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Article

Optimization design of coal crusher based on biomechanics characteristics

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Abstract: Background: With the increasing demand for equipment performance in the coal industry, traditional coal crushers face problems such as high vibration, high noise, insufficient wear resistance, and frequent mechanical failures during long-term operation. To this end, the study adopts a combination of biomimetic structural design and multi-layer composite material optimization to improve the performance of coal crushers. **Method:** Based on biomechanical characteristics, this method optimizes the design of the coal crusher from three aspects: overall results, crushing components, and shock absorption and noise reduction performance, in order to reduce its vibration and noise while maintaining or improving its mechanical strength and wear resistance. **Result:** The optimized support structure of the coal crusher improved its seismic performance by at least 20% when subjected to impact forces, effectively reducing the concentration of local stress and the occurrence of mechanical failures. The hammer crushing component made of multi-layer composite materials has an HRC hardness of about 67 and an impact toughness of about 15 J/cm^3, significantly improving the crushing efficiency and service life of the coal crusher. **Conclusion:** The optimized coal crusher exhibits excellent performance in vibration control, noise reduction, and wear resistance, providing a more efficient and environmentally friendly coal crushing equipment for the coal mining industry.

Keywords: biomechanics; coal crusher; hard materials; energy conversion efficiency; vibration

1. Introduction

The progress of the coal industry has made coal crushers a key piece of equipment in the coal mining and processing process, and their performance and operational efficiency have a crucial impact on the entire production process [1]. Traditional coal crushers face many challenges in long-term operation, such as high vibration, high noise, insufficient wear resistance, and frequent mechanical failures. These issues not only affect the service life of equipment but also have adverse effects on the health and working environment of operators. In recent years, the application of biomechanics in the field of engineering has become increasingly widespread, providing new ideas for solving these problems [2]. Biomechanics, which studies the mechanical properties and structural functions of living organisms, provides valuable inspiration for engineering design [3]. Among them, biomimetic design has achieved significant results in multiple mechanical fields. Deng et al. proposed a biomimetic toothed plate structure that mimics the convex structure of the head and body surface of a dung beetle to address wet concave soil being difficult to effectively crush with existing crushers, and analyzed it using the Discrete Element Method (DEM). Compared to ordinary tooth plates without biomimetic structures, biomimetic crushing tooth plates exhibited better performance and higher efficiency in crushing wet concave soil [4]. Dang et al. [5] improved the adhesion and agglomeration of crusher tools caused by high moisture content in newly excavated concave soil by combining bionics and DEM. The biomimetic device could effectively increase the disturbance of concave soil particles and reduce their accumulation in front of the tool. At the same time, the designed crocodile tooth biomimetic tool had low rock-breaking resistance and energy consumption. Yuan et al. [6] proposed a high-traction track shoe tooth based on ostrich sole structure to address the difficulty of walking, slipping, and sinking of track-type combine harvesters in wet and soft rice fields during the rainy season. It extracted biomimetic information from the non-smooth surface of the dung beetle and designed a track surface with biomimetic convex hull patterns based on geometric similarity principles and adhesion experiments. The optimized track teeth significantly improved the traction force in wet and soft rice fields. Traditional microwave-absorbing materials were easily exposed to multispectral detection and harsh service environments. In view of this, Xu et al. [7] proposed a method for obtaining efficient stealth materials with multiple properties by introducing biomimetic concepts into structural and material design. The proposed material had good anti-monitoring performance.

The above research indicates that the use of bionic principles can optimize the structure design of equipment and improve its performance. However, the materials used for key parts such as the hammer head, sieve plate, support structure, and shell of the equipment still need to be further optimized. Multi-layer composite materials have been widely used in aerospace, automotive manufacturing, and other fields due to their excellent mechanical properties and structural design flexibility. Ibrahim et al. used techniques such as *X*-ray fluorescence, *X*-ray diffraction, thermogravimetric analysis, and scanning electron microscopy to characterize the composition of composite materials composed of aluminum alloy, brown pumice, and coal ash to improve their tensile strength. They also used the Taguchi method for experimental design and optimization. The optimized multi-layer composite exhibited thermal stability at 614.01 °C and was suitable for brake disc applications [8]. There was currently a demand for constructing electrode materials with lightweight, ultra-thin, flexible, and high capacitance performance. Wang et al. [9] proposed the use of simple vacuum filtration and freeze-drying methods to prepare cellulose nanofiber/carbon nanotube/waste activated carbon composite materials with multi-layered graded conductive structures. This multi-layer graded composite material had stable energy storage performance and EMI shielding performance and had broad application prospects in energy storage and intelligent electromagnetic interference shielding. Lead-based potassium sodium niobate ceramics suffered from poor temperature stability of piezoelectric charge coefficient due to polymorphic phase boundaries. Therefore, Zheng et al. [10] designed a composition gradient multi-layer composite material with multiple continuous phase transitions to solve this problem. This structural gradient ceramic exhibited excellent temperature reliability, far superior to previously reported lead-based potassium sodium niobate materials.

Although biomimetic design and multi-layer composite materials have made some progress in the mechanical field. For example, Deng et al. demonstrated that biomimetic design has significant effects in improving mechanical surface friction, anti-adhesion, and traction performance; Xu et al. [7] validated the potential application of biomechanics in complex service environments; Wang et al. [9] demonstrated the advantages of multi-level design in functional integration. However, if these methods are directly applied to the optimization of coal crushers, there are still certain problems. Firstly, existing biomimetic designs mostly focus on optimizing the surface structure, and there is relatively little research on the overall structural optimization of complex mechanical systems such as coal crushers. Especially under high load and high wear conditions, how to improve the overall performance of coal crushers through biomimetic design is still an urgent problem to be solved. Secondly, the application of multi-layer composite materials in coal crushers is still in its early stages, especially in the material selection and structural design of key components such as hammers, which lack systematic research and optimization. Further exploration is needed on how to achieve effective application of materials in coal crushers while ensuring their high performance. In view of this, this study optimizes the overall structure, crushing components, and shock absorption and noise reduction performance of the coal crusher based on its biomechanical characteristics. It is expected to provide new theories and methods for the design and optimization of coal crushers, and to provide more efficient and environmentally friendly coal crushing equipment for the coal mining industry.

The innovation of the research is to optimize the rotor, rocker arm, and sieve plate structure of the coal crusher through the principle of spider bionics to improve its wear resistance and crushing efficiency. At the same time, it selects high-performance multi-layer composite materials to optimize the macro, micro, and nano microstructures of the hammer head, improving wear resistance and impact toughness.

2. Optimization design of coal crusher based on biomechanical characteristics

2.1. Structural design of coal crusher based on spider web bionics

The ring hammer coal crusher is one of the important pieces of equipment in the coal transportation system of thermal power plants and is widely used as a crushing machine for coal crushing in China. It uses a ring hammer suspended on the rotor (rotating at high speed) to impact and crush materials. After being impacted, the material is subjected to compression, shearing, grinding, and other effects between the ring hammer and the sieve plate, reaching the required particle size, and then discharged through the lower outlet of the sieve plate grid hole [11–14]. The specific structure is shown in **Figure 1**.

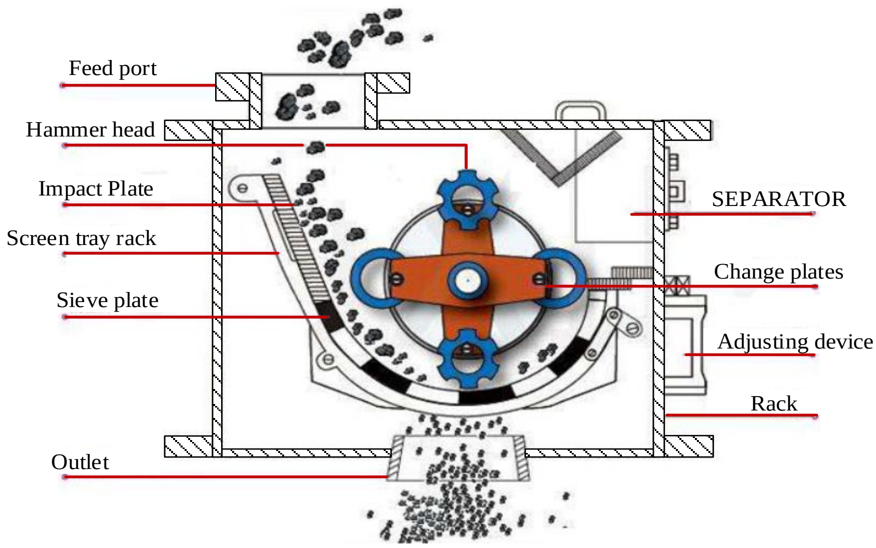

Figure 1. Structure of ring hammer coal crusher.

In **Figure 1**, the ring hammer coal crusher is mainly composed of a body, a cover, a rotor, a sieve plate, and a sieve plate regulator. The rotor is the core component of the coal crusher, consisting of the main shaft, flat key, disc, spacer, rocker arm, ring hammer, ring shaft, and bearing seat. The ring hammer impacts and crushes coal during the rotation of the rotor, and the crushed coal is discharged through the sieve plate. However, traditional ring hammer coal crushers still have room for improvement in crushing efficiency and wear resistance [15]. Therefore, this study proposes a structural design of a ring hammer coal crusher based on spider web biomimetics, optimizing the performance of the coal crusher through biomimetic principles. Firstly, based on the biomimetic principle of spider webs, the optimization of the rotor structure of the coal crusher is shown in **Figure 2**.

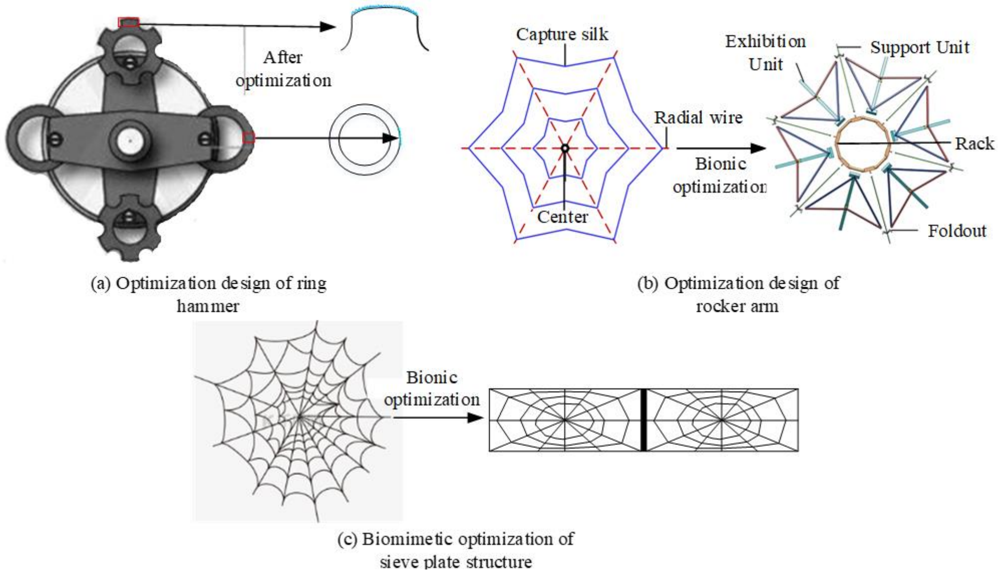

Figure 2. Optimization of rotor structure based on spider web biomimetics: **(a)** Optimization design of ring hammer; **(b)** Optimization design of rocker arm; **(c)** Biomimetic optimization of sieve plate structure.

Figure 2a shows the biomimetic design of the ring hammer of the ring hammer coal crusher. Traditional ring hammers are usually circular or toothed, which can meet basic crushing needs to some extent, but there is still significant room for improvement in wear resistance and crushing efficiency. Spider silk is a layered structure composed of β-folded crystals (rigid phase) and α-helical amorphous regions (flexible phase), with a toughness of up to 150 MJ/m^3 and a fracture elongation of about 30%. Under external force, the amorphous molecular chains absorb energy through slip recombination, while the crystalline region provides rigid support, forming a "sacrificial bond hidden length" effect to avoid brittle fracture caused by stress concentration. Based on this mechanism, the study selected tungsten carbide hard coating (hardness ≥ 2200 HV) and high toughness alloy steel flexible matrix (yield strength ≥ 800 MPa) as gradient material design for coal crusher components to improve impact fatigue resistance. Inspired by the extremely high friction and adhesion properties of spider silk micro nano structures, this study investigates the introduction of similar micro nano structures on the surface of a ring hammer. The laser-etched ring hammer surface forms multi-level micro protrusions (scale 10–100 μm), simulating spider silk surface nanofibers, which can increase the friction coefficient by 40% and enhance coal block adhesion. The micro convex body increases its surface hardness by 1000 HV through the Hall-Petch effect, while the groove structure guides the directional discharge of wear debris, reducing abrasive wear. Research has shown that spider silk exhibits a strain rate strengthening effect under dynamic impact (the higher the velocity, the higher the modulus), with an energy absorption capacity of 1×10^5 J/kg, far exceeding the 1×10^2 J/kg of steel. The viscoelastic hysteresis characteristics of biomimetic spider silk can dissipate high-frequency vibration energy and reduce resonance damage.

Figure 2b shows the biomimetic design of the rocker arm of the ring hammer coal crusher. The rocker arm adopts a multi-layer mesh structure of spider webs to increase its strength and toughness. By setting up multiple layers of support structures inside the rocker arm, similar to spider web node connections, stress can be effectively dispersed and the service life of the rocker arm can be improved. Related studies have shown that interweaving radial and spiral threads resembling spider webs can reduce the maximum stress of the rocker arm of a ring hammer coal crusher under alternating loads by 35%. 3D-printed titanium alloy node connectors simulate spider web "viscous droplets", which can dissipate energy through plastic deformation and increase fatigue life to 2×10^6 cycles, while traditional structures only have 5×10^5 cycles.

Figure 2c shows the biomimetic design of the sieve plate of the ring hammer coal crusher, which adopts a geometric shape similar to a spider web and is designed as a multi-layer mesh structure. Each layer of sieve plates is connected by elastic connectors, similar to the nodes of a spider web. The acceleration of the sieve plate of the ring hammer coal crusher can reach 50cm/s^2, resulting in loose connecting bolts and clogged sieve holes. The sieve plate design can achieve wideband vibration suppression, reducing the resonance peak by 60%. At the same time, the sieve holes are designed with irregular polygons, similar to the mesh of a spider web, which increases the flux by 25% and reduces the blockage rate to 3%, thereby improving the pass rate and crushing effect of the sieve holes.

2.2. Design of coal crusher hammer crushing components based on multi-layer composite materials

After designing the overall structure of the coal crusher, the next step is to focus on the hammer head. As a key component in coal crushers, the hammer head's performance directly affects the crushing efficiency and service life of the crusher. Although traditional hammer materials such as high manganese steel and high chromium alloy have certain wear resistance and impact resistance, their performance still has shortcomings under high hardness and high wear conditions. Multilayer composite materials have become a potential material for improving the performance of coal crusher hammers due to their excellent mechanical properties and flexible structural design. The multi-level design of the crushing components of the coal crusher hammer head is shown in **Figure 3**.

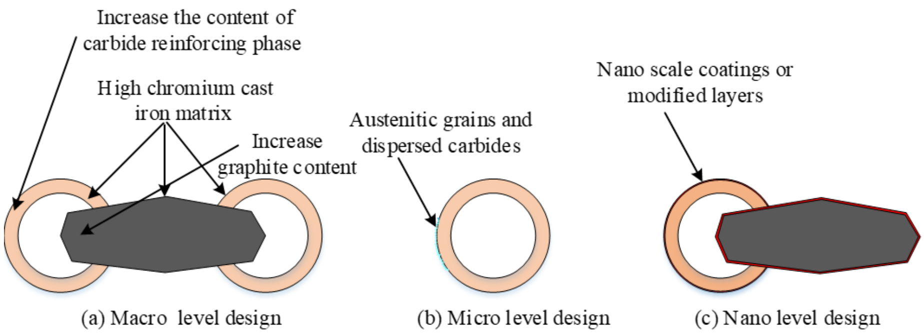

Figure 3. Multi-level design of the crushing components of the coal crusher hammer head: **(a)** Macro level design; **(b)** Micro level design; **(c)** Nano level design.

In **Figure 3**, this study selects high chromium cast iron metal material with high strength, high toughness, and high hardness as the matrix. To further improve the hardness and wear resistance of the hammer head, hard phases such as carbides are selected as reinforcing materials. At the same time, to improve the toughness of the hammer head, ductile phases such as graphite are selected as reinforcing materials. Graphite has good lubricity and toughness, and can absorb some energy when impacted, preventing crack propagation.

Figure 3a shows the macroscopic hierarchical design of the crushing components of the coal crusher hammer head. The overall structure of the hammer head is made of a high chromium cast iron matrix, forming a macroscopic mechanical support structure. In the head area of the hammer, this study increases the content of the carbide-reinforcing phase by 5% to improve the hardness and wear resistance of the crushing end. The content of graphite and other tough phases in the handle area of the hammer head is increased by 8% to improve the toughness of the connecting part and prevent fracture during installation and operation. Touhami et al. [16] found through fracture toughness testing that when the amount of graphite added was 8%, the impact absorption energy of high chromium cast iron increased by 40% compared to the graphite-free matrix, and the tensile strength only decreased by 5%. The layered structure of graphite can effectively hinder crack propagation and reduce the risk of handle fracture [16].

Figure 3b shows the macroscopic and microscopic design of the crushing components of the coal crusher hammer head. In the high chromium cast iron matrix, fine austenite grains and dispersed carbides are formed by controlling the solidification process and heat treatment process. The solidification process involves cooling molten metal at a high speed of approximately 500 to 1000 m per second. This process can significantly refine the austenite grains, allowing their size to be precisely controlled between 10 and 20 microns. The heat treatment process involves heating the material to a high temperature range of approximately 1000 °C to 1200 °C and maintaining it for 3 h to ensure that the carbides can fully dissolve in the matrix. Subsequently, by rapid cooling to room temperature, the carbides will re precipitate as small particles with a size of 1 to 5 microns and be uniformly distributed in the matrix. This micro level structural design can fully leverage the synergistic effect of the matrix and reinforcement phase, improving the overall performance of the material.

Figure 3c shows the nano micro design of the crushing component of the coal crusher hammer head. The surface of tungsten carbide particles is coated with a layer of nano ceramic coating, with a thickness of 10–50 nanometers. This coating can improve the bonding strength between tungsten carbide and the substrate, while also providing some lubrication during the crushing process and reducing wear. For graphite reinforced phase, nano silver particles are introduced on its surface to improve the interface bonding between graphite and matrix, and enhance the toughness of the hammer head.

2.3. Vibration and noise reduction design of coal crusher based on dynamic response analysis

The above has designed the structural performance of the main components of the coal crusher, and the progress of the power industry has put forward higher requirements for the performance and operational stability of the coal crusher. The vibration and noise generated by the coal crusher during operation not only affect the service life of the equipment but also have adverse effects on the surrounding environment and the health of operators. Therefore, this study optimizes the shock absorption and noise reduction performance of the HCSZ800 ring hammer coal crusher based on dynamic response analysis. The process is shown in **Figure 4**.

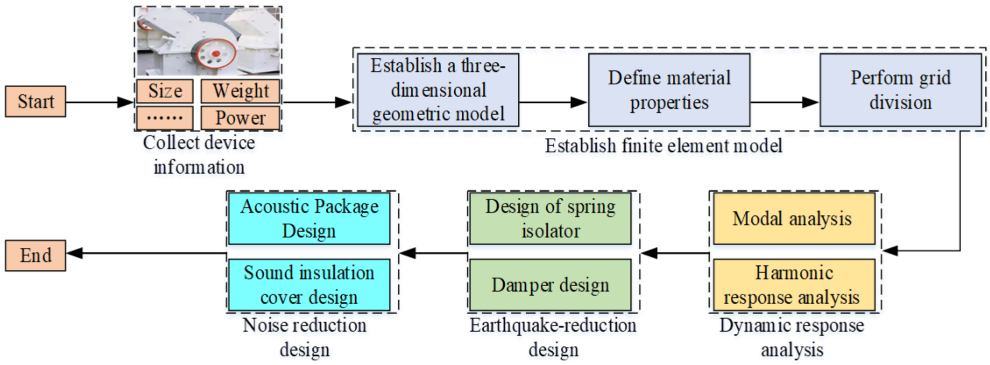

Figure 4. Design process of shock absorption and noise reduction for coal crusher based on dynamic response analysis.

In **Figure 4**, the detailed parameters of the HCSZ800 ring hammer coal crusher are first obtained, and the material properties of the coal crusher are defined. Then, MSC NASTRAN finite element analysis software is used to mesh the various components of the coal crusher, including key parts such as the hammer head and rotor, which are meshed with finer grids (mesh sizes ranging from 5mm to 10mm), to establish a 3D geometric model of the coal crusher. The specific design parameters and material properties of the HCSZ800 ring hammer coal crusher are shown in **Table 1**.

Table 1. Design parameters and material properties of coal crusher.

Productivity		**t/h**	**800**
Broken materials		\	Bituminous coal, smokeless coal, lignite, etc.
Maximum feeding block size		mm	≤ 350
Discharge size		mm	≤ 25
Rotor	Diameter	mm	1370
	Working Length	mm	1905
	linear velocity	m/s	42.6
	Rotating body mass	Kg	6972
	Moment of flywheel	N·m^2	38,465
	Disturbance value	KN	27.2
Ring hammer	Number	Arrange	4
		Individual	Gear ring 20; Circular 18
	Quality	Kg	Gear ring 36; Circular 47
Motor	Model	\	YKK5003-10
	Power	KW	400
	Voltage	V	6000
	Rotational speed	r/min	594
	Quality	Kg	4300
Material properties	Elastic modulus	GPa	200–210
	Poisson's ratio	\	0.3
	Density	kg/m^3	7800

Subsequently, dynamic response analysis is conducted on the ring hammer coal crusher, including modal analysis and harmonic response analysis. Modal analysis uses subspace iteration method to solve the modal of the ring hammer coal crusher structure, obtaining the first few natural frequencies and corresponding vibration modes. The calculated natural frequency is compared with the operating frequency of the coal crusher to determine if there is a risk of resonance. Harmonic response analysis simplifies the disturbance force of the coal crusher equipment as a harmonic load and applies it to the finite element model. The steady-state response of the coal crusher at different frequencies is analyzed to evaluate whether the vibration level of the equipment meets the design requirements. According to the above tests, if the vibration level of the optimized coal crusher does not meet the requirements, vibration reduction and noise reduction design will be carried out. For the abnormal vibration problem of the coal crusher, this study sets up 12 sets of spring isolators. The vertical stiffness of each set of isolators is 1.12 kN/mm, the horizontal stiffness is 1.18 kN/mm, and the damping coefficient is 112.42 kN·s/m. By adjusting the stiffness and damping coefficients, the shock absorption effect is optimized. To further improve the shock absorption effect, this study also sets dampers with damping coefficients of 38.12 kN·s/m–133.24 kN·s/m. The abnormal noise problem of the coal crusher adopts a composite structure of glass wool material and rubber soundproof material as the acoustic package of the coal crusher shell to reduce the radiation of noise. The entire device adopts a double-layer steel plate structure, with sound-absorbing materials filled in the middle to reduce noise leakage.

3. Performance analysis of improved coal crusher

3.1. Analysis of stability and seismic performance results of coal crusher support structure

In order to analyze the stability and seismic performance of the optimized support structure of the coal crusher, the study first used a spirit level to test the horizontal deviation of the main shaft of the crushed material under no-load and full-load conditions. In order to enhance the rigor of the experiment, it was meticulously conducted in a vibration isolation laboratory. The ambient temperature was strictly maintained at a constant 25 ± 1 °C, and the relative humidity was controlled to be no more than 50%. A vibrating feeder was employed to ensure the uniform distribution of materials, effectively avoiding biased load interference. Moreover, all test hammers were sourced from the same batch, thus eliminating the influence of differences in material performance. The no-load and full-load tests were each repeated five times, and the average value was taken as the final experimental result, which is presented in **Figure 5**.

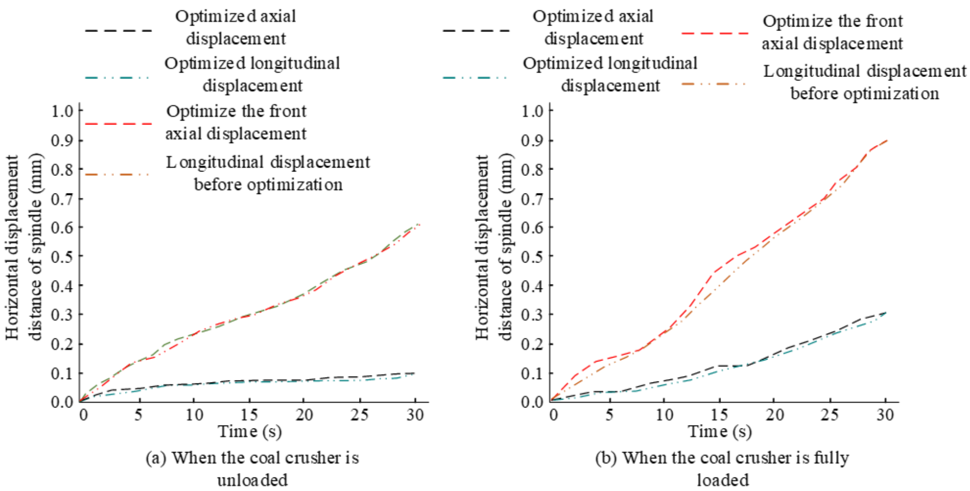

Figure 5. Comparison of spindle horizontal deviation before and after optimization of coal crusher: **(a)** When the coal crusher is unloaded; **(b)** When the coal crusher is fully loaded.

Figure 5a shows the horizontal deviation of the main shaft during the no-load operation of the coal crusher. Before optimization, the axial and longitudinal horizontal offsets of the spindle are relatively large, reaching about 0.61 mm. However, after optimizing using research methods, this value significantly decreases, and the axial and longitudinal horizontal offsets of the coal crusher spindle are only about 0.09 mm, indicating a very significant optimization effect. **Figure 5b** shows the horizontal deviation of the main shaft during full load operation of the coal crusher. When not optimized, the axial and longitudinal horizontal offsets of the spindle are more severe, about 0.89 mm. After applying the research method, the axial and longitudinal horizontal offsets of the spindle are significantly reduced to about 0.31 mm. This fully demonstrates the effectiveness of optimization measures in improving spindle stability under full load conditions. Subsequently, high-precision displacement sensors (LVDT-200, range ± 5 mm, resolution 0.001 mm) were used to monitor key nodes of the supporting structure in real-time. In the experiment, three sets of dynamic impact loads with amplitudes of 20 kN, 30 kN, and 40 kN were applied through a hydraulic servo excitation system (model HY-3000). The impact waveform was set as a half sine pulse (frequency 5 Hz, pulse width 50 ms) to simulate transient impact events in actual working conditions. Each load condition was strictly repeated three times in the test, and the arithmetic mean of the displacement response peak values was taken as the valid data after removing outliers. The results are shown in **Figure 6**.

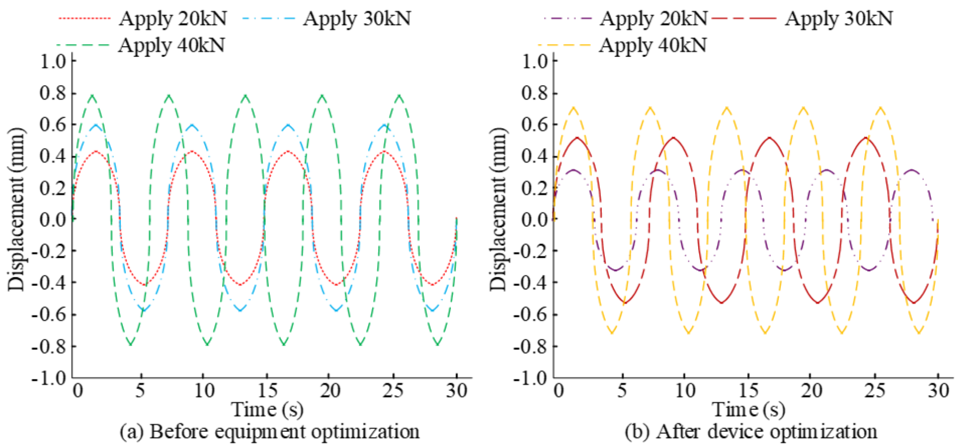

Figure 6. Comparison of support structure displacement before and after optimization of coal crusher: **(a)** Before equipment optimization; **(b)** After device optimization.

Figure 6a shows the displacement of the support structure when different impact forces are applied before optimizing the coal crusher. When a 20 kN impact force is applied, the displacement range of the supporting structure is [−0.39 mm, 0.39 mm]. When a 30 kN impact force is applied, the range of displacement changes expands to [−0.61 mm, 0.61 mm]. When a 40 kN impact force is applied, the range of displacement changes further increases to [−0.81 mm, 0.81 mm]. **Figure 6b** shows the displacement of the optimized coal crusher when different impact forces are applied. After optimization, the displacement range of the support structure was significantly reduced to [−0.31 mm, 0.31 mm] when applying a 20 kN impact force. When applying an impact force of 30 kN, the displacement variation range is [−0.49 mm, 0.49 mm]. When applying a 40 kN impact force, the displacement variation range is only [−0.68 mm, 0.68 mm]. A comprehensive comparison of the data before and after optimization shows that the seismic performance of the optimized coal crusher support structure has been significantly improved, at least by 20%, when subjected to impact forces. This improvement not only effectively reduces the concentration of local stress but also significantly reduces the probability of mechanical failures, thereby greatly enhancing the stability and reliability of the coal crusher in actual operation.

3.2. Analysis of performance test results for hammer crushing components

To analyze the wear resistance and impact toughness of the optimized coal crusher hammer crushing components, a dry sand rubber wheel wear tester is used for wear resistance testing. The experiment is conducted in accordance with the national standard GB/T 3960-2016 "Plastic Sliding Friction and Wear Test Method". The hammer head sample is fixed on the fixture of the testing machine, and the testing machine speed is set to 75 r/min with a grinding wheel pressure of 15 N. The wear rate is calculated to evaluate the wear resistance of the hammer head. The pendulum-type bending impact testing machine is used for impact toughness testing. The size of the instrument preparation is 10 mm × 10 mm × 55 mm, with a notch depth of 2 mm and a notch angle of 45° for the hammer crushing component experimental sample. The sample is placed on the support of the impact testing machine, with the notch aligned with the impact point of the pendulum. The experiment is conducted and the impact toughness value of the sample is calculated, as shown in **Figure 7**.

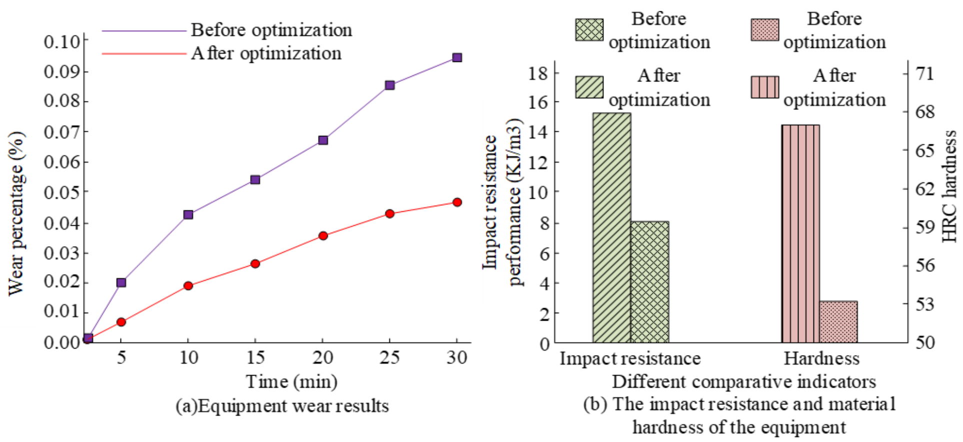

Figure 7. Analysis of performance testing results of hammer crushing components: **(a)** Equipment wear results; **(b)** The impact resistance and material hardness of the equipment.

In **Figure 7a**, after 30 min of testing before equipment optimization, the wear degree of the hammer sample is about 0.093%. However, after using research methods to improve the multi-layer composite material of the hammer head sample, the wear amount within the same time period is significantly reduced, only about 0.042%. In **Figure 7b**, the hammer head test sample before optimization has an impact toughness value of 8 J/cm^3 and an HRC hardness of 53. After optimization design, the performance of the hammer specimen has been significantly improved, with an increase in impact toughness value to 15 J/cm^3 and an increase in HRC hardness to 67. This indicates that through the design improvement of multi-layer composite materials, the wear resistance of hammer specimens has been significantly enhanced, and their impact toughness and hardness have also made a qualitative leap. The service life and work efficiency of the equipment have been significantly improved under high load and high wear conditions.

To comprehensively evaluate the comprehensive performance of the optimized hammer crushing components, experimental data on fatigue performance, interface bonding strength, and actual working condition life verification were further supplemented in the study. Firstly, a high-frequency fatigue testing machine with the model number Instron 8874 was used to conduct cyclic impact testing on the hammer specimens before and after optimization. The experiment set the impact load to 80% of the rated working load, with a frequency of 5 Hz and a total of 10 cycles. The test results are shown in **Table 2**.

Table 2. Fatigue performance test results of hammer crushing components.

Test project	Before optimization	After optimization	Increase/decrease percentage (%)
Number of cycles of initial crack occurrence	5×10^5	8×10^5	+60
Initial crack length (mm)	0.2	0.1	−50
Crack growth rate	2.1×10^{-6}	0.8×10^{-6}	−62
Remaining tensile strength (MPa)	900	1200	+33

Then, the scratch test was used to evaluate the bonding strength between the nano ceramic coating on the surface of tungsten carbide particles and the substrate. The experiment used a diamond indenter with a radius of 100 μm, a loading rate of 10 N/min, and a maximum load of 50 N. The results showed that the critical load of the coating was 38.2 N, and there was no peeling phenomenon at the interface, indicating good adhesion between the coating and the substrate. The nanoindentation test of the graphite nanosilver interface showed that the hardness of the interface area was 4.2 GPa, the elastic modulus was 85 GPa, and the compatibility with the substrate (hardness 3.8 GPa, modulus 78 GPa) was excellent, without interface delamination. Finally, a comparative test was conducted on the hammer heads before and after optimization at a coal mine site, recording the cumulative crushing volume and wear volume. The results are shown in **Table 3**.

According to **Table 3**, the optimized hammer head has an extended lifespan of 36.5% and a reduced wear rate of 57%, verifying the engineering applicability of multi-layer composite material design.

Table 3. Fatigue performance test results of hammer crushing components.

Test project	Before optimization	After optimization	Increase/decrease percentage (%)
Accumulated amount of broken lignite (ton)	12,300	19,654	+59.8
Wear volume (cm^3)	1.45	0.62	−57.2
Service life (h)	10,000	13,651	+36.5

3.3. Analysis of vibration and noise levels of coal crusher

To investigate the vibration and noise reduction effects of the designed spring isolator and acoustic package on the coal crusher, this study selects three operating conditions for testing the spring isolator. **Table 4** shows the parameters of the spring isolator under three operating conditions.

Table 4. Spring isolators under three operating conditions.

Working condition	**Condition A**	**Condition B**	**Condition C**
Maximum bearing capacity (kN)	63.2	64.2	68.9
Vertical stiffness (kN/mm)	1.172	2.234	3.241
Horizontal stiffness (kN/mm)	1.168	2.183	3.196
Installation dimensions: length (mm) × width (mm)	200 × 200	200 × 200	200 × 200
Damping coefficient (kN·s·m^{-1})	100	100	100

To accurately evaluate the vibration reduction effect of optimized design, this study conducted finite element analysis using MSC NASTRAN software based on the parameters in **Table 4**, and accurately calculated the velocity amplitude frequency curves of key points at different frequencies. The analysis focuses on the longitudinal vibration velocity, and the relevant results are shown in detail in **Figure 8**.

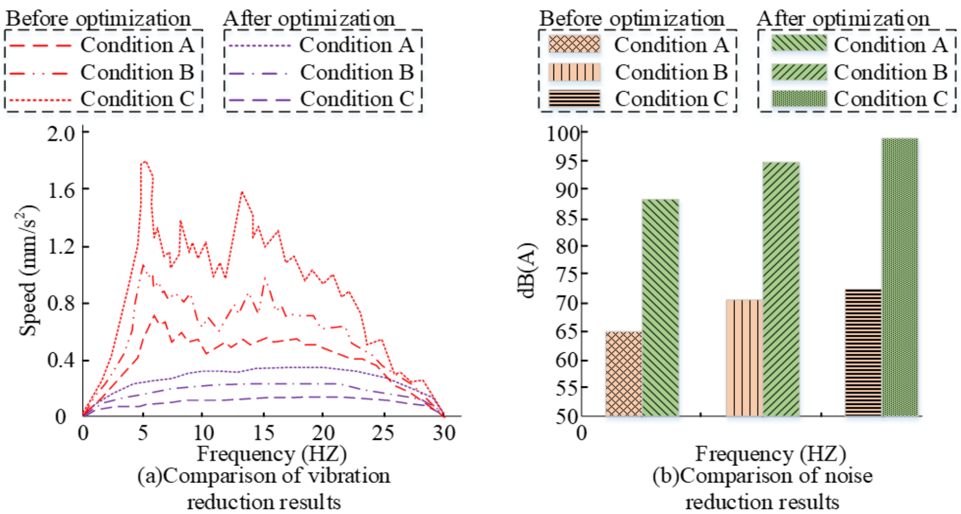

Figure 8. Comparison of vibration and noise reduction effects before and after optimization of coal crusher: **(a)** Comparison of vibration reduction results; **(b)** Comparison of noise reduction results.

Figure 8a shows the comparison of vibration reduction effects before and after optimizing the coal crusher. Before optimization, the velocity amplitude frequency curve of the coal crusher shows significant fluctuations under different operating conditions, with a peak vibration velocity of 1.78 mm/s^2. This indicates that there is significant vibration during the operation of the device. However, after optimizing the research methods, the velocity amplitude frequency curve became relatively stable, and the maximum vibration velocity is effectively controlled within 0.38 mm/s^2. This fully demonstrates the significant effectiveness of optimization measures in reducing equipment vibration. **Figure 8a** shows the comparison of noise reduction effects before and after optimizing the coal crusher. Before optimization, the noise decibel values of the coal crusher under operating conditions A to C are approximately 87.6 dB (A), 94.2 dB (A), and 97.1 dB (A), respectively. The noise level is relatively high and had a significant impact on the surrounding environment and the health of operators. After optimization, the noise decibel values under the same operating conditions are significantly reduced, with the noise decibels of the three operating conditions dropping to about 65.1 dB (A), 70.2 dB (A), and 71.2 dB (A). The optimized coal crusher performs well in noise reduction, providing strong support for creating a quieter and more comfortable working environment.

To further highlight the superiority of the optimized coal crusher in this study, three mainstream coal crushers on the market were selected for comparison: Sandvik's hybrid crusher, Meizuo Outotec's NP series impact crusher, and Northern Heavy Industries' dual rotor ring hammer coal crusher. Comparative experiments were conducted to quantitatively analyze the vibration velocity of four coal crushers through three sets of repeated experiments. The data analysis was conducted using one-way ANOVA to verify significance, and the 95% confidence interval was calculated. The results are detailed in **Table 5**.

Table 5. Performance comparison results of four coal crushers.

Performance index	Sandvik	Meizuo Outotec	Northern Heavy Industries	Research and optimize aircraft models	*P* value
Peak vibration velocity (mm/s^2)	2.10 ± 0.13	1.95 ± 0.09	2.30 ± 0.12	0.38 ± 0.01	< 0.01
Noise decibels (dB (A))	89.5 ± 4.6	91.2 ± 4.8	93.8 ± 5.6	68.8 ± 3.2	< 0.01
Hammer head lifespan (h)	10,235	10,520	9635	13,651	< 0.01

According to **Table 5**, the optimized coal crusher outperforms the other three mainstream coal crushers in terms of peak vibration speed, noise decibels, and hammer life. This stems from the optimization of research in multiple aspects: The rotor adopts a spider web biomimetic design, combined with multi-layer mesh support and elastic connectors, effectively disperses dynamic loads, and is precisely tuned with spring isolators to significantly suppress vibration energy transfer; The double-layer acoustic package and nano coating work together to block noise radiation, while the irregular mesh design of the biomimetic sieve plate reduces material collision noise. Hierarchical composite material design and nano-interface strengthening technology significantly improve wear resistance and impact toughness.

4. Conclusion

Research on optimizing the performance and structure of coal crushers through spider-inspired design and the application of multi-layer composite materials. The experimental results show that the stability and seismic performance of the supporting structure are significantly improved. The lateral displacement of the main axis is reduced by 85% and 65% under no-load and full-load conditions, respectively. The seismic performance is improved by at least 20% under different impact forces; The performance of the hammer crushing component has been improved, with increased wear resistance and a 55% reduction in wear rate; Hardness increased from HRC 53 to 67 (an increase of 26%); increased impact toughness by 88%; The fatigue life is extended by 36.5%, and the hammer head life reaches 13,651 h; The vibration and noise control effect is significant, with a peak vibration speed reduction of 80% and a decrease in noise decibels from 97.1 dB (A) to 71.2 dB (A), a decrease of 26.6 dB (A).

After optimization, the noise level is lower than that of mainstream equipment; the comprehensive performance is superior to mainstream products in the market. Compared with brands such as Sandvik and Meizuo Outotec, the optimized coal crusher performs excellently in peak vibration speed, noise level, and hammer head life. However, there are still potential issues such as limitations in experimental conditions, increased material costs, and insufficient validation of long-term operational stability. Future research will first expand experimental conditions and simulate a wider range of operating conditions to comprehensively evaluate the performance of optimized designs in complex environments. Secondly, conduct a detailed cost-benefit analysis to evaluate the balance between the increase in material costs and performance improvement brought about by optimized design, ensuring its economic feasibility in industrial applications. In addition, long-term operational testing will be conducted to verify the stability of the equipment during continuous operation, identify potential issues, and further improve the design. These studies will provide more efficient, low-noise, and durable coal crusher solutions for the coal industry, promoting the development of coal crushing operations towards a more sustainable and efficient direction, reducing equipment maintenance costs and energy consumption, and reducing environmental impact.

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