

Formation of Force Chains in the Crushing Zone of Roller Crushers and Strategies for Improving Unit Productivity

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Abstract

Addressing issues such as increased crushing force and energy consumption caused by the formation of force chains within the crushing zone during the operation of roller crushers, a new roller-type vibrating crusher that utilizes vibration to eliminate or reduce the formation of stress chains is proposed. Data is used to illustrate the superiority of this new roller-type vibration crusher, while demonstrating the methodology and support provided by EDEM for solving similar problems. Force reduction: The secondary crushing roller experienced a 57.27% reduction in load compared to high-pressure grinding rolls. The following results were obtained through simulation: Kinetic enhancement: Particle velocity increased by 28.5%, accompanied by a 23.34% rise in crushing ratio. Energy efficiency: Specific energy consumption decreased by 36.83%, while unit productivity surged by 58.3%.

Keywords

New Roller-Type Vibrating Crusher; EDEM; High-Pressure Roller Mill; Comparative Analysis.

1. Introduction

The traditional roller crusher crushes materials by increasing the pressure, resulting in serious wear, low unit capacity, excessive energy consumption and other problems, for which it is necessary to develop high-efficiency, energy-saving and environmentally friendly crushing equipment, and develop a new type of roller vibration crusher by introducing vibration to make full use of the concept of "loose effect". Through EDEM discrete element simulation, the crushing performance of the new roller vibration crusher and the high-pressure roller mill is compared and analyzed, and the addition of vibration increases the unit production capacity of the roller crusher by 58.3% and reduces the energy consumption by 36.83%. It provides a new technical route and theoretical support for the technical improvement of crushing equipment.

2. The Formation and Breaking Mechanism of the Force Chain

Force Chain^[1] as the core network of stress transfer between particle materials, its formation, evolution and visual characterization have always been important directions in particle mechanics research^[2]. Particulate materials (such as sand, ore, grain, etc.) are ubiquitous in our daily lives, and the force chain will have an impact on the macroscopic mechanical properties of particles^[3]. As shown in Fig. 1, the force chain describes the magnitude and direction distribution of the contact force

between the particles. In the crushing process, the formation and evolution of the force chain play a key role in the crushing efficiency and crushing quality^[4].

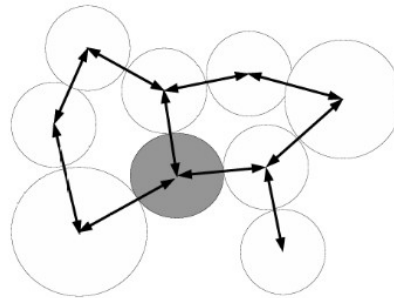


Fig. 1 Schematic diagram of the force chain

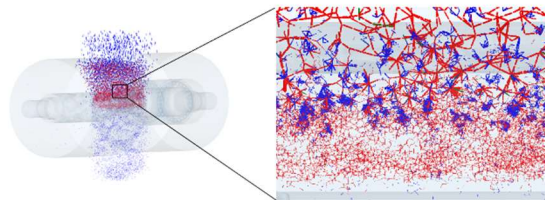


Fig. 2 Distribution diagram of the force chain in the fracture flow field

As shown in Fig. 2, the particles inside the fracturing zone are compressed and touch each other to form a force chain. The contact inside the material layer is not uniform, the red part indicates a large contact force, and the blue part indicates a small contact force. The force chain showed multi-scale dynamic evolution characteristics during the whole process of particle breaking, and the magnitude and direction of the contact force between particles in different times and spaces were different. At the same time, the magnitude and direction of the contact force of particles in the same space are also different. As the material is crushed, the closer the material is to the discharge port, the higher the degree of crushing and the greater the extrusion density. At this time, the number of force chains increases geometrically, and the contact between force chains becomes more and more stable. Experimental findings^[5], The local non-uniformity of the particle displacement field and the abrupt change of the velocity field are the precursors of the force chain break. The loading rate of external loads and boundary conditions significantly affect the stability of the chain^[6].

The traditional roller crusher must apply greater external force to overcome the stability of the force chain with crushing force^[7]; However, when the force chain is unevenly distributed or the strong chain is overly concentrated, it may lead to uneven energy transfer during the crushing process, excessive local stress, and aggravated local wear on the roller surface, which will affect the crushing effect of the material in the long run. In the process of material compression, due to the delay in breaking the balance of the force chain, the crushing force surges, resulting in the material compaction density reaching a critical state, the friction between the rollers rises sharply, the power consumption intensifies, and finally causes the phenomenon of stiffness.

In view of the adverse effects of the force chain on crushing, a new type of roller vibration crusher is proposed, which adopts the vibration idea and makes full use of the loosening effect in the process of rock crushing. The new roller vibration crusher adopts an eccentric shaft structure, and the vibration provided by the eccentric shaft will break the balance of the force chain, so that the material particles are redistributed and contacted, which can alleviate the formation of the force chain.

3. Structural Principle of Roller Vibrating Crusher

This paper proposes a new type of roller vibratory crusher with high efficiency and high capacity^[8], On the basis of the traditional roller crusher^[9], the crushing method of high-frequency vibration is adopted, so that the material undergoes multiple extrusion-loosening processes in the compression zone, giving full play to the advantages of lamination crushing^[10] (material group crushing) and single particle crushing, which can effectively reduce the crushing force and improve product quality and crushing efficiency.

The structural principle of the new roller vibratory crusher is shown in Fig. 3, which is mainly composed of main crushing roller 1, sub-crushing roller 2, main motor 3, magnetic coupler 4, main reducer 5, coupling 6, main crushing roller fixed bearing 7, hydraulic cylinder 8 and 13, flywheel 9 and 14, cylindrical roller bearing 10, eccentric shaft 11, sub-crushing roller fixed bearing 12, floating shaft 15, sub-reducer 16, sub-coupling 17, auxiliary motor 18 and other structures.

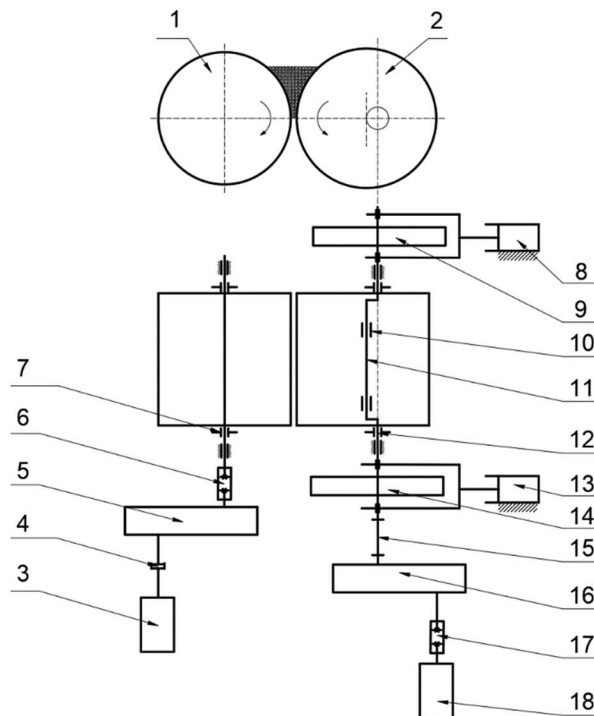


Fig. 3 Schematic diagram of the structure of the new roller vibratory crusher

When working, the main motor is started, the main reducer is driven by the magnetic coupler, the main reducer reduces the speed of the main motor, and increases the output torque, and is connected to the main crushing roller through the coupling to meet the requirements of "strong and low speed" of the main crushing roller. The auxiliary motor drives the eccentric shaft to achieve high-speed rotation, and under the eccentric action, the auxiliary crushing roller will carry out alternating movements near and far to achieve the emergence of the extrusion-loosening process.

The main motor and auxiliary motor are fixed on the frame by bolts to ensure the stable operation of the crusher; The interference fit between the spindle and the main crushing roller is adopted; The secondary crushing roller is assembled in the middle of the eccentric shaft through cylindrical roller bearings, and the secondary crushing roller can rotate freely on the eccentric shaft^[11]; The flywheel is equipped with flywheels at both ends of the eccentric shaft, which converts electrical energy into kinetic energy and stores it during empty travel, and the flywheel releases the stored energy during the working stroke to help the motor overcome crushing resistance and reduce instantaneous power

fluctuations. The two ends of the floating shaft are connected by flange couplings, which realize the dual functions of power transmission and axis compensation, and can be extended and rotated to avoid interference when the auxiliary crushing roller is retracted. The magnetic coupler is a transmission device that transmits power and torque through a magnetic field, and there is no mechanical connection between the motor and the load shaft, and the power transmission between the drive end and the load end is realized through the non-contact relative movement between the conductor rotor and the permanent magnet rotor. Magnetic couplers^[12] have overload protection due to their non-contact torque transmission mechanism and magnetic field slip characteristics. When the crusher encounters hard or unbreakable materials, the torque at the load end exceeds the set threshold, and the magnetic field between the inner and outer magnetic rotors will appear "slipping", the rotor at the driving end continues to rotate, and the rotation speed of the rotor at the load end is no longer synchronized with the driving end, that is, the motor can stop rotating the main crushing roller without stopping; Due to its non-contact characteristics, it improves the safety and reliability of system operation without damaging the mechanical mechanism.

4. Crushing Simulation of Roller Vibrating Crusher

In order to further optimize the working parameters and structure of the roller vibration crusher, it is necessary to obtain the relevant force and energy parameters during crushing work, such as crushing force, torque, material movement law in the crushing area, etc., due to the complexity of the problem itself, these parameters are difficult to obtain by analytical method, numerical simulation has become an effective means, through computer simulation, not only a single parameter can be obtained, but also the influence of multiple parameter combinations on the working performance of the crusher. In addition, numerical simulation can also provide data such as velocity field and stress field distribution of particles, which effectively makes up for the shortcomings of analytical methods.

4.1 Crusher Model Creation

In order to simulate the machine more effectively, based on a high-pressure roller mill, the structural parameters are simplified on the premise of ensuring the accuracy of the core physical mechanism, focusing on the key parameters that have a significant impact on crushing force, energy consumption and particle flow characteristics, and ignoring or simplifying secondary factors^[13]. A simplified geometric model of the crushing cavity of a new roller vibratory crusher composed of shaft, bearing, crushing roller and shell was established by using SolidWorks. Import the geometry model into Ansys and set the material properties (modulus of elasticity, Poisson's ratio, density, etc.) constitutive parameters in Ansys; Intelligent grid division is carried out, and the rollers directly involved in crushing are finely gridded, which can improve the accuracy of the rollers in the simulation analysis, so that they can more accurately reflect the mechanical properties in the actual crushing process. This setting can not only meet the needs of the basic characteristics of the simulation analysis related components, but also effectively reduce the overall calculation volume, improve the calculation efficiency, and ensure that the entire simulation and analysis process can run more efficiently and stably. After completing the finite element modeling, the boundary conditions are determined and applied, the rotating pair and vibration are applied to the eccentric shaft, the displacement constraint is set at the bearing housing, the fixed support is applied at the bottom of the housing, the model is imported through the EDEM-Ansys coupling interface, and the key discrete element parameter settings are performed. The particle model was imported, and the contact parameters were set using the Hertz-Mindlin bond contact model^[14], perform discrete element analysis. The simulation process is shown in Fig. 4.

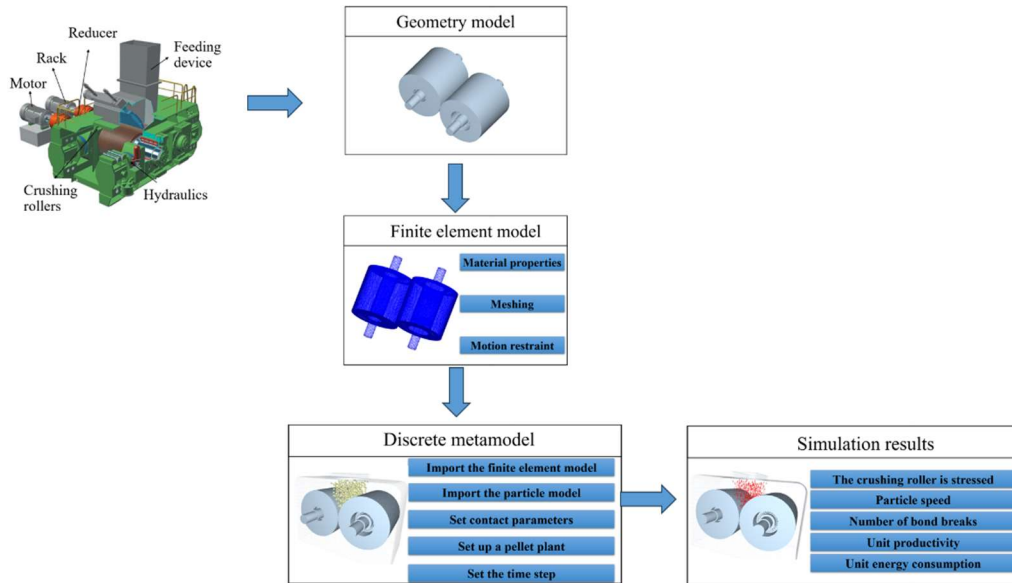


Fig. 4 Schematic diagram of the simulation process

4.2 Establishment of Ore Crushing Model and its Parameter Setting

The mechanical properties of ore particles directly affect the crushing behavior. In order to restore the real material properties, the ore model needs to be parameterized. The ore type selected in this paper is iron ore^[15], The physical property parameters, material contact parameters and bonding parameters of iron ore crushing were obtained by uniaxial compression test^[16].

Selection of Bonded particle model (BPM) The particle bonding model consists of several small particles bonded by bonding bonds to form a large particle. Under a certain load, part of the bonding bond will break to simulate the effect of breaking. The advantage is that the shape of the crushed material can be obtained, but the disadvantage is that the crushed particle size cannot be counted, and the calculation amount is large and the calculation time is long^[17].

In order to improve the simulation speed, the shape of rock particles is simplified and spherical. In order to improve the computational efficiency, the secondary development function of EDEM API is used to realize the sub-region replacement of particles^[18], Finally, a particle replacement model plugin is generated for subsequent discrete element simulation work. As shown in Fig. 5, Figure A is a schematic diagram of the particles before replacement, Figure B is a schematic diagram of the particles after replacement, and Figure C is a schematic diagram of the bonding bond.

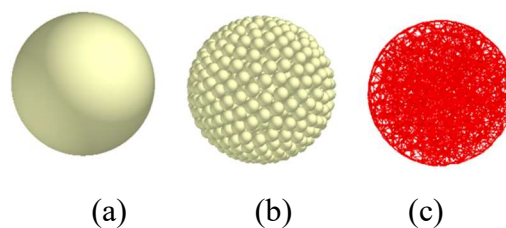


Fig. 5 Schematic diagram of particle bonding

The initial diameter of the ore particles is set to 40 mm, and the diameter of the small particles after replacement is 3 mm^[19], and the number of bonded small particles is calculated to be 1327. The number of simulated particles selected was 100, and the number of initial bonding bonds was 132700.

4.3 Simulation Result Analysis

Using the maximum force on the surface of the sub-crushing roller, the number of bond breaks, the maximum particle velocity and the unit capacity as evaluation indicators, the performance of high-

pressure roller mills^[20] and new roller vibratory crushers with the same parameters was compared and analyzed by discrete-element-finite element coupling simulation technology^[21]. The performance comparison of the two under the same conditions is shown in Table 1.

Table 1. Comparison table of the impact of vibration on crushing performance

	The crushing roller is stressed(N)	Particle speed(m/s)	Number of bond breaks	Unit capacity (t/h)
High pressure roller mill	43628.5	5.12	56274	239.4
New type of roller vibratory crusher	19242.7	6.58	87249	378.9

(1) The maximum force change of the secondary crushing

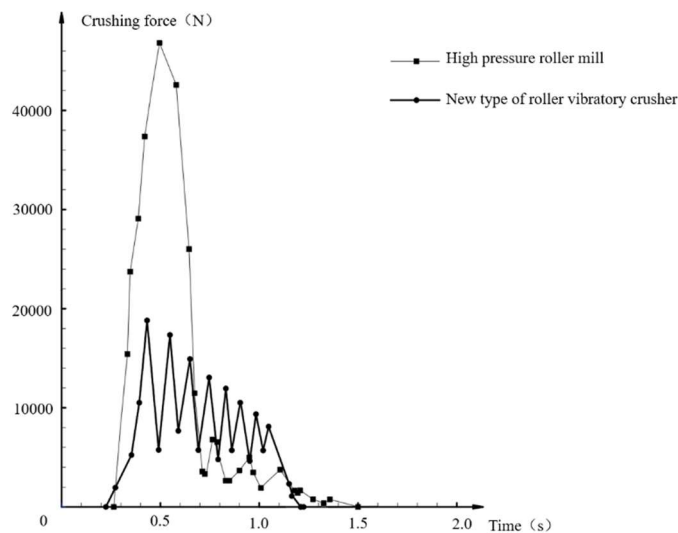


Fig. 6 Change curve of the force on the crushing roller

As shown in Fig. 6, the maximum force of the secondary crushing roller of the new roller vibrating crusher is 19242.7N, the maximum force of the high-pressure roller mill is 43628.5 N, and the force of the sub-crushing roller of the new roller vibrating crusher is reduced by 55.89% compared with that of the high-pressure roller mill.

The different characteristics of the high-pressure roller mill and the new roller vibration crusher can be seen from the force change curve of the secondary crushing roller in the crushing process. The high-pressure roller mill starts from 0.25 s to enter the crushing stage, the force of the auxiliary crushing roller begins to surge, the force reaches the maximum at 0.5 s, and the force decreases at 0.5 s~0.8 s, indicating that during this period, the crushing roller has been in a high pressure state, and the crushing mechanism of the high-pressure roller mill is to overcome the stability between the force chains with high pressure. At 0.8 s~1.5 s, the force gradually decreases, and after 1.5 s, the crushing is completed, and the secondary crushing roller is no longer stressed, at which time the crushing is completed. The force of the new roller vibration crusher increases from 0.23 s, and the force fluctuates between 0.23 s~1 s, and the frequency of the fluctuation is the vibration frequency of the eccentric shaft. The pressure on the subrollers is significantly reduced due to the addition of vibration. With each vibration, the material undergoes a "squeeze-loose" process. In the extrusion stage, the roller

compresses the material to form a force chain and transmit pressure, and the vibration in the loose stage promotes the displacement of particles and destroys the stability of the force chain.

This data fully reflects that in terms of the force of the sub-crushing roller, the new roller vibratory crusher has obvious advantages compared with the high-pressure roller mill. This is because the vibration of the eccentric roller changes the interaction between the material and the crushing roller, in the absence of vibration, the material is only crushed by the extrusion and shear action of the two crushing rollers, after the introduction of vibration, the material will be affected by the crushing roller while also being subjected to the additional force and inertial force generated by the vibration, so that the material in the crushing process has a complex motion state, thus reducing the contact area between the material and the crushing roller, the material and the material, the combined effect of these forces makes the material produce stress concentration, resulting in the material is more likely to be crushed. This advantage means that the pressure of the sub-crushing roller of the new roller vibration crusher is less during operation, which will reduce the wear of equipment parts to a certain extent and improve the stability and service life of the equipment.

(2) Change of maximum particle velocity

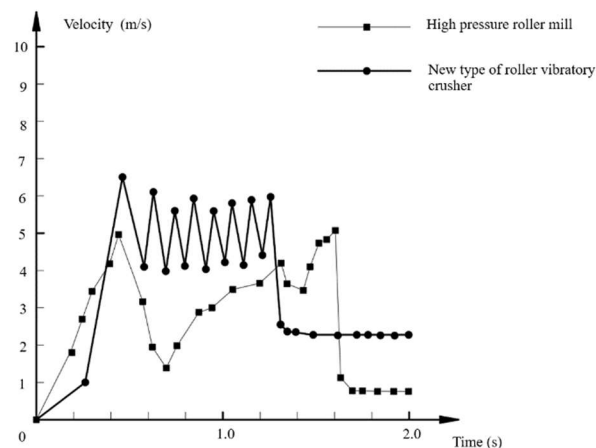


Fig.7 Particle velocity change curve

As shown in Fig.7, under the same conditions, the maximum particle velocity of the high-pressure roller mill is 5.12 m/s, and the particle velocity of the new roller vibration crusher is 6.58 m/s, which is 28.5% higher than that of the high-pressure roller mill.

The particle velocity curve of the high-pressure roller mill and the new roller vibrating crusher was analyzed, and the particle velocity increased from 0 s~0.4 s when the high-pressure roller mill was crushed, and the material velocity began to increase under the action of gravity. 0.4 s~0.8 s particle velocity decreases to the lowest, indicating that the material begins to crush, the particle velocity gradually decreases, when the particles reach the bottom of the crushing area, the crushing force is the largest, the force chain reaches the most stable state, and there is almost no movement between the particles. At 0.8 s~1.2 s, some materials are crushed, some materials are discharged, and the particle speed begins to increase again, and at 1.2 s~1.5 s, all materials enter the discharge stage. The particle velocity increases from 0 s~0.4 s and fluctuates in 0.4 s~1.2 s when crushing the new roller vibrating crusher, which is due to the vibration brought by the eccentric shaft, the particles go through the extrusion stage, the auxiliary crushing roller is close to the main crushing roller to compress the material, and the force chain is formed between the particles, and the particle speed decreases. In the loosening stage, the secondary crushing roller moves away, the interparticle force chain is redistributed, and the particle velocity increases. After 1.2 s, the particle velocity tends to be stable, indicating that the crushing is complete.

The results show that the introduction of vibration not only improves the overall motion speed of particles, but also promotes the collision between particles and the adaptive speed of position, thus increasing the chance of particles participating in the crushing process. This dynamic effect helps to break the particle accumulation and arching effect that may occur in high-pressure roller mills, making the material more uniformly distributed in the crushing chamber, thereby achieving more efficient crushing operations.

(3) The number of bond bond breaks

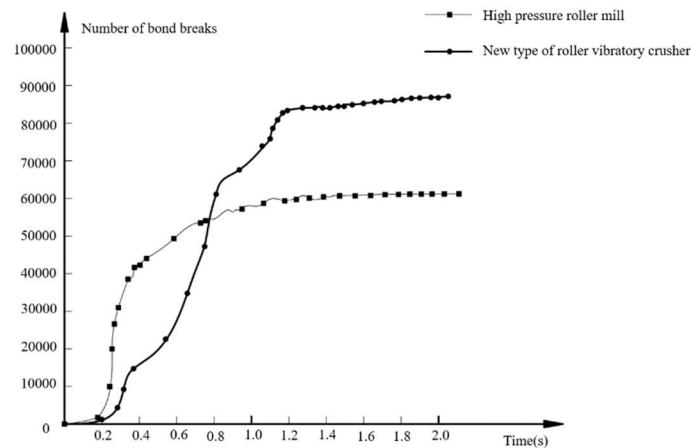


Fig.8 Bond break number curve

The number of bond bond breaks from the feed port to the discharge port is shown in Fig.8, the number of bond bond breaks of the high-pressure roller mill is 56274, the crushing ratio is 42.41%, and the maximum number of bond breaks of the new roller vibration crusher is 87249, and the crushing ratio is 65.75%, which is 23.34% higher than that of the high-pressure roller mill. The increase in the crushing ratio means that during the crushing process, large particles are effectively crushed into smaller particles, which directly indicates that the crushing effect of the particles has been significantly improved.

(4) Unit production capacity and unit energy consumption

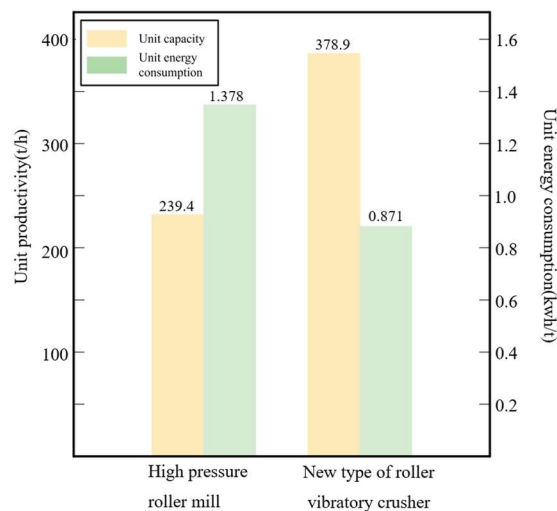


Fig. 9 Comparison chart of unit capacity and unit energy consumption

As shown Fig. 9, the unit capacity of the high-pressure roller mill is 239.4 t/h, the unit energy consumption is 1.378 kWh/t, the unit capacity of the new roller vibration crusher is 378.9 t/h, the unit energy consumption is 0.871 kWh/t, and the unit capacity has increased by 58.3%; The unit energy consumption decreased by 36.83%. The growth of unit production capacity improves the efficiency of resource utilization, is conducive to the rational allocation and effective use of resources, and promotes the sustainable development of the entire industry. The decrease in unit energy consumption means that energy consumption is reduced in the production process, reducing dependence on energy resources, and also reducing environmental pollution caused by energy consumption.

5. Conclusion

The introduction of vibration has significantly improved the working performance of the crusher. Specifically, it is manifested as:

- (1) The force of the sub-crushing roller is reduced by 55.89%, which can effectively extend the service life of the equipment.
- (2) The particle speed increased by 28.5% and the crushing ratio increased by 23.34%, which promoted the fluidity of the material in the crushing chamber and achieved better particle size control.
- (3) The unit production capacity increased by 58.3%, and the unit energy consumption decreased by 36.83%, and the effect of high energy and low consumption was remarkable.

Acknowledgments

Inner Mongolia Autonomous Region Higher Education Research Project (NJZZ23060);
Key R&D and Achievement Transformation Program of the Autonomous Region (2022YFHH0142);
Grant-in-Aid for Research in Universities Directly Affiliated to Inner Mongolia Autonomous Region (2024QNJ098).

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