness values of the test piece material. The hardness value was 51HRC.

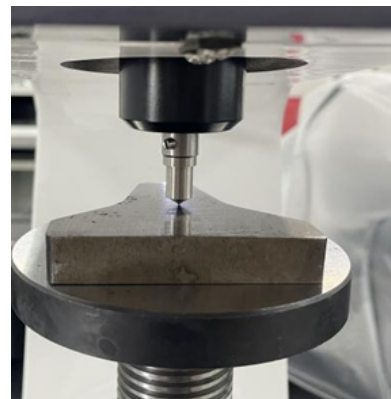


Fig. 11. Hardness test of disk cutter ring

Table 2. Chemical composition of disk cutter ring material

Chemical element	C	Cr	Mn	Si	Mo	V	S	P
Chemical composition of cutter ring (%)	0.49	5.15	0.47	1.07	1.46	0.98	0.009	0.012
Chemical composition of 4Cr5MoSiV1 (%)	0.32–0.45	4.75–5.50	0.20–0.50	0.80–1.20	1.10–1.75	0.80–1.20	≤ 0.03	≤ 0.03

3.1.2. Impact test

According to GB/T229-2020, a cut test piece was cut to a size of 10 mm × 7.5 mm × 55mm notchless impact test piece and was subjected to an impact test using a JB-300 pendulum impact testing machine. As shown in Figure 12, three groups of tests were measured, and the average values were the impact toughness values of the test piece material. The impact energy was 32.43 J/cm².

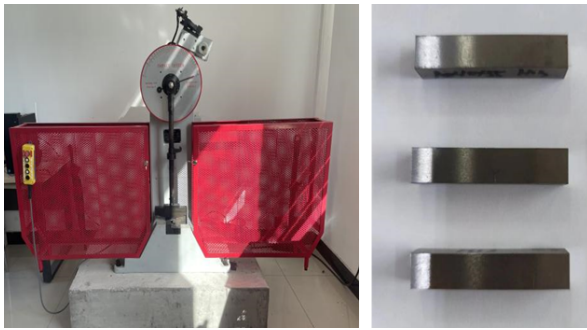


Fig. 12. Impact test of disk cutter ring

3.1.3. Metallographic analysis and chemical composition test

To facilitate the observation of the metallographic structure of the disk cutter ring material, the cut test pieces were processed into scanning electron microscope (SEM) test pieces. When using SEM instruments, an energy-dispersive spectrometer (EDS) is an important accessory. However, considering the inaccuracy of the EDS in the determination of certain chemical elements, optical emission spectroscopy (OES) was used in combination to determine the chemical composition of the material. As shown in Figure 13, SEM observation and OES testing were performed on the disk cutter ring material samples.

The metallographic structure and chemical composition of the disk cutter ring material were

measured using SEM and OES [19]. The chemical elements of the ring are shown in Table 2, and the metallographic structure of the cutter ring material is shown in Figure 14.

It can be seen from the aforementioned that the carbon content of the cutter ring materials is high, which will make the cutter ring have better toughness, but lower strength. By analyzing the metallographic structure, it can be seen that the matrix is mainly martensite and a small amount of austenite, and the white precipitates at the grain boundary are carbides of other elements. The physical properties of austenite are higher in strength and hardness than those of ferrite, but also have good toughness. The physical properties of martensite are high in strength and hardness. The lath martensite not only has high hardness but also has good plasticity and toughness. It is not easy to appear notch and overload.

3.2. Geological distribution along the line

Geological conditions are one of the decisive factors in determining the disk cutter wear. Rock samples were taken by drilling the geology along the line, as shown in Figure 15. Tests (uniaxial compression and tensile test) [20, 21] were carried out on the rock samples. According to the national standard engineering rock mass classification standard GB/T50218-2014, the stratum classification and strength distribution along the line were obtained, as shown in Figure 16.

It can be seen from Figure 16 that the length of class II surrounding rock accounts for the most significant proportion of the total length, followed by class III and then classes IV–V. The uniaxial compressive strength of the rock was primarily concentrated in the range of 80–140 MPa, mainly medium to slightly weathered granite hard rock.

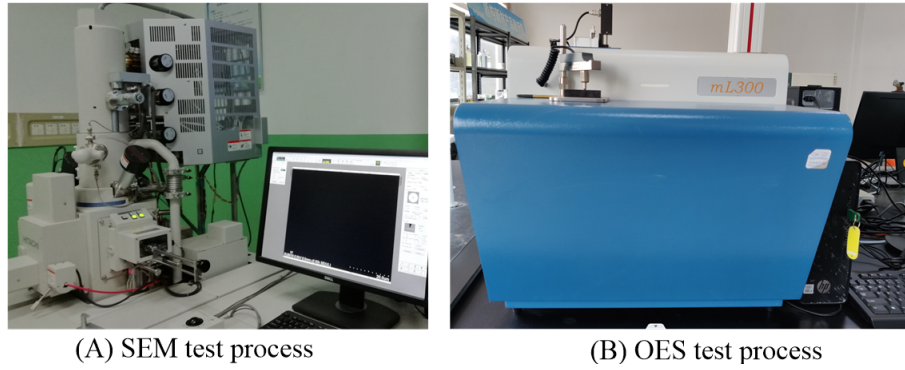


Fig. 13. SEM and OES test of disk cutter ring material. (A) SEM test process. (B) OES test process. OES, optical emission spectroscopy; SEM, scanning electron microscope

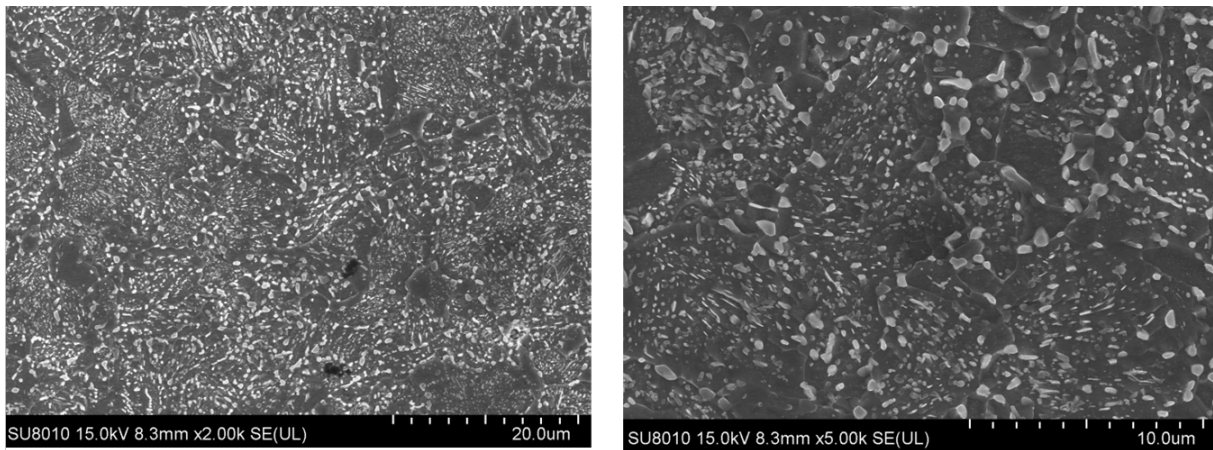


Fig. 14. Metallurgical structure of disk cutter ring material



Fig. 15. Rock samples

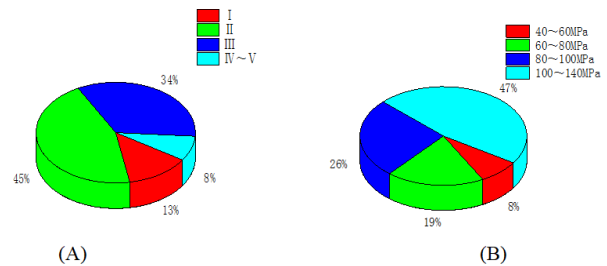


Fig. 16. Geological conditions along the line. (A) Stratum classification. (B) Rock mass strength distribution

3.3. Establishment of the model for predicting disk cutter wear considering sliding friction and rolling friction

3.3.1. Methodology

According to the theory of contact mechanics, rolling is defined as the relative angular motion of two objects in contact with each other around the axis parallel to the common tangent plane. Sliding is defined as the relative circumferential motion of two surfaces at the contact point [22]. The disk cutter realizes the rock breaking movement, which is realized by the combined action of the disk cutter under the thrust and torque of the cutter head and the friction generated by embedding the rock. According to the conditions of friction generation, there are sliding friction and rolling friction when the disk cutter breaks the rock. The contact between disk cutter and rock produces elastic-plastic deformation. Under the action of tangential force, the different tangential strain at the contact point between the cutter ring and rock leads to the relative displacement of the particle at the contact point, which is sliding on the macro level. Most studies [23] believe that the wear of the disk cutter is caused by the relative sliding of the objects in contact with each other. However, only considering the sliding friction will reduce the accuracy of the wear prediction value. Therefore, this study considers the combined effect of sliding friction and rolling friction to cause the wear of disk cutters. By analyzing the relationship between friction energy and material wear, a wear prediction model of the disk cutter based on the energy method was established, and the prediction of the wear data of disk cutters was realized.

When the tangential force increases to the limit friction force, the object will be at the moment of sliding, and there will be a trend of relative displacement between the contact points. The interaction of the material surface roughness peaks, especially the harder roughness peaks penetrate and cut the softer material to form a groove effect, resulting in the loss of sliding friction energy [24, 25]. The function of sliding friction can be expressed as follows:

$$Q_s = F_f S_0 \quad (1)$$

where $F_f = \mu F_v$, F_f is the sliding friction force, μ is the coefficient of sliding friction, F_v is the vertical force on the disk cutter, and S_0 is the slip distance.

According to the working principle of the disk cutter, the length of the slip arc at the breaking point of the disk cutter is a three-dimensional curve in the process of rock breaking. The analytical solution of the sliding distance S_0 of any rock breaking point on the disk cutter is as follows [26]:

$$S_0 = \frac{2}{R_0} \left[\sqrt{\frac{R_r}{2}} \sqrt{2R_r R_0^2 + 2R_r^3} + R_0^2 \ln \left(R_r \sqrt{2R_r} + \sqrt{2R_r R_0^2 + 2R_r^3} \right) - \frac{\sqrt{2R_r - h}}{2} \sqrt{2R_r R_0^2 + R_r^2 (2R_r - h)} - R_r^2 \ln \left(R_r \sqrt{2R_r - h} + \sqrt{2R_r R_0^2 + R_r^2 (2R_r - h)} \right) \right] \quad (2)$$

where R_r is the installation radius of the disk cutter, R_0 is the radius of the disk cutter, and h is the penetration value.

The rolling friction mainly comes from the internal friction of the material and the rolling resistance produced by the adhesion point. Internal friction is mainly due to the elastic hysteresis effect caused by the viscoelastic properties of materials [27, 28]. The hysteresis effect shows that the strain curve and stress curve of the material do not coincide after the load is applied and unloaded [29, 30]. Simplify the contact between the disk cutter and the rock, using cylindrical and planar contact instead. Since it can be assumed that the contact is plane contact; the contact area is shown in Figure 17 [31].

By analyzing the contact stress distribution, the vertical pressure distribution can be calculated using Hertz's formula:

$$p_0 = \frac{2F_v}{\pi c l_0} \left(\sqrt{1 - \frac{x^2}{c^2}} \right) \quad (3)$$

where l_0 is the contact length, $l_0 = T + 2h \tan(\theta/2)$, T is the width of the disk cutter, θ is the blade angle, x is the arbitrary distance from the normal of the contact zone, c is the half

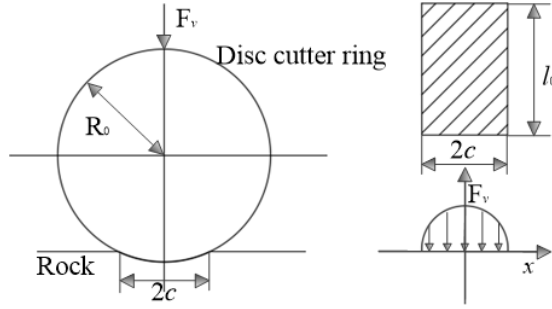


Fig. 17. Contact force diagram

of contact width, $c = \sqrt{(4F_v R)/(\pi l_0 E_\alpha)}$, $E_\alpha = [E_2(1 - \nu_1^2) + E_1(1 - \nu_2^2)] / E_1 E_2$, E_α is the comprehensive elastic modulus of contact between two elastic objects, ν_1 is the Poisson ratio of the disk cutter, ν_2 is the Poisson ratio of the rock, E_1 is the elastic modulus of the disk cutter, and E_2 is the elastic modulus of the rock.

Resistance moment of elastic force of half part before contact to the rolling center:

$$T_0 = \int_0^c p_0 l_0 x dx = \int_0^c \frac{2F_v}{\pi a l_0} \left(\sqrt{1 - \frac{x^2}{c^2}} \right) l_0 x dx \quad (4)$$

$$= \frac{2F_v c}{3\pi}$$

When rolling x distance, the work of resistance torque is as follows:

$$Q_0 = T_0 \frac{x}{R} = \frac{2F_v c x}{3\pi R} \quad (5)$$

Because of the elastic work loss caused by the hysteresis effect, the elastic hysteresis loss coefficient is introduced β , which can be obtained using rolling friction tests [32]. At this time, the work done by the second half of the resistance torque in the contact area is as follows:

$$Q_1 = \beta Q_0 = \frac{2F_v c x \beta}{3\pi R} \quad (6)$$

The adhesion points at the back half of the contact area are subject to tensile action. When the outermost adhesion point is pulled off from the material, the material wear will occur. The distribution of adhesion stress can be expressed as follows [31]:

$$\sigma(x) = \sigma_s + \frac{\sigma_b - \sigma_s}{c} x \quad (7)$$

where σ_s is the yield strength of the material and σ_b is the ultimate strength of the material.

According to Archard's wear law [33], the resistance moment of adhesion to the rolling center can be expressed as follows:

$$T_1 = \int_0^c \sigma(x) x l_0 \xi dx = \frac{F_v c (2\sigma_b + \sigma_s)}{12H_r} \quad (8)$$

where $l_0 \xi dx$ is the actual contact area at position x , is ξ the proportion of the actual area in the total area, and H_r is the surface hardness of the disk cutter.

When rolling x distance, the work of adhesion torque is as follows:

$$Q_2 = T_1 \frac{x}{R} = \frac{F_v c (2\sigma_b + \sigma_s) x}{12H_r R} \quad (9)$$

The energy loss of rolling friction can be expressed as the sum of elastic hysteresis and work done to overcome adhesion points:

$$Q_r = Q_1 + Q_2 \quad (10)$$

The total work done by sliding friction and rolling friction in the process of disk cutter breaking rock can be expressed as follows:

$$Q_f = Q_s + Q_r \quad (11)$$

Assuming that the volume wear of the disk cutting machine is proportional to the friction loss energy, the energy wear rate k is taken as the proportional coefficient of the volume wear and the friction loss energy, which is obtained using the abrasion test [34]. The relationship between volume wear and friction loss energy of the disk cutter can be expressed as follows:

$$V_i = k Q_i \quad (12)$$

where $i = r, f$; V_r represents the wear volume caused by sliding friction only; and V_f represents the wear volume caused by sliding and rolling friction.

Assuming that the wear state does not change, considering the measurement method of the disk cutter, the wear of the cutter is generally reflected in

Table 3. Structure parameters of disk cutter ring

Outer diameter of cutter ring (mm)	Width of cutter ring (mm)	Blade width (mm)	Cutting edge angle	Fillet radius (mm)
483	89	19	24°	32

Table 4. Rock attributes of each working condition

Condition	Compressive strength (MPa)	Tensile strength (MPa)	Density (g/mm ³)
Condition 1	120	11.2	2.9×10^{-3}
Condition 2	90	8.7	2.7×10^{-3}
Condition 3	70	6.9	2.6×10^{-3}
Condition 4	50	4.4	2.5×10^{-3}

the change of the diameter. According to the TBM motion law, when the tunnel length is D , the wear data of the disk cutter can be calculated as follows:

$$w_i = \frac{ViDR_r}{2\pi R_0^2 Th} \quad (13)$$

where $i = r, f$; w_r is the wear data of the disk cutter considering only sliding friction; and w_f is the wear data of the disk cutter considering sliding friction and rolling friction. According to Eq. (13), the wear data of the disk cutter can be calculated, but the force and friction work of disk cutter under the condition of considering sliding friction and rolling friction during rock breaking need to be further calculated by other methods.

3.3.2. Parameter determined

Considering that the aforementioned formula, parameters were obtained through experiments, and the cost and time consumption were large. ABAQUS finite element software can simulate the rock breaking process. Therefore, the model for rock breaking with the disk cutter based on ABAQUS was established by analyzing the material performance parameters of the cutter ring combined with the actual rock properties and tunneling parameters, as shown in Figure 18. Considering that the disk cutter only contacts with the rock during rock breaking, the disk cutter only establishes the cutter ring. The size of cutter ring was 19 inch. The material was 4Cr5MoSiV1, and the structural parameters are given in Table 3. The dimensions of rock models are 200 mm × 120 mm × 1000 mm,

and the Drucker–Prager criterion is set to achieve its failure [35].

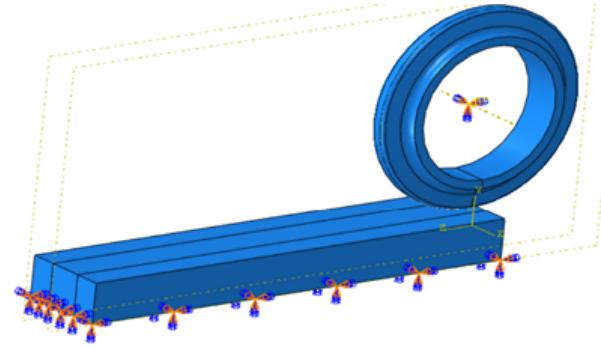


Fig. 18. Model for rock breaking with disk cutter

According to the stratum classification and rock mass strength distribution along the tunnel, it can be divided into the following four working conditions. The rock mechanical parameters of each working condition take the mean value of the range. The properties of the rock are shown in Table 4.

According to the actual tunneling data, when TBM start–stop phase was eliminated, the rotation speed of the cutter head was always between 0.133 and 0.167 r/s, and the penetration was always between 6 and 8 mm. The installation radius of the brought back disk cutter was 1.001 m. Therefore, the load of the disk cutter was set as follows: (1) penetration 7 mm and (2) cutting translation speed 838.6 mm/s, and rotation speed 3.47 rad/s. Finally, the operation was completed. According to the simulation results, the force and friction energy in the

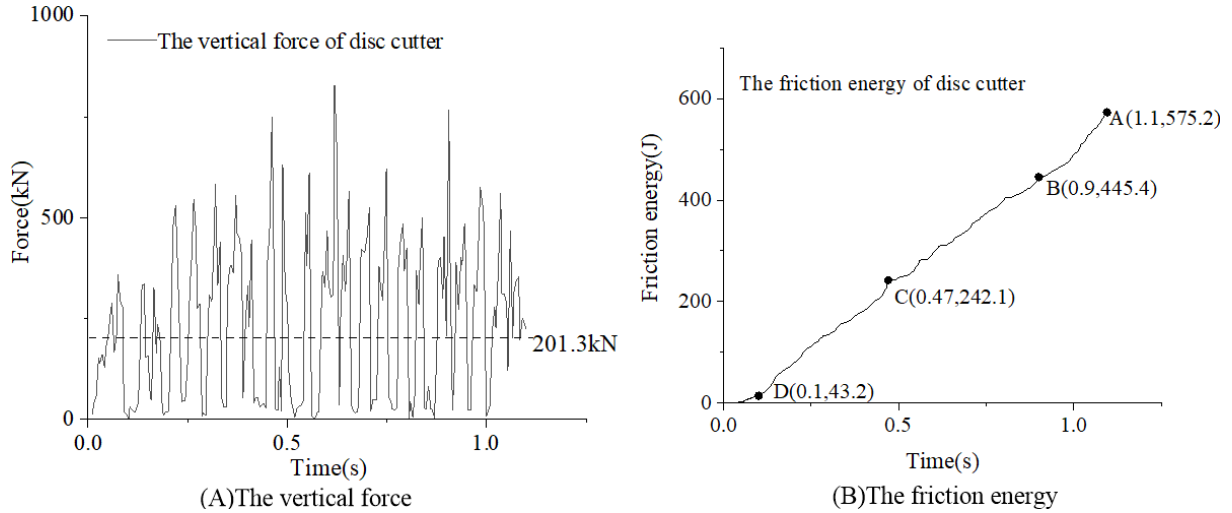


Fig. 19. Simulation results derived post-processing

Table 5. Comparison of vertical forces from simulation and theoretical models

Condition	Average vertical force of simulation model (kN)	Vertical forces calculated by CSM model (kN)	Absolute value relative error
Condition 1	201.3	205.9	2.2%
Condition 2	149.4	156.3	4.3%
Condition 3	116.2	122.3	4.9%
Condition 4	77.8	84.1	7.5%

CSM, Colorado School of Mines

simulation process can be obtained in the post-processing module. As Figure 19 shows the vertical force and friction energy of the disk cutter under working condition 1.

It can be seen from Figure 19, due to the step nature of the rock, the disk cutter bears an alternating load in the process of rock breaking, but it fluctuates up and down around the value [36]. The average value of the vertical force was 201.3 kN. During the simulation period, the friction energy of the disk cutter for rock breaking was 575.2 J in total.

For the force analysis of the disk cutter, scholars have done a lot of work. At present, the stress prediction model proposed by CSM is widely used [37]. It is based on the summary of a large number of engineering data. The vertical force on the disk cutter can be expressed as follows:

$$F_v = \frac{C\phi R_0 T}{1 + \psi} \left(\frac{S\sigma_c^2 \sigma_t}{\phi \sqrt{R_0 T}} \right)^{\frac{1}{3}} \cos\left(\frac{\phi}{2}\right) \quad (14)$$

The average force of the disk cutter was compared with the CSM force model, and the comparison results are shown in Table 5 to verify the correctness of the simulation.

It can be seen from Table 5 that under various working conditions, the force increases with the increase in rock strength. Meanwhile, the simulation result is close to the theoretical calculation, and the relative error of the vertical force was not more than 7.5%, which proves the correctness of the simulation model.

According to the simulation results, the wear volume of the disk cutter can be calculated by using Eq. (12). Using the control variable method to change the working conditions in the model, the force and friction energy of the disk cutter under different working conditions can be obtained, and the wear volume of the disk cutter under different working conditions can also be calculated by using the aforementioned steps. Combined with Eq. (13),

the wear value of the disk cutter can be obtained.

4. Comparison and verification of predictive wear and actual data of disk cutter

According to the obtained force and friction work, the relevant parameters in the disk cutter wear prediction model are determined. The predicted values of disk cutter wear considering only sliding friction and sliding friction and rolling friction were calculated. Simultaneously considering that adjusting the penetration is the main way to deal with the change of geological conditions, the impact of penetration on the model was analyzed, the predictive wear value under each penetration was calculated, and its average value was taken as the predictive wear value considering penetration. The predictive wear value was compared with the actual wear data, and it was verified to improve the prediction accuracy. The method for disk cutter wear prediction based on the energy method was developed.

4.1. Predictive wear of disk cutter

According to Eq. (13) and the weight of geological parameters under various working conditions, the wear prediction value considering only sliding friction was $w_r = 11.6$ mm, and the wear prediction value considering the combined effect of sliding and rolling friction was $w_f = 12.38$ mm, when the penetration rate of the whole construction section was 7 mm and the installation radius was 1.001 m.

According to the installation radius of each disk cutter, the prediction model was applied to the front cutter on the entire cutter head. The wear value of all the front cutters on the cutter head under different geological conditions in the whole construction section can be obtained, and the values were compared with the actual cutter wear data to verify the correctness of the model for disk cutter wear prediction. The comparison between the predictive wear values and the actual wear data of disk cutter is shown in Figure 20.

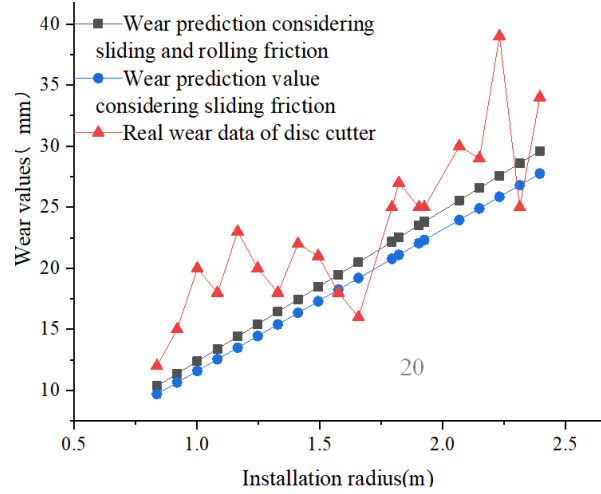


Fig. 20. Comparison between the predicted wear values and the actual wear data

It can be seen from Figure 20 that the predicted wear value of the disk cutter had the same trend as the actual wear data. The average relative error between the predicted wear value considering sliding friction and the actual disk cutter wear was 18.3%, and the average relative error between the predicted wear value considering sliding friction and rolling friction and the actual disk cutter wear was 12.8%. To a large extent, the accuracy of wear prediction value improved, and the correctness of the prediction model of disk tool wear was verified. Error reasons could be as follows: (1) The influence of the height difference between the replaced cutter and the adjacent disk cutter on wear is not considered in the simulation process; (2) abnormal wear will cause sudden changes in the actual wear data of the disk cutter; or (3) the second wear of rock slag on the disk cutter itself.

4.2. Analyzing the influence of penetration on the model

When the TBM is faced with changes in geological conditions, the tunneling parameters are often tuned up to enable the TBM to accommodate the geological conditions. Changing the penetration values in the tunneling parameters is one of the major approaches. According to the actual tunneling parameter data, penetration values were an adjustment target in the model for rock breaking

with the disk cutter, and then the simulation results were obtained. Similarly, the predicted wear values of in the whole construction under other penetration can be calculated by using Eqs (12) and (13). the predictive wear values were compared with the actual wear data, as shown in Figure 18.

It can be seen from Figure 21 that with the increase in penetration, the predicted wear value of disk cutter is also increased, which is consistent with the change trend of the actual wear data of the disk cutter. As the actual wear data of disk cutters was the statistical value in the tunneling section, the adjustment of penetration to adapt to the geology was generally based on manual experience in the actual tunneling process, so the penetration was often in a changing state. It can be considered that the predicted wear values were in the section surrounded by different penetration degrees in the figure. The average of the predicted wear values under different penetration values was taken as the predicted wear values of disk cutter considering penetration. Compared with the actual disk cutter wear, the average relative error between them was 12.2%, which was closer to the actual disk cutter wear than the disk cutter wear prediction value without considering penetration.

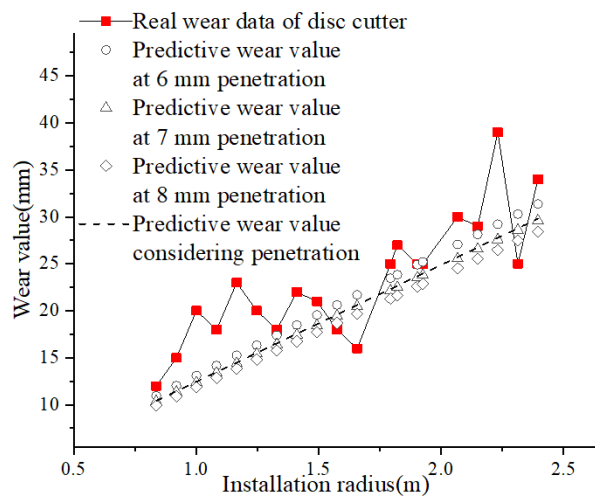


Fig. 21. Comparison between actual wear data and predicted wear values under different penetration

5. Conclusion

According to the energy wear theory, a model for the disk cutter wear prediction considering sliding friction and rolling friction was established, and a new method for disk cutter wear prediction based on energy method was proposed to realize the prediction of disk cutters under different geological conditions in the whole construction. Comparing the predicted wear value only considering sliding friction and the predicted wear value considering sliding friction and rolling friction with the actual wear value of disk cutter, we can see that the relative average error between the former and the actual wear value was 18.3%, and the relative average error between the latter and the actual wear value was 12.8%, which improves the accuracy of wear prediction. The influence of penetration on wear was studied. The average of the predicted wear values under different penetration values was taken as the predicted wear values of disk cutter considering penetration, and the predicted wear value was compared with the actual value. The average relative error between the predicted wear value of the disk cutter considering penetration and the actual wear data was 12.2%. It shows that the model for disk cutter wear prediction considering sliding friction and rolling friction was correct, and the influence of penetration improved the prediction accuracy. The research results can provide an effective method for disk cutter wear.

Acknowledgements

The authors are grateful for the comments and help of reviewers and editors.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the National Natural Science Foundation of China (grant number 11872256) and the Key research and development (R&D) projects of Hebei Province (grant number 22351901D).

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

- [1] Parriaux A, Tacher L, Joliquin P. The hidden side of cities – towards three-dimensional land planning. *Energy Build.* 2004;36(4): 335–41. doi:10.1016/j.enbuild.2004.01.026.
- [2] Gertsch R, Gertsch L, Rostami J. Disc cutting tests in Colorado red granite: implications for TBM performance prediction. *Int J Rock Mech Min Sci.* 2007;44(2): 238–46. doi:10.1016/j.ijrmms.2006.07.007.
- [3] Sun W, Zhang X, Zhao KS. Multi-stage force prediction model of single disc cutter based on the dense nuclear theory. *Mech Des Manuf.* 2015;292(06): 9–12. doi:10.19356/j.cnki.1001-3997.2015.06.003.
- [4] Xia Y-M, Ouyang T, Zhang X-M, Luo D-Z. Mechanical model of breaking rock and force characteristic of disc cutter. *J Cent South Univ.* 2012;19(7): 1846–52. doi:10.1007/s11771-012-1218-8.
- [5] Zhang H. Analysis of damages of TBM disc cutters and countermeasures. *Mod Tunnel Technol.* 2010;47(06): 40–45+50. doi:10.13807/j.cnki.mtt.2010.06.008.
- [6] Yang Y-D, Chen K, Li F-Y, Zhou J-J. Wear prediction model of disc cutter. *J China Coal Soc.* 2015;40(6): 1290–6. doi:10.13225/j.cnki.jccs.2014.3037.
- [7] She L, Zhang S-R, He S-W, Chao W, Lei L, Yong J, et al. Prediction model for TBM disc cutter wear based on dense core theory. *Chin J Geotech Eng.* 2022;44(5): 970–8. doi:10.11779/CJGE202205021.
- [8] Rostami J. *Development of a force estimation model for rock fragmentation with disc cutters through theoretical modeling and physical measurement of crushed zone pressure.* Dept. Of Mining Engineering, Colorado School of Mines; 1997.
- [9] Zhang G, Tan Q, Lao T. Analysis of rock breaking mechanics model for TBM disc cutter. *J Cent South Univ.* 2020;51(10): 2792–9. doi:10.11817/j.issn.1672-7207.2020.10.011.
- [10] Liu Q, Liu J, Pan Y, Zhang X, Peng X, Gong Q, et al. A wear rule and cutter life prediction model of a 20-in. TBM cutter for granite: a case study of a water conveyance tunnel in China. *Rock Mech Rock Eng.* 2017;50(5): 1303–20. doi:10.1007/s00603-017-1176-4.
- [11] Rong X, Lu H, Wang M, Wen Z, Rong X. Cutter wear evaluation from operational parameters in EPB tunneling of Chengdu metro. *Tunnelling Underground Space Technol.* 2019;93: 103043.1–8. doi:10.1016/j.tust.2019.103043.
- [12] Li X, Su X. A new method for forecasting shield's disc-cutters wearing based on Elman neural network. *J Liaoning Tech Univ.* 2010;29(6): 1121–4. doi:10.3969/j.issn.1008-0562.2010.06.030.
- [13] Elbaz K, Shen SL, Zhou A, Yin ZY, Lyu HM. Prediction of disc cutter life during shield tunneling with AI via the incorporation of a genetic algorithm into a GMDH-type neural network. *Engineering.* 2021;7(2): 238–51. doi:10.1016/j.eng.2020.02.016.
- [14] Shen X, Chen X, Fu Y, Cao C, Yuan D, Li X, et al. Prediction and analysis of slurry shield TBM disc cutter wear and its application in cutter change time. *Wear.* 2022;498–9: 204314. doi:10.1016/j.wear.2022.204314.
- [15] Song L. *Based on the theory of energy dissipation TBM disc cutter rock breaking energy field analysis and application research.* China: Tianjin University; 2016.
- [16] Geng Q. Analytical research on the wear mechanism of TBM disc cutters based on an energy approach. *Chin J Mech Eng.* 2018;54(1): 36–43. doi:10.3901/JME.2018.01.036.
- [17] Farrokh E. Cutter change time and cutter consumption for rock TBMs. *Tunnelling Underground Space Technol.* 2021;114: 104000. doi:10.1016/j.tust.2021.104000.
- [18] Fleischer G. Energy Balancing of the Material Friction as a Basis for Calculating Dynamic Wear. Pt. 3. *Schmierungstechnik.* 1977;8(2): 49–55.
- [19] Fu J, Xia Y, Zhang L, Lin L, Zhang X, Zhao S. Failure analysis on the fracture of disc cutter in EPB shield machine. *Eng Fail Anal.* 2020;108: 104341. doi:10.1016/j.engfailanal.2019.104341.
- [20] Naeimipour A, Rostami J, Buyuksagis IS, Frough O. Estimation of rock strength using scratch test by a miniature disc cutter on rock cores or inside boreholes. *Int J Rock Mech Min Sci.* 2018;107: 9–18. doi:10.1016/j.ijrmms.2018.03.020.
- [21] Exadaktylos G, Xiroudakis G, Stavropoulou M. Rolling disc model for rock cutting based on fracture mechanics. *Int J Rock Mech Min Sci.* 2018;107: 191–200. doi:10.1016/j.ijrmms.2018.04.056.
- [22] FengHua L, ZongXi C, Yi Lan K. A theoretical model for estimating the wear of the disc cutter. *Appl Mech Mater.* 2011: 90-93;2232–6. doi:10.4028/www.scientific.net/AMM.90-93.2232.
- [23] Zhao H, Shu B, Xia Y, Zheng W. Study of wear prediction for TBM cutter based on abrasive wear model. *J Railw Sci Eng.* 2014;11(04): 152–8. doi:10.19713/j.cnki.43-1423/u.2014.04.025.
- [24] Lu J, An Q. Calculating method for the wear of metal-to-metal dry sliding based on elastic–plastic contact theory. *Proc Inst Mech Eng Part J: J Eng Tribol.* 2018;232(10): 1215–29. doi:10.1177/1350650117743879.
- [25] Hua X, Puoza JC, Zhang P. The influence of laser surface texture on the tribological properties of friction layer materials in ultrasound motors. *Proc Inst Mech Eng Part J: J Eng Tribol.* 2022;236(6): 1123–32. doi:10.1177/13506501211052763.
- [26] Zhang Z, Aqeel M, Li C, Sun F. Theoretical prediction of wear of disc cutters in tunnel boring machine and its application. *J Rock Mech Geotech Eng.* 2019;11(1): 111–20. doi:10.1016/j.jrmge.2018.05.006.
- [27] Greenwood JA, Tabor D. The friction of hard sliders on lubricated rubber: the importance of deformation losses. *Proc Phys Soc.* 1958;71(6): 989–1001. doi:10.1088/0370-1328/71/6/312.
- [28] Zhang Y, Si C, Zhang Y, Zhang D, Cui Y. Effect of wear-resistant coatings on the comprehensive performance of finger seal. *Proc Inst Mech Eng Part J: J Eng Tribol.* 2019;233(4): 570–9. doi:10.1177/1350650118787912.

- [29] Bonfanti G, Colturato M, Rossi R. Global existence for a highly nonlinear temperature-dependent system modeling nonlocal adhesive contact. *Nonlinear Anal Real World Appl.* 2022;66: 103511. doi:10.1016/j.nonrwa.2022.103511.
- [30] Zhang S, Wang D, Cheng P, Shao C. Experimental and numerical analysis of the wear mechanism in spring coil forming die and the effects of die geometry on wear. *Proc Inst Mech Eng Part J: J Eng Tribol.* 2022;236(11): 2087–94. doi:10.1177/13506501211070097.
- [31] Guo J. The mechanism of producing rolling friction force and its calculation. *Lubr Eng.* 1988;1:19–24.
- [32] Li L, Wang H-Y, Zhou A-G. Nonlinear elastic deformation of magnesium and cobalt by Preisach-Mayergoyz model. *Trans Nonferrous Met Soc China.* 2012;22(9): 2220–5. doi:10.1016/S1003-6326(11)61452-0.
- [33] Telliskivi T. Simulation of wear in a rolling–sliding contact by a semi-Winkler model and the Archard’s wear law. *Wear.* 2004;256(7-8): 817–1. doi:10.1016/S0043-1648(03)00524-6.
- [34] Liu H, Qu C, Qin Q. Experimental investigation on skimming wear mechanism between TBM cutter ring and rock. *Exp Mech.* 2015;30(03): 289–98. doi:10.7520/1001-4888-14-16.
- [35] Li J, Huang Y, Zhang X, Sun Y, Guo J. Disc cutter wear prediction based on the friction work principle. *Trans Can Soc Mech Eng.* 2021;45(3): 384–95. doi:10.1139/tcsme-2020-0153.
- [36] Zhang ZH, Gong GF, Gao QF, Sun F. Fragmentation energy-saving theory of full face rock tunnel boring machine disc cutters. *Chin J Mech Eng.* 2017;30(4): 913–9. doi:10.1007/s10033-017-0159-4.
- [37] Rostami J, Ozdemir L, Nilson B. Comparison between CSM and NTH hard rock TBM performance prediction models. In: *Proceedings of Annual Technical Meeting of the Institute of Shaft Drilling Technology.* Las Vegas; 1996. p. 1–10.

Received 2023-02-19

Accepted 2023-04-19