Study on the wear of spiral drum cutting coal containing rock

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Abstract
Significant load fluctuations are encountered when cutting the coal rock using the shearer spiral drum, causing excessive drum wear. Thus, a coupling discrete element model of coal-rock was developed, and the discrete element method and multi-body dynamics were used to build a two-way coupling simulation model of coal rock drum cutting. The drum wear was analyzed, along with the pick and spiral blade wear positions. The results have shown that the pick wear is primarily concentrated at the pick tip and the shaft shoulder, while the outer spiral blade edge blade is generally worn near the pick root. The maximum wear depth obtained in the simulation was 0.00316 mm. The tangential cumulative energy of the drum and the normal cumulative energy were 1.794e5 and 7.819e4 J, respectively. The friction wear of the drum was more prominent compared to the impact wear. By using a single factor method, the relationship between the drum rotational speed, traction speed, rock firmness coefficient, cutting depth, and spiral blade angle, and drum wear was obtained. Finally, it was concluded that the study at hand provides a quick and straightforward way to study drum wear law.

Keywords
ADAMS, coal, DEM, drum, wear

1 INTRODUCTION

Spiral drum wear is rather prominent when cutting coal rock, with teeth wear being especially notable. This phenomenon affects both the efficiency and cost of mining. Since it is laborious and uneconomical to study the wear cost by using the experimental method, a good way to reduce the drum wear is through the use of virtual simulation methods. Such methods enable the drum wear reduction in actual production. Further, many scholars have used the discrete element simulation method to study the drum wear; however, there are no studies on drum wear based on the two-way coupling of the discrete element method (DEM) and multi-body dynamics (MBD) method.

Currently, coal is among the most important energy sources and since the coal rock is generally found within the stone layer, the shearer pick is subjected to heavy loads during the extraction. Most frequently, the pick fails due to wear\(^1\); thus, studying the spiral drum shearer wear is of great practical importance. For this reason, both the
crack propagation and wear progression of the Sialon ceramic tool while cutting Ni-based super-alloy Inconel 718 were studied using both the DEM simulation and experimentally. The drum cutting coupling model in complex coal seam was established using the DEM. The drum wear distribution and the influence of corresponding operational parameters were studied to further explore the wear mechanism. Moreover, aiming to improve both the pick wear and corrosion resistance, plasma surface spraying technology was used to apply a composite coating on the segments susceptible to wear. The resulting microstructure was then used to determine the structural properties of the coating area.

Additionally, neural networks were also used to study the wear of mining machinery. The pick and knife shapes and the novel type of pick were compared and analyzed. The cutting power and torque were measured before and after the wear took place. Furthermore, power and accompanying signals were processed to classify the wear that occurred. The processing was carried out using the wavelet noise reduction method. Moreover, by establishing a quantitative functional relationship between the wear and subsequent debris, the properties of the latter were analyzed to detect the wear mechanism. The shearer tooth made of 40Cr was heat-treated to improve the pick hardness and wear resistance. The authors have studied the wear mechanism by analyzing the pick surface wear scars, aiming to improve the mining capacity and increase the pick service life.

Regarding the low shearer efficiency, which is caused by the severe pick wear failure, corresponding cutting and cutting interference models were established using the mining theory. The orthogonal test was used to determine wear conditions of 28 coal cutting groups. Both the cutting and rotation angles were varied and the experiment has shown that a combination of smaller rotation angle and larger cutting angle should be selected (if allowed by theoretical installation range). Moreover, the neural system was used to analyze the resistance signal transmitted by the mining cutting head during the mining operation. This allowed the authors to check mechanical wear while also verifying the method's applicability to various mining machinery types.

The mechanical wear of mining machinery caused by the combined influence of erosion and oxidative wear was studied. Simultaneously, both the corrosion and wear resistance of different alloy materials were tested, aiming to reduce the machinery failure rate. The durability of high-speed steel milling cutters made using powder metallurgy coated with AlTiN was also studied. The effects of cutting speed and depth on tool wear and surface roughness were studied. By using the Gamma process and the Bayesian parameter update method to study the road header cutter wear degradation, a prediction model for the calculation of the remaining cutter life was proposed. The model is about the relationship between wear and time. Additionally, a multi-feature signal recognition method based on PNN neural network was suggested and used to determine the pick wear degree. The method was then applied to study the online recognition problem of road header pick wear. The vibration and acoustic emission feature signals of picks with various degrees of wear during the cutting process were extracted and analyzed.

The effects of conical pick wear resistance, characteristics, and its effect on the cutting force were studied both experimentally and numerically. A detailed cutting test was carried out using different types of rock and drill bits of various degrees of wear. The authors aimed to evaluate the cutting bluntness impact on the cutting force and the specific energy. The relationship between the wear plane and cutting force, the specific energy, along with the specifics of various rock properties were studied and discussed. The EBZ260W longitudinal axis road header was tested and analyzed. The quality, wear scar shape and pick temperature were observed before and after the test. The authors have found that the pick tooth body was mainly affected by abrasive wear, while the head wear was closely related to thermal fatigue. The wear shape of each pick segment was related to the cutting condition. It was determined that conical pick was affected by four wear mechanisms, including the coal/rock intermixing, plastic deformation, rock channel formation, and crushing and cracking. Based on the wear resistance study of the surface layer of four alloy powders produced using different material ratios, the results have shown that the mining pick wear resistance increases with the increase in the alloy powder TiC content. Its addition has significantly improved the mining pick coating wear resistance. Although many scholars have studied drum wear, there are few reports on the two-way coupling between drum and coal. The two-way coupling of MBD and DEM can solve the above-listed problems very efficiently.

In this study, the discrete element and multi-body dynamics collaborative methods were applied to study drum wear. A rigid-flexible coupling shear model was established and the two-way coupling method of DEM and MBD was used. The influences of various factors such as drum speed, traction speed, cut depth, and blade spiral angle on the shearer screw were analyzed.
2 | WEAR THEORY

Abrasive wear is among the most common wear forms encountered when cutting coal using coal shearsers. As the shearer cuts the coal, the pick comes in direct contact with the coal rock, which causes abrasive wear. Thus, it is evident that the stone in the coal rock damages the pick. Depending on the friction forms and the contact stress magnitudes, the wear can be divided into three categories—low-stress abrasion, high-stress crushing, and lastly, chiseling.

According to the Archard wear theory, which considers both the micro-cutting and indentation mechanism, abrasive wear is primarily caused by abrasive particles. Those particles are partially pressed into the material surface by the external pressure, causing the groove-like wear of the contact surface. The associated theoretical model is shown in Figure 1. The load perpendicular to the coal rock direction acts on the hard particles, which are then vertically pressed into the material surface. Next, the relative sliding motion between the particles and the material occurs, causing a pear-groove-shaped debris removal area on the material surface.

The amount of wear caused by this mechanism can be calculated as:

\[ N_i = \frac{1}{2} \pi r^2 \sigma_s \]  

where \( N_i \) is the positive pressure acting on the particles, N; \( r \) is the groove half-width, mm; and \( \sigma_s \) is the material hardness, MPa.

Assuming that \( dL \) is the relative sliding distance and that the particle shape is equiaxed, the wear volume can be expressed as follows:

\[ dV = rhdL = r^2 dL \cot \theta \]  

When the particles move for a unit distance, the material wear volume is:

\[ \frac{dV}{dL} = r^2 \cot \theta \]  

From formula (1), we obtain:

\[ r^2 = \frac{2N_i}{\pi \sigma_s} \]  

FIGURE 1  Micro-cutting model
By substituting formula (4) into formula (3), expression (5) is obtained:

$$\Delta V = \frac{dV}{dL} = \frac{2N_i}{\pi \sigma_s} \cot \theta$$  \hspace{1cm} (5)

By integrating Equation (5), the total volume of material removed by the particle when the sliding distance is equal to \(L\) is found:

$$V = \int_0^L \Delta V dL = \frac{2N_i L}{\pi \sigma_s} \cot \theta$$  \hspace{1cm} (6)

where \(h\) is the depth to which the hard particles were pressed into the material, mm; \(V\) is the total wear volume, mm\(^3\); \(L\) is the sliding distance, mm; and \(\theta\) is the particle cone half-angle, °.

By substituting \(K = \frac{2\cot \theta}{\pi}\) into expression (6), we obtain the following\(^2\):

$$V = \frac{KN_i L}{H}$$  \hspace{1cm} (7)

where \(K\) represents the wear coefficient of abrasive particles.

3 | TWO-WAY COUPLED SHEARER SIMULATION MODEL

Developing a two-way coupled model of shearer for cutting coal requires two models. The discrete element model of drum cutting coal is established first, followed by a multi-body system dynamics model of the coal shearer. Regardless of whether a cutting section model (discrete element or dynamic), the three-dimensional solid model of the shearer should be established first.

3.1 | Rigid-flexible coupling dynamics model of the shearer

The three-dimensional solid model of the shearer was established using Pro/e and was based on the design of the MG2 \(\times\) 70/325-BW type shearer. The model includes the shearer cutting part, moving part, planetary gear, sun gear, rocker shell, spiral drum, and motor, among others. The drum pick arrangement is shown in Figure 2(A), including the pick designations. The maximum spiral drum cutting diameter is 800 mm. The drum and shear models were created using Pro/e (see Figure 2(B,C)).

The shearer was assembled and interference checked was carried out. The shearer assembly model was imported into ADAMS using MECHANISM/Pro, the interface between the Pro/e and ADAMS. The material, density, and other part parameters were set according to the part materials. Shearer parts were connected by articulation, sliding, and matching. Based on the shearer motion form, constraints were included for each part and the constraints, including rotation pairs, plane pairs, and linear pairs, were selected.\(^2\) The constraints and drive were added to the motor output shaft, and the motor drive was included in the form of the STEP function. The gear movement was generated by adding the rotating pair and contact. According to the Hertz contact theory,\(^2\) the contact stiffness between gears can be calculated according to expressions (8)–(10):

$$\frac{1}{R} = \frac{1}{R_1} \pm \frac{1}{R_2}$$  \hspace{1cm} (8)

$$\frac{1}{E} = \frac{(1 - \nu_1^2)}{E_1} + \frac{(1 - \nu_2^2)}{E_2}$$  \hspace{1cm} (9)

$$K = \frac{4}{3} R^{1/2} E$$  \hspace{1cm} (10)

where “+” denotes external gearing; “−” denotes internal gearing; \(R_1\) and \(R_2\) are the pitch circle radii, mm; \(\nu_1\) and \(\nu_2\) are the Poisson ratios of each gear; and \(E_1\) and \(E_2\) are the Young moduli each gear, N/mm\(^2\).
ANSYS was used to generate the modal neutral file (MNF file) for the rocker arm shell, planet carrier, and planetary shaft, respectively. The process is as follows:

First, key points should be established. The key point positions and numbers are determined by the assembly relationship between the flexible part and the connected parts. The key points were meshed using mass2I mass elements to establish interface nodes, while solid elements were used to mesh flexible parts. The rigid area was defined next and connect to the interface nodes. Finally, the Export to ADAMS command was used to generate the MNF modal neutral file. The rigid to flex command in ADAMS was applied to replace the rigid cutting part shell, planet carrier, and planet shaft in the model with the corresponding flexible parts. When replacing the flexible parts, the corresponding MNF file was selected. Once all the flexible parts were replaced, the flexible parts were constrained according to the shearer assembly relationship. Finally, the rigid-flexible coupling multi-body dynamic model of shearer was established (as shown in Figure 3).
3.2 | Discrete element model of the drum cutting coal rock

3.2.1 | Discrete element model of the coal rock

The coal and rock samples were obtained from Yangcun Mine (Shandong Province, China). The obtained samples were tested, and the density, tensile strength, compressive strength, Young modulus, Poisson ratio, cohesion, internal friction angle, and ruggedness factor were obtained. All the measured coal rock parameters are shown in Table 1. The Hertz–Mindlin bonding contact models were applied to both the coal and rock. The particle contact model parameters obtained via calibration are shown in Table 2. The coal particles were non-uniform and spherical, and the sphere radii varied between 6 and 18 mm. By using the coal and rock particle factory, coal and rock models were obtained by including their particles. The filled particles were compressed to a certain degree, meaning that the distance between them reaches bonding radius, joining the particles. The resulting parameters are shown in Table 2.

3.2.2 | The DEM drum model

Generated drum model was imported into discrete element simulation software (EDEM) and the shear modulus, Poisson ratio, and drum density were included. The dynamic friction coefficients, static friction coefficients, and recovery coefficients between the coal, drum, and rock used in the model are shown in Table 3. The particle contact model and geometry were set according to the Hertz–Mindlin models. Finally, the wear coefficient of coal rock and drum is 1.98e-11.

3.3 | Two-way coupling settings and simulation

The time step was set to 5.45e-6 s to ensure the EDEM simulation stability. The target storage time interval was 0.01 s, and the grid size was five times the minimum particle radius.

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**Table 1: The parameters of coal rock**

|                | Density (kg/m³) | Tensile strength (MPa) | Compressive strength (MPa) | Elastic modulus (MPa) | Poisson’s ratio | Cohesion (MPa) | Internal friction angle (°) | Ruggedness factor |
|----------------|----------------|------------------------|-----------------------------|-----------------------|----------------|----------------|----------------------------|------------------|
| Coal           | 1466.92        | 2.38                   | 15.43                       | 3940                  | 0.33           | 4.5            | 38                         | 1.4              |
| Rock           | 2455.80        | 6.22                   | 34.62                       | 20,960                | 0.16           | 14.2           | 34                         | 3.5              |

**Table 2: Parameters of the particle contact model**

|                      | Normal stiffness (N m⁻³) | Tangential stiffness (N m⁻³) | Normal stress (MPa) | Tangential stress (MPa) |
|----------------------|----------------------------|------------------------------|---------------------|-------------------------|
| Coal–coal            | 1.13 × 10⁸                | 9.01 × 10⁷                   | 8.32                | 2.36                    |
| Rock–rock            | 1.98 × 10⁸                | 1.59 × 10⁹                   | 26.4                | 13.30                   |
| Coal–rock            | 1.44 × 10⁸                | 1.15 × 10⁹                   | 17.00               | 7.40                    |

**Table 3: Coal rock particle parameters**

|                  | Dynamic friction coefficient | Static friction coefficient | Recovery coefficient |
|------------------|------------------------------|----------------------------|----------------------|
| Coal–coal        | 0.05                         | 0.8                        | 0.5                  |
| Rock–rock        | 0.05                         | 0.7                        | 0.5                  |
| Coal–rock        | 0.05                         | 0.75                       | 0.5                  |
| Coal–drum        | 0.01                         | 0.5                        | 0.5                  |
| Rock–drum        | 0.01                         | 0.6                        | 0.5                  |
In the experiment, the drum rotational velocity was 95 r/min, while the traction speed was 4 m/min. The drive was included in the motor output shaft, and the step function was used to simulate it. In ADAMS, the motor speed was set to 10,266.028°/s, and the corresponding drum speed was 95 r/min. The traction motor speed was set to 6663°/s, and the corresponding traction speed was 4 m/min, while the simulation time was 5 s. Two-way couplings were conducted using both the discrete elements and ADAMS. The discrete element simulation of drum cutting coal rock was shown in Figure 4.

4 | ANALYSIS OF SIMULATION RESULTS

4.1 | Drum wear

The drum wear was obtained via simulations and is shown in Figure 5. It is evident that the pick tip is the most affected drum area, followed by the shoulder at which the pick tip is in contact with the body. The maximum wear depth found during the simulation was 0.00316 mm.
The normal and tangential cumulative energies measure the cumulative energy impact and sliding caused by coal and rock, respectively. Figure 6 shows the total cumulative contact energy; it can be seen that the drum cumulative contact energy in the tangential direction is greater compared to the normal contact energy. This indicates that the drum wear is dominated by tangential wear. Furthermore, it can also be seen that the tangential cumulative contact energy is $1.794 \times 10^5$ J, while its normal counterpart is $7.819 \times 10^4$ J. In other words, the tangential cumulative contact energy is 2.294 times larger than the normal contact energy. Both cumulative contact energies are related to the impact and friction wear of the drum caused by particles. Thus, it can be concluded that the drum friction wear is more severe than the impact wear.

4.2 Tooth and blade wear

The evolution of pick wear is shown in Figure 7. The wear first appears at the alloyed pick tip head, followed by the pick tip wear. Next, the wear area spreads to the tooth body and, finally, at the pick body shoulder. It can also be seen from the figure that pick wear gradually increases.
Aiming to better illustrate the pick wear, a more detailed pick wear view is shown in Figure 8(A). The cutting tip wears mostly in the vicinity of the alloyed head tip. Since the alloyed head has the main role in the coal cutting operation, the wear is rather severe. Second, it should be noted that the segment where the tooth body is in contact with the coal wall is also worn. However, both the amount of wear and its area are lower compared to the alloyed head. Lastly, notable wear was also detected at the connection between the tooth body and the alloyed head (the wear amount did not exceed 0.000182 mm). The pick angles from sections A to E were 47°, 35°, 20°, 12°, and 0°, while the corresponding wears were 0.5727e-4, 0.9884e-4, 1.2630e-4, 1.7023e-4, and 2.1966e-4 mm. The blade was 0° pick angle with the wear of 1.823e-4 mm.

The spiral blade wear mainly occurs at the blade edge, while the secondary wear area is located in front of the blade pick root. The blade wear was less prominent when compared to the pick wear; its maximum value was 2.16e-005 mm (see Figure 8(B)).

The drum wear was obtained experimentally to validate the simulation accuracy. The rotating speed of the experimental drum was 95 r/min, while the traction speed was 4 m/min. The worn drum obtained through the drum cutting coal and rock wear test is shown in Figure 9. The location of the drum wear shown in Figure 9 is consistent with the simulation analysis, confirming the simulation accuracy.

4.3 Analysis of the factors contributing to the drum wear

The drum wear is the result of multiple factors—complex loading conditions, coal properties, harsh operating conditions (high temperature and humidity), motion parameters, and structural parameters of the coal. Thus, the influences of the five factors on the spiral drum wear were studied. The selected factors were the rotational speed of the drum, its traction speed, rock firmness coefficient, cutting depth, and blade spiral angle. The single factor method was mainly used to analyze drum wear.

4.3.1 The rotating speed of the drum

The shearer traction speed of 5 m/min was selected, along with the drum cutting depth of 630 mm, and the blade helix angle of 18°. Furthermore, four different drum speeds were used in the simulation, including 75, 85, 95, and 105 r/min.
The drum wear was obtained for each rotation speed and the results are $3.6207\times10^{-3}$, $3.3733\times10^{-3}$, $3.23\times10^{-3}$, and $3.0737\times10^{-3}$ mm, respectively.

The relationship between the drum rotation speed and wear was obtained, as shown in Figure 10. As the rotation speed of the drum increases, the wear nonlinearly decreases. This is mainly due to the reduced cutting thickness per drum revolution caused by the increase in the rotation speed. The force acting on the drum is reduced per unit time, meaning that the wear is also reduced. The relationship between the drum speed \( n \) and wear \( w \) was obtained by the curve fitting method and is shown in Equation (11). The SSE was $1.633\times10^{-28}$ and the R-square was 1.

\[
w(n) = -1.952 \times 10^{-5}n^3 + 0.005497n^2 - 0.5291n + 20.61
\]  

where \( w \) is the drum wear, $1e-3$ mm; and \( n \) is the rotating speed of the drum, r/min.
4.3.2  The traction speed

To determine the effects of the traction speed on the wear, the shearer drum speed was set to 95 r/min, the drum cutting depth was 630 mm, and the blade helix angle was 18°. Four traction speed levels were analyzed—3, 4, 5, and 6 m/min. The drum wear values obtained through simulation were 1.7322e-3, 2.2011e-3, 3.23e-3, and 4.4413e-3 mm, respectively. The relationship between the drum traction speed \( v_q \) and the wear \( w \) is shown in Figure 11. As the traction speed increases, the drum wear increases non-linearly. This is mainly since the increase in traction speed increases the cutting thickness per drum revolution. The force acting on the drum increases per unit time, increasing the wear. The relationship between the drum traction speed and wear is given in Equation (12); the SSE was 8.722e-29 and the R-square was 1.

\[
w(v_q) = -0.06293 \times 10^{-5} v_q^3 + 1.035 v_q^2 - 4.449 v_q + 7.462 \tag{12}\]

where \( w \) is the drum wear, 1e-3 mm; and \( v_q \) is the traction speed, m/min.

4.3.3  The cutting depth

A simulation was carried out using the shearer drum speed of 95 r/min, the traction speed of 5 m/min, while the blade helix angle was 18°. The cutting depths were varied and set to 480, 530, 580, and 630 mm. The simulations were carried out for each cutting depth separately, obtaining drums with various cutting depths. The wear results were 2.6344e-3, 2.7230e-3, 2.8923e-3, and 3.23e-3 mm, respectively. The relationship between the drum depth and the wear was shown in Figure 12. It is clear that the drum wear increases non-linearly with the increase in cutting depth. This is mainly since the increase in cutting depth increases the number of picks involved in cutting, thus increasing the total drum wear. The relationship between the drum cutting depth \( B \) and wear \( w \) is shown in Equation (13), where SSE is 3.075e-28, and R-square is 1.

\[
w(B) = 1.169 \times 10^{-7} B^3 - 0.0001698 B^2 + 0.08372 B - 11.36 \tag{13}\]

where \( w \) represents the drum wear, 1e-3 mm, and \( B \) is the drum cutting depth, mm.

4.3.4  The coal rock firmness factor and blade helix angle

The same method was used to obtain the relationship between the coal firmness coefficient, blade helix angle, and wear, as shown in Figure 13. It can be seen from the figure that with the increase of the coal rock firmness coefficient, the
The relationship between the cutting depth and wear increases nonlinearly. Similarly, the blade spiral angle also increases, while the wear first increases which is followed by a decrease. The relationship between the coal rock firmness coefficient \( f \), blade spiral angle \( \beta \), and wear \( w \) is shown in Equations (14) and (15). The SSE was selected as 1.124e-29 and 3.649e-26, while the R-square was 1.

\[
w(f) = 0.09332f^3 - 0.9048f^2 + 3.532 - 3.409 \tag{14}
\]

\[
w(\beta) = 0.0227\beta^3 - 1.322\beta^2 + 25.44\beta - 158.7 \tag{15}
\]

where \( w \) is the drum wear, 1e-3 mm; \( f \) is the coal rock firmness coefficient; and \( \beta \) is the blade spiral angle, \(^\circ\).

Based on the above-presented analysis, the lowest drum wear was obtained for the rotating speed of 105 r/min, traction speed of 3 m/min, 480 mm cutting depth, the coal rock firmness coefficient of 4, and the blade helical angle of 21°. When the rotating speed was 75 r/min, with the traction speed 6 m/min, the blade cutting depth 630 mm, the coal rock firmness coefficient 7, and the blade helical angle 17.76°, the drum wear is the largest. For two parameters sets outlined before, the drum wears of 2.19e-3 and 1.46e-2 mm were obtained through simulation, respectively.

\section*{5 | CONCLUSION}

A two-way coupling simulation model of rock cutting drum was built using EDEM and ADAMS, and the drum wear position and magnitude were obtained using simulation. Based on the results, the authors concluded the following:
1. The pick wear was most severe at the pick tip and the shaft shoulder. Notable wear was also detected at the outer spiral blade edge near the pick root—the wear of 0.00316 mm was measured. The tangential and normal cumulative energies of the drum are 1.794e5 and 7.819e4 J, respectively. Finally, it was found that the drum friction wear is more impactful than the impact wear.

2. The relationship between the drum rotational speed, traction speed, rock firmness coefficient, cutting depth, and blade spiral angle, and drum wear was obtained using a single factor method.

3. The optimal cutting condition was obtained through simulation. The lowest drum wear was simulated for the rotating speed of 105 r/min, the traction speed of 3 m/min, 480 mm cutting depth, the coal rock sturdiness coefficient of 4, and the blade helical angle of 21°. For said parameters, the simulated drum wear was 2.19e-3 mm.

The study provides a quick and easy way to study the drum wear law.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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All data are available.

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