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Study on Synergistic Optimization of Tooth Profile and Tooth Number of Toothed Roll Crusher based on EDEM-Tavares Model

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Abstract

The toothed roll crusher is a key crushing equipment in the fields of mining, metallurgy and other industries, and the rationality of its structural parameters directly affects crushing efficiency, energy consumption and equipment service life. To improve the comprehensive performance of the toothed roll crusher, based on the Discrete Element Method (DEM), the EDEM software was used to construct the Tavares crushing model and Relative wear model for the simulation and optimization research on two key parameters: tooth profile and tooth number. Firstly, in accordance with the process requirements such as output and particle size, the structural parameters of the toothed roll were designed, with a roller diameter of 800 mm, length of 1200 mm, center distance of 845 mm and pitch of 20 mm. Secondly, through EDEM simulation, the wear characteristics and crushing effects of three tooth profiles (eagle beak type, spear type and trapezoidal type) under the same working conditions were compared systematically. The results show that the eagle beak tooth profile has more uniform force distribution and lower wear, and the particle size of the crushed material is mainly concentrated in the range of 15~21 mm, which meets the discharge requirements. Finally, the simulation of tooth number optimization was carried out for the eagle beak tooth profile with five working conditions set, and the analysis was conducted from the aspects of crushing efficiency and particle size distribution. The simulation results indicate that when the tooth number per ring is 45, the crushing efficiency is the highest, the complete crushing time is the shortest, and the proportion of qualified particle size in the crushed products is the largest. This study provides a theoretical basis and simulation support for the structural optimization of toothed roll crushers, and has certain engineering guiding significance for improving equipment efficiency and reducing wear.

Keywords

Toothed Roll Crusher; Discrete Element Method; EDEM Simulation; Tavares Model; Tooth Profile Optimization; Tooth Number Optimization; Wear Analysis.

1. Introduction

As key equipment in industrial fields such as mining, metallurgy, building materials and coal, crushers have a direct impact on production efficiency and resource utilization rate with their

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technical performance. Among numerous crushing equipment, the double toothed roll crusher has been widely applied in coal, metallurgy, chemical industry and other industries due to its advantages of simple structure, convenient manufacturing and maintenance, reliable operation and strong adaptability. Especially in the coal preparation process, the crushing link exerts an important influence on the subsequent separation and washing efficiency, and the toothed roll crusher has become one of the key equipment in this process by virtue of its good over-crushing control capability and high processing efficiency. Traditional toothed roll crushers still have room for optimization in terms of production capacity, crushing particle size distribution, wear life and energy utilization rate. In particular, when processing materials with medium hardness or above, they often face problems such as low crushing efficiency, severe wear of toothed rolls and poor uniformity of product particle size. Therefore, carrying out research on the structural optimization and performance improvement of toothed roll crushers has clear engineering significance and economic benefits for promoting industrial technological upgrading, reducing production energy consumption and prolonging equipment service life.

Li Min carried out the improved design of the spacing adjustment mechanism and bearing seal structure of a certain type of double toothed roll crusher aiming at the problems existing in its actual operation, which improved the reliability and maintenance convenience of the equipment[1]. Li Yongqiang et al. used EDEM software to simulate and analyze the working process of the roll crusher, and discussed the influence of parameters such as roll speed and roll spacing on the crushing effect[2]. Sun Gang et al. put forward suggestions on the structural strength and morphology optimization of crushing teeth by combining the Finite Element Method with wear analysis, which provided a reference for improving the service life of tooth bodies[3]. Manuel Moncada et al. used Rocky DEM software combined with the Tavares crushing model to model and simulate the cone crusher, and calibrated the model parameters through experimental data, realizing the accurate prediction of crushing torque, product particle size and other indicators[4]. Titus Nghipulile et al. carried out DEM simulation for a new type of rotary offset crusher, studied the crushing performance under different motion modes, and provided a theoretical basis for equipment optimization[5].

Therefore, this study aims to build a simulation system of toothed roll crusher based on the Tavares crushing model relying on the EDEM discrete element simulation platform, systematically analyze the crushing efficiency, wear characteristics and product particle size distribution under different tooth profile and tooth number configurations, so as to provide a theoretical basis and data support for the structural optimization design of toothed roll crushers and promote their development towards the direction of high efficiency, low consumption and long service life.

2. Design of Structural Parameters of Toothed Roll

According to the production requirements of a coal mine enterprise, the crushed material is coal with medium hardness, containing a certain amount of pyrite and gangue. The feed particle size is ≤500 mm, the product particle size is ≥15 mm, and the processing capacity is not less than 50 t/h. Based on the above conditions, the main parameters of the toothed roll crusher are determined as follows:

(1) Determination of roller diameter

The roller diameter D is related to the maximum feed particle size d_{max}, and the value range is generally 1.5~6 in general design. To balance the equipment compactness and processing capacity, the ratio is taken as 1.6 in this design, so the roller diameter is:

$$D=1.6\times d_{max}=1.6\times 500=800mm$$

(2) Rotating speed of toothed roll

The rotating speed n of the toothed roll mainly depends on the material hardness and particle size. For medium-hard materials (coal containing gangue), the rotating speed is taken as

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n=30r/min with reference to engineering experience. This rotating speed can control the wear rate of roll teeth while ensuring high production efficiency.

(3) Determination of roller length

Core design formula for toothed roll length:

Considering the structural arrangement and process allowance, the length L is finally determined as 1200 mm. For the length-diameter ratio, the length of the toothed roll is generally 1~3 times its diameter, so the designed roller length meets the requirements.

(4) Verification of production capacity

$$Q=k\times\rho\times\pi\times D\times e\times n\times L$$

Where:

L – roller length,

D – roller diameter,

e – toothed roll spacing,

n – rotating speed of toothed roll,

k – ore loose coefficient (0.25 for coal),

ρ – density of crushed material.

The calculated output Q is 50.54 t/h, which is higher than the required output.

3. Establishment of Crushing Simulation Model based on EDEM

The Discrete Element Method (DEM) is a numerical method used to simulate the motion and mechanical behavior of discontinuous media. Its basic idea is to discretize bulk materials into independent elements, and solve the system dynamic response iteratively by calculating the contact force and motion state between elements. As a leading discrete element simulation platform, EDEM has powerful modeling, calculation and post-processing capabilities, and is widely used in the analysis of particle systems in mining, metallurgy, agriculture and other fields.

3.1 Theoretical Basis of Tavares Model

The Tavares model is a single particle crushing model based on the energy criterion, whose core hypothesis is that particles break when the impact energy they bear exceeds their crushing energy threshold. Based on the Hertz-Mindlin contact model, this model introduces the crushing mechanism through the secondary development of API, which can simulate the wear, strength attenuation and complete crushing process of particles, and reflect the crushing behavior of materials more realistically. The particle crushing process is shown in Fig. 1.

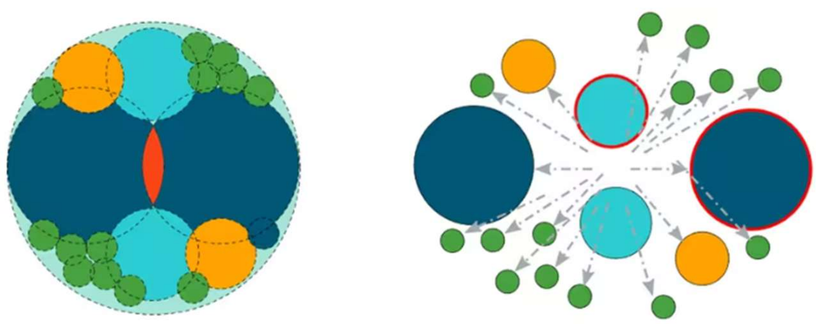

Fig. 1 Tavares crushing model

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Compared with the Bonding function, the Tavares function fully considers the wear process of materials in the simulation process with higher calculation efficiency. The post-processing can directly obtain results such as crushing ratio and particle size distribution, which are more intuitive, and the simulation speed is fast.

3.2 Determination of Model Parameters

The parameters of the Tavares model are mainly obtained by fitting crushing experiment and sieving data. Taking coal as the research object in this paper, the key parameters of the model are determined through literature research and data fitting, as shown in Table 1.

Table 1. Parameter design of Tavares model

Parameter name	Value
Damage constant	5
Global damping time	0 s
Global damping strength	0
Crushing energy threshold	213.5 J/kg
Fitting parameter 1	8.07
Fitting parameter 2	1.22
Fracture energy standard deviation	0.799
Alpha Percentage	67.7
B	0.029
Minimum crushing particle size	15 mm
Minimum collision energy	0.0001 J
Shear energy fraction	0
Truncation ratio	100

3.3 Setting of Material Parameters for Particles and Equipment

The physical properties and contact parameters of materials involved in the simulation are shown in Table 2. The parameters are derived from material handbooks and relevant literatures, which ensures the engineering reliability of the simulation.

Table 2. Basic parameters of particles and equipment

Material/Contact pair	Poisson's ratio	Elastic Modulus (Pa)	Density (kg/m^3)	Coefficient of restitution	Static friction coefficient	Rolling friction coefficient
Toothed roll	0.3	7.8×10^{11}	7850	-	-	-
Coal	0.18	1.8×10^{9}	1350	-	-	-
Coal-Toothed roll	-	-	-	0.1	0.5	0.2
Coal-Coal	-	-	-	0.1	0.5	0.2

3.4 Crushing Process Simulation

The Tavares simulation crushing process of the toothed roll crusher is shown in Fig. 2. Particles are generated at 1e-12 s, and the time step is set to 5% to ensure the accuracy of the results. The toothed

 Volume 12 Issue 3, 2026
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rolls contact with materials at 0.1 s and start crushing. The simulation ends at 5 s, and all materials are completely crushed.

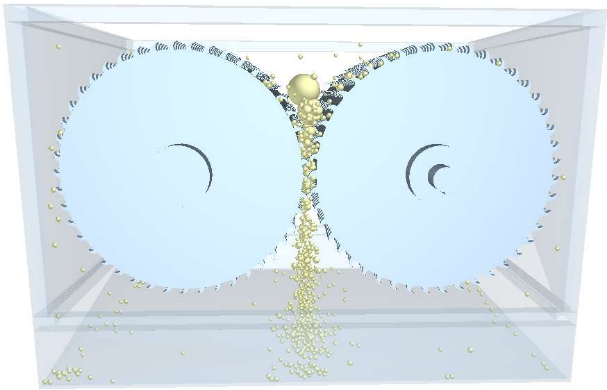

Fig. 2 Tavares simulation crushing process

4. Analysis of Simulation Results

4.1 Tooth Profile Analysis

There are several types of roll teeth: eagle beak type, spear type, blade type and rectangular belt type, as shown in Fig. 3.

Fig. 3 Tooth profiles of toothed roll

The significance of toothed roll tooth profile design is to improve efficiency and reliability through structural innovation, which not only meets the current energy-saving demand for equipment, but also ensures high production efficiency and good crushing force. In this paper, the eagle beak type, spear type and trapezoidal type tooth profiles are compared from the aspects of crushing tooth force and particle size distribution after crushing. The rotating speed of the toothed roll is set to 30 r/min, and other parameters remain unchanged.

4.1.1 Influence of Tooth Profile on Roll Tooth Wear

Material wear can be divided into adhesive wear, abrasive wear, fatigue wear and erosive wear according to different wear mechanisms. Among them, roll tooth fracture and toothed roll wear are the main failure modes.

Fracture failure: Fracture occurs when the stress exceeds the strength limit of the toothed roll under the action of external load. This fracture is completed instantaneously, causing huge losses, and fracture failure mainly occurs on the toothed roll. When selecting the material of toothed rolls, strength should be the primary consideration to ensure sufficient safety and avoid fracture.

Toothed roll wear: Material loss or transfer occurs on two mutually contacting surfaces when relative motion takes place. During crushing, toothed roll wear is prone to occur when the impact force and extrusion force are large. In the crushing process, materials contact the toothed rolls repeatedly, leading to local work hardening and falling off of crushing teeth.

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The Relative wear model is used in this paper, which expresses the wear amount by the cumulative energy on the surface, and the results are more accurate compared with the Achard wear model.

The Relative wear model mainly calculates four relative wear characteristics: normal cumulative energy, tangential cumulative energy, normal cumulative force and tangential cumulative force. Normal cumulative energy is used to measure the accumulated energy generated by material impact, and tangential cumulative energy is used to measure the accumulated energy generated by material sliding.

When *Vn*<0:

$$E_n = \sum |F_n V_n \delta t|$$

Where:

Vn – normal relative velocity (m/s), which is negative under loading conditions.

$$E_t = \sum |F_t V_t \delta t|$$

Where:

Vt – tangential relative velocity (m/s).

At this time, $V_{n-1} < 0$, $V_n > 0$

$$F_{nc} = \sum |F_n|$$
$$F_{tc} = \sum |F_t|$$

Where:

Fn – normal cumulative force borne by the equipment during crushing (N);

Ft – tangential cumulative force borne by the equipment during crushing (N).

After the simulation, the force nephograms of the tooth ring are exported, as shown in Fig. 4 (Force nephogram of spear tooth profile), Fig. 5 (Force nephogram of eagle beak tooth profile) and Fig. 6 (Force nephogram of trapezoidal tooth profile).

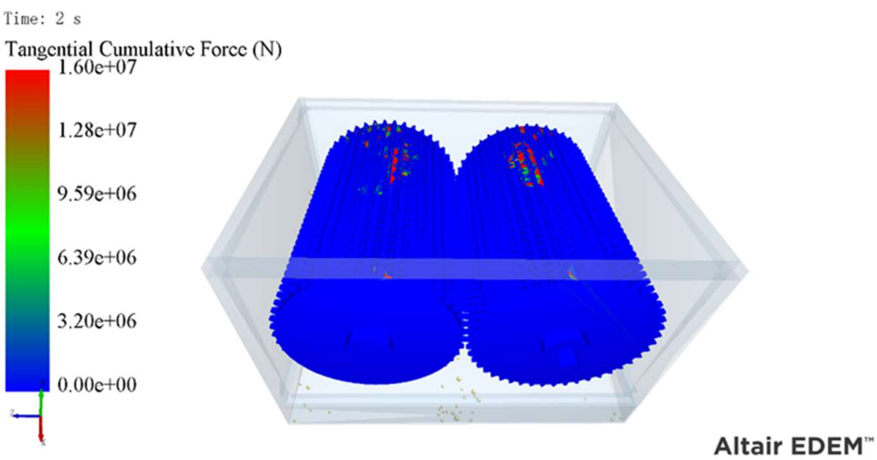

Fig. 4 Force nephogram of spear tooth profile

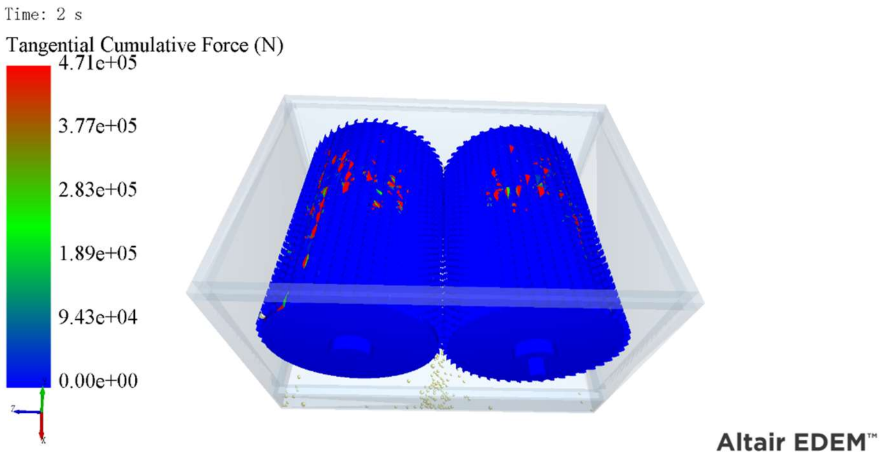

Fig. 5 Force nephogram of eagle beak tooth profile

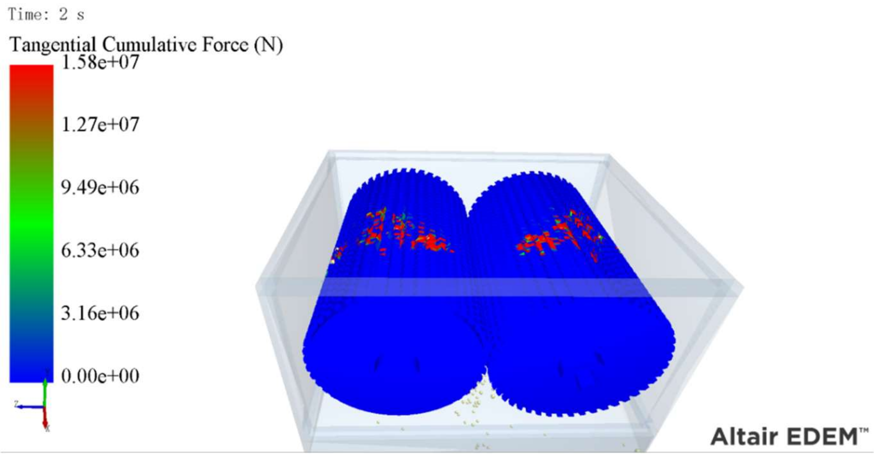

Fig. 6 Force nephogram of trapezoidal tooth profile

After the simulation, the wear distribution nephograms of the tooth ring surface are extracted, with the results shown above. From the perspective of force and energy accumulation:

Eagle beak tooth profile: The wear distribution is relatively uniform, with no obvious stress concentration areas. Its smooth transition of tooth profile contour helps to disperse impact force and reduce local peak stress, thereby reducing the risk of fatigue wear and brittle fracture.

Spear tooth profile: Wear is mainly concentrated at the tooth tip, showing obvious characteristics of local high stress. Its sharp structure leads to concentrated impact force when biting materials, which is easy to cause excessive wear and even fracture of the tooth tip, especially when processing hard materials such as gangue.

Trapezoidal tooth profile: Wear areas are distributed at the transition between the tooth side and tooth root. Due to the complex structure and sharp edges and corners of the tooth profile, materials are prone to shearing and jamming during the crushing process, leading to increased sliding wear, and the stress concentration phenomenon is more obvious than that of the eagle beak type.

Comprehensive wear analysis shows that the eagle beak tooth profile exhibits better crushing performance among the three types, with uniform wear distribution and low stress concentration, which is conducive to prolonging the service life of toothed rolls and reducing the maintenance frequency.

4.1.2 Analysis of Crushing Effects of Different Tooth Profiles

To evaluate the influence of different tooth profiles on crushing quality, the analysis is carried out from two dimensions: particle size distribution of crushed products and crushing efficiency. The particle size distribution of crushed products under each tooth profile is counted through the EDEM post-processing module, and the results are shown in Table 3.

Table 3. Crushed particle size distribution of different tooth profiles

Tooth profile	15~21 (mm)	21~27 (mm)	27~33 (mm)	Total (pcs)
Spear type	231	47	38	316
Eagle beak type	286	34	15	335
Trapezoidal type	211	62	48	311

The eagle beak tooth profile has the highest proportion of qualified particle size (15–21 mm) in the crushed products, reaching 85.1%, and the least number of oversize particles (>21 mm), indicating that its crushing particle size uniformity is good and it is more in line with the discharge control requirements.

The spear type and trapezoidal type tooth profiles have a lower proportion of qualified particle size with more residual large particles, which indicates that their crushing effect is mainly based on cleavage and impact, and their uniform crushing capacity for materials is weak.

In terms of crushing efficiency, combined with the observation of material flow and crushing process in the simulation, the eagle beak tooth profile can achieve more stable biting and extrusion due to its reasonable tooth surface contour, with fast material passing speed and few blockage phenomena, making the overall crushing process more smooth.

4.2 Tooth Number Analysis

On the basis of determining the eagle beak tooth profile as the optimal one, this chapter further studies the influence of tooth number on crushing performance. The tooth number directly affects the contact frequency, occlusal capacity and throughput between the toothed roll and materials, and is a key parameter for optimizing crushing efficiency and product quality. Five groups of different tooth numbers (30, 36, 45, 50, 60 teeth per ring) are set for simulation in this chapter, and a systematic analysis is carried out from the aspects of crushing time and product particle size distribution to determine the optimal tooth number configuration.

4.2.1 Analysis of Crushing Time with Different Tooth Numbers

Crushing time is an important index to evaluate the working efficiency of equipment. Under the same feeding conditions and roll speed (30 r/min), simulations are carried out for different tooth number working conditions, and the time required to complete the specified crushing task is recorded, with the results shown in Table 4.

Table 4. Complete crushing time

Tooth number per ring	Crushing time for 2×160 mm material (s)	Crushing time for 150 kg material (s)
30	2.513	4.564
36	2.478	4.786
45	2.374	3.745
50	2.549	4.264
60	2.645	5.124

The results show that: When the tooth number is 45, the crushing time is the shortest (3.745 s) and the efficiency is the highest. When the tooth number is too small, the number of occlusal points is insufficient and the crushing effect is inadequate; when the tooth number is too large, the inter-tooth space decreases, the material passing is hindered, which is easy to cause repeated crushing and blockage, and instead reduces the efficiency. It can be seen that there is an optimal range for the tooth number, and 45 teeth per ring shows the best crushing time efficiency under the research conditions of this paper.

4.2.2 Analysis of Particle Size Distribution with Different Tooth Numbers

The tooth number not only affects the crushing speed, but also directly affects the product particle size composition. The statistics of crushed product particle size distribution under different tooth number working conditions are shown in Table 5.

Table 5. Crushed particle size distribution with different tooth numbers

Tooth number per ring	15~21 (mm)	21~27 (mm)	27~33 (mm)	Proportion of qualified particles
30	218	42	35	73.9%
36	264	21	26	84.9%
45	286	34	15	85.1%
50	274	38	13	84.3%
60	238	44	19	79.1%

Data analysis shows that: When the tooth number is 45, the proportion of qualified particles is the highest (85.1%) with the least residual large particles; as the tooth number increases from 30 to 45, the qualification rate is gradually improved and the crushing effect is gradually optimized; when the tooth number continues to increase to 60, the qualification rate decreases instead, indicating that an excessive number of teeth may lead to insufficient crushing space and affect particle size control.

5. Summary

Based on the EDEM discrete element simulation platform, this study carried out systematic simulation analysis and optimization on the tooth profile and tooth number of the toothed roll crusher by constructing the Tavares crushing model and Relative wear model. The Tavares crushing model and Relative wear model are combined to synchronously evaluate the crushing effect and wear characteristics in the same simulation framework, which improves the systematicness of optimization. The results show that under the same working conditions, the eagle beak tooth profile is superior to the spear type and trapezoidal type in terms of wear distribution uniformity, crushing efficiency and product particle size control. In the tooth number optimization, the configuration of 45 teeth per ring can achieve the shortest crushing time (3.745 s) and the highest proportion of qualified particles (85.1%). Considering the interaction effect of tooth profile and tooth number on crushing performance comprehensively, a synergistic optimization scheme of "eagle beak type + 45 teeth per ring" is proposed. This study provides a clear parameter basis for the structural design of toothed roll crushers, and the research results can provide technical reference for the structural optimization and performance improvement of such equipment in engineering practice..

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